

Cold Spray Assisted Mg/Al Dissimilar Resistance Spot Welds

by

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Statement of Contributions

- [1] **M. Oheil**, D. Saha, H. Jahed, and A. Gerlich, “Dissimilar resistance spot weld of Ni-coated Aluminum to Ni-coated Magnesium using cold spray coating technology,” *Metals*, August, pp. 1–20, 2025
- [2] **M. Oheil**, H. Jahed, and A. Gerlich, “Fatigue of Cold Spray-Assisted Resistance Spot Welding of Aluminum to Magnesium,” in *HI-AM*, 2025, vol. 8, no. 75, pp. 25–28.
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- [4] W. Hou, Z. Shen, N. Huda, **M. Oheil**, Y. Shen, H. Jahed, and A. P. Gerlich, “Enhancing metallurgical and mechanical properties of friction stir butt welded joints of Al–Cu via cold sprayed Ni interlayer,” *Materials Science and Engineering: A*, vol. 809, no. February, p. 140992, 2021.

Abstract

The increasing demand for lightweight vehicles to improve fuel efficiency and reduce greenhouse gas emissions has encouraged the use of materials such as aluminum (Al) and magnesium (Mg) in automotive design. These metals offer excellent strength-to-weight ratios and recyclability but present challenges when joined together due to the formation of brittle intermetallic compounds (IMCs) during traditional welding processes. Resistance spot welding (RSW), a common method in automotive manufacturing, is particularly limited when directly joining Al and Mg because of these IMC-related issues.

This study investigates the use of cold spray (CS) technology to enable reliable RSW of dissimilar Al/Mg joints. Cold spray is a solid-state deposition method that can create interfacial coatings, acting as a physical barrier between the base metals and reducing IMC formation. In this research, nickel (Ni) and titanium (Ti) powders were selected as interlayer materials due to their high melting points and favorable metallurgical properties. These coatings help isolate the Al and Mg during welding, improving bond quality and weld durability.

Ni and Ti coatings were applied to Al 6022-T4 aluminum and AZ31B magnesium alloy sheets using a low-pressure cold spray system. Ni was deposited at 485–500 °C and 1.5 MPa, while Ti was applied at 500 °C and 1.4 MPa using nitrogen as the carrier gas through a DeLaval nozzle. Coating thicknesses ranged from 80–120 μm for Ni and 260–350 μm for Ti. RSW was then conducted using optimized welding parameters: 27 kA current for Ni-coated and 22 kA for Ti-coated samples, both under 4 kN force with two pulses of 15 cycles each. Lap shear testing showed maximum strengths of 4.3 kN for Ni and 4.2 kN for Ti, significantly higher than the 0.833 kN strength observed in direct Al/Mg welds.

Post-weld characterization using optical microscopy (OM) and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDX) revealed minimal IMC formation at the Al/Mg interface for both coating types. Mg was detected at the Ni-to-Ni and Ti-to-Ti interfaces

within the weld nugget, indicating some elemental diffusion but no significant degradation of joint quality. Since the welding was carried out using a novel approach, both the weld mechanism and the behavior of magnesium during the process represent unobserved phenomena. This reveals a unique joining mechanism, offering new insights into how Mg reacts under such conditions and emphasizing the innovative contribution of this study to dissimilar metal welding research. Also, Ti coatings provided slightly better IMC suppression, attributed to Ti's strong affinity for Mg and its role in forming a stable transition layer.

Fatigue and monotonic testing were conducted to assess long-term joint performance under cyclic and static loading. The results demonstrated substantial improvements in both durability and mechanical performance when using cold spray coatings. On average, joint strength increased by a factor of 4.6 with a Ti coating and 4.9 with a Ni coating compared to direct RSW joints that achieve 0.833kN load. For the cyclic load, the fatigue strength at 2M cycles reached 1.28 kN max load for Ni-coated Al/Mg joint and reached 1 kN max load for Ti coated Al/Mg joint. It is worth to mention that the Ti-coated joint reached its level of strength and fatigue performance after approximately 3% of Al powder was mixed with the Ti powder and then deposited only on the Al sheet using the cold spray technique, which underscored the critical role of powder mixing in improving joint integrity and mechanical performance.

This study highlights the excellent role of cold spray technology in enabling reliable resistance spot welding of dissimilar aluminum and magnesium alloys. By applying Ni and Ti coatings through cold spray, intermetallic compound formation is significantly reduced, enhancing joint strength and durability. The coatings act as diffusion barriers and improve metallurgical compatibility, making cold spray a key innovation for joining lightweight metals in automotive applications.

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Chapter 1: Introduction

In recent times, there has been a significant industrial shift towards mitigating emissions resulting from fossil fuel combustion, driven by the urgent need to combat climate change and reduce greenhouse gas emissions. The automotive sector in particular has been actively exploring avenues to minimize vehicle weight as a means to lower fuel consumption, manufacturing costs, and harmful gas emissions, all in an effort to protect our environment. However, it is crucial to emphasize that while striving for these objectives, vehicle safety and reliability cannot be compromised. In the pursuit of these goals, dissimilar combinations of aluminum (Al), magnesium (Mg), and composite materials emerge as prime candidates for achieving substantial weight reduction in vehicles. Although composite materials may achieve some of the highest specific strength and stiffness values commercially available, they often come with a higher price tag, making Al and Mg exceptionally attractive alternatives for light-weighting in automotive body structures. These materials offer promising opportunities to revolutionize the automotive industry and drive toward a more sustainable and eco-conscious future. Composites also cannot be joined by conventional methods, while metals are readily welded throughout the automotive industry.

In the automotive industry, resistance spot welding (RSW) stands out as the most prevalent and cost-effective joining technology. When it comes to incorporating Al and Mg sheet materials into automotive structures, the challenge lies in welding them together effectively, especially in dissimilar RSW joints. Directly welding Al and Mg poses a considerable challenge as it tends to result in the formation of weak and brittle intermetallic compounds, which severely limits the utility of these materials in

combination [1]. To address this issue, one approach reported widely involves the use of an interlayer foil, which will be examined further in the literature review. However, it is worth noting that while this approach offers a solution, it comes with the drawback of increasing the number of components and poses challenges in terms of implementation [2].

Cold spray (CS) coating technology has emerged as a promising solution in the realm of coating technologies, offering the potential to create a suitable interface for high-quality Al to Mg welding. What sets cold spray coating apart is its capability to build layers from powder on a substrate surface without transitioning to a liquid state. This unique attribute can prove to be highly advantageous in preventing the formation of notoriously brittle Al-Mg intermetallic compounds (IMCs), thereby enhancing the overall welding process and the resulting joint quality.

1.1 Research motivation

The automotive industry is increasingly focused on the imperative task of reducing vehicle weight to enhance efficiency, minimize fuel consumption, and lower greenhouse gas emissions. Within this context, resistance spot welding (RSW) has emerged as a favored method for joining materials in automotive applications, particularly in the construction of vehicle body structures. RSW offers a host of advantages, including the absence of added weight from welded materials, as well as a swift and relatively straightforward welding process when compared to other methods. This aligns seamlessly with the industry's objectives, as it can contribute to the overall weight reduction of vehicles. To further bolster these weight-reduction efforts, the industry has turned to lightweight materials, such as Mg and Al, for use in automotive body structures. These materials offer significant weight advantages. However, a significant challenge arises

when welding Mg and Al directly together due to the formation of intermetallic compounds-problematic issues as these phases are both weak and brittle, hampering the structural integrity of the welded joint [3]–[5]. While the application of interlayers has demonstrated promise in addressing the challenges posed by dissimilar material welding, particularly in the automotive industry, widespread adoption presents certain logistical difficulties [5]–[8].

The selection of Al and Mg for various applications is based on several key advantages and properties that these materials offer. Here are some of the primary reasons for choosing Al and Mg in various engineering and manufacturing applications:

- Low density: Both Al and Mg are lightweight metals. Al, in particular, is known for its very low density, making it an attractive choice when reducing weight is a critical design consideration. Lightweight materials can lead to improved fuel efficiency in transportation and reduced overall structural weight in various applications.
- High strength-to-weight Ratio: Despite their low density, both Al and Mg offer good strength-to-weight ratios. This means they can provide adequate structural integrity while keeping the weight of components to a minimum, making them suitable for applications where strength and weight are important factors.
- Thermal conductivity: Both Al and Mg are excellent conductors of heat, making them suitable for applications where efficient heat dissipation is required. This is particularly beneficial in industries such as electronics, automotive, and thermal management.
- Machinability: Al and Mg are relatively easy to machine and process, which simplifies manufacturing and fabrication processes. They can be cast, extruded, and

machined into various shapes, which is advantageous when complex components or tight tolerances are needed.

- **Recyclability:** Both Al and Mg are highly recyclable materials. Recycling not only reduces environmental impact but also offers cost savings in material procurement, contributing to sustainable and environmentally friendly practices.
- **Electrical conductivity:** Al is an excellent conductor of electricity and is used in electrical applications, including electrical wiring and conductors.
- **Cost-effectiveness:** Al and Mg are often more cost-effective than other light-weight materials such as composites, making them economically attractive for various applications.
- **Aesthetic appeal:** Al and Mg can be easily finished and have an attractive, often shiny appearance, making them desirable for products where aesthetics are important.

While Al and Mg offer many advantages, it is essential to consider their limitations and the specific requirements of each application. For instance, Mg can be more reactive and susceptible to some environmental conditions, and Al may not have the same strength as some other materials. Therefore, engineers need to carefully assess the trade-offs and select materials based on the unique needs of each project. Additionally, surface treatments and alloying can be used to enhance the properties and performance of Al and Mg in various applications. And since Al and Mg have lower densities than steel, their lower stiffness means larger material thickness is needed to achieve comparable resistance to deflection.

In an automotive body structure, there can be an extensive number of spot welds, ranging from 3000 to 5000, and incorporating interlayers at each of these weld points

becomes a complex and cumbersome endeavor. The substantial quantity of spot welds increases the challenge of introducing interlayers systematically. Furthermore, the use of interlayers can potentially elevate the bending moment experienced by the welded components, primarily due to an increase in the offset between the sheets being joined. This trade-off between addressing the intermetallic issue and introducing unintended mechanical consequences necessitates a more nuanced approach to welding dissimilar materials in the automotive sector.

Cold spray coating technology on the other hand is a new versatile coating technology which operates at low temperatures. Many metal powders, including pure Al [9], Zn and AA7075[10], steel [11], have been successfully coated on a variety of substrates, including Mg [9], [10] and Al [11], [12]. Multilayer coatings have also been recently explored [13]. The significant progress in cold spray technology has positioned it as a promising candidate for various applications, including additive manufacturing using different metal powders and serving as an interlayer for dissimilar material joints. Traditional interlayers employed in dissimilar welding have primarily focused on two critical functions: (1) creating bonds through ultrathin intermetallic layers, often several micrometers thick, and (2) preventing direct contact between molten Al and Mg to avert the formation of brittle intermetallic compounds. Cold spray technology offers the potential to fulfill both of these roles effectively. Furthermore, one pivotal aspect that enhances the suitability of cold spray coating is its adaptability for automation and implementation by robotic systems in the automotive industry. This convergence of resistance spot welding and cold spray coating, both amenable to automation, augments their utility, particularly in an industrial context. Consequently, cold spray coating

emerges as a more practical and efficient alternative to traditional interlayers. Additionally, the ability to optimize and control coating thickness holds the promise of reducing the bending moment applied to RSW joints. In essence, this research aims to harness cold spray coating technology to facilitate resistance spot welding of dissimilar Mg/Al joints, thereby addressing a critical need in the automotive sector.

1.2 Objectives

The objectives of this research are classified to primary and secondary goals as follows:

Primary goal:

1. To obtain a reliable dissimilar Al/Mg resistance spot weld using a cold spray coating interlayer.

To facilitate the welding joint between Al and Mg, the following steps will be employed

- ✓ Coating with Ni powder and Ti powder and welding the samples.
- ✓ Prepare metallographic samples to study the microstructures, to measure the coat thickness and to obtain the material component by using SEM and observe the Mg effect on the weld.
- ✓ Perform tensile testing for samples welded with the best welding parameters to determine the maximum load capacity.

Secondary goals:

2. Finding cold spray coating parameters of the candidate metal powders to coat the Al and Mg sheets using a low pressure system.

The utilization of cold spray coating as a facilitator for resistance spot welding in dissimilar joints, such as Mg/Al, represents a novel approach in this research. The choice of powder materials for the coating is influenced by previous literature where materials

like Zn and Ni have been employed as interlayers. To ensure the success of this approach, the following key points must be addressed:

- Compare different interlayer metals (e.g., Zn, Ni, Ti) and determine which one yields the most favorable welding outcomes.
- Optimize the coating parameters for each specific powder metal, including considerations related to coating thickness and potential surface treatments.
- Identify the specific welding parameters that are most closely associated with the chosen powder metal, ensuring that the welding process is well-suited to the coating.

The powder selected as an interfacial coating should meet the following considerations:

- ✓ **Compatibility:** The chosen powder material must exhibit compatibility with both the Mg and Al substrates to facilitate effective bonding.
 - ✓ **Intermetallic formation:** An ideal powder should help in avoiding or minimizing the formation of undesirable intermetallic compounds during welding, which can weaken the joint.
 - ✓ **Mechanical properties:** The selected powder metal should possess suitable mechanical properties, including strength and ductility, to ensure the integrity and durability of the resulting joint.
 - ✓ **Coating parameters:** To optimize the cold spray coating, parameters such as gas type, pressure, temperature, feed rate, nozzle velocity, and standoff distance should be fine-tuned for the specific powder material in use.
3. Characterize quasi static and cyclic behavior of the joints to find and describe the weld strength and the fatigue strength.

4. To determine the role of powder mixture in improving cold spray coating performance such as enhancing coating integrity and interfacial bonding and to establish selection criteria for future interlayer powders based on material compatibility, mechanical properties, and suitability for cold spray-assisted dissimilar welding applications.
5. Evaluate a method for in-situ early crack detection in spot welds under cyclic loads.

Developing an in-situ method for early crack detection in spot welds subjected to cyclic loads holds significant promise for improving the monitoring and assessment of spot weld integrity. This method aims to enable the timely detection of crack initiation at the nugget root, without the need for test interruption. The approach should not only identify cracks at their nascent stage but also track their progression until final failure. Moreover, the ability to accurately measure the true strain within the hot spot zone, where crack formation is most critical, is of paramount importance. In the case of tensile shear welded specimens, cracks tend to initiate at the periphery of the nugget, at the interface between the two joined sheets, making it a challenging task to pinpoint the exact moment when crack nucleation occurs. As a result, early-stage crack initiation within this zone has historically gone undetected unless visible on the outer surface or until the test is randomly interrupted and the presence of a crack is subsequently confirmed. This research initiative aims to address these challenges and develop an effective in-situ method for early crack detection, enhancing the assessment of spot weld integrity under cyclic loads.

1.3 Thesis overview

The presented thesis encompasses a multifaceted exploration of dissimilar resistance spot welding (RSW) joints, integrating various aspects including the adoption of cold

spray technology, optimization of parameters using different material powders, and the development of experimental procedures. The work conducted within the thesis covers an array of experimental facets, encompassing welding, metallography, tensile tests, fatigue tests, and innovative crack detection methods. The structure of the thesis unfolds as follows:

Chapter 2 delves into the foundational understanding of resistance spot welding, highlighting the methodologies and mechanisms involved in spot welding and providing a comprehensive review of crack detection techniques. Furthermore, it addresses the intricacies of dissimilar joints in resistance spot welding, considering the challenges and implications of joining materials with distinct properties. The chapter offers insights into the innovative application of cold spray technology and the associated knowledge gap that this research endeavors to bridge.

Chapter 3 the experimental procedures employed throughout the thesis are meticulously detailed. This includes a thorough exposition of the materials selected for the study, including the powders and base metals of the substrates, as well as the specifications of the test specimens. The parameters governing the cold spray process and resistance spot welding are listed in detail. The chapter encompasses a comprehensive account of micro-characterization methods utilized to assess the welded areas, with a focus on the results of scanning electron microscopy (SEM) and metallography for both the Ni and Ti-coated sample groups. The chapter progresses to analyze the resulting microstructure and presents the outcomes of cyclic and monotonic tests, accompanied by a discussion of the observed failure modes in the resistance spot welding specimens.

Chapter 4 details an additional segment of the experimental work dedicated to a novel crack detection method, including the selection of materials, specimen dimensions, finite element (FE) models, and the corresponding test matrix. The outcomes of the displacement and strain (DIS) analysis for the crack detection method are thoughtfully discussed.

Chapter 5, this chapter focuses on the characterization of dissimilar spot welds, offering detailed information about the Al/Mg base materials and the Ni powder used. It discusses the properties of the cold-sprayed Ni-coated Al/Mg sample group, followed by an analysis of the joining mechanism and the failure behavior of the Ni-coated joint

Chapter 6 focuses on the characterization of dissimilar spot welds, offering insights into the Al/Mg substrate materials and the Ti powder used. It examines the properties of the cold-sprayed Ti-coated Al/Mg sample group and presents a comparative analysis between Ti and Ni coatings. The chapter concludes with a summary of the key findings.

Chapter 7 centered on the fatigue behavior of dissimilar spot welding Al/Mg joints, this chapter delves into a comprehensive exploration of the fatigue characteristics exhibited by the developed Ni-coating Al/Mg and Ti-coating Al/Mg joints. It juxtaposes the noteworthy observations related to the fatigue behaviors of these developed joints, facilitating a comparative analysis between the Ni-coating and Ti-coating groups.

Chapter 8 concluding the thesis, this chapter succinctly summarizes the contributions made throughout the research. It draws together the key findings, underscores the principal conclusions, and offers recommendations for prospective avenues of research. The thesis collectively represents a significant contribution to the field, addressing critical challenges in dissimilar joint welding and expanding the frontiers of knowledge and

manufacturing applications. Below is a graphical abstract in Figure 1:1 that shows how the challenging of welding the Al to Mg has been carried out adopting the cold spray technology.

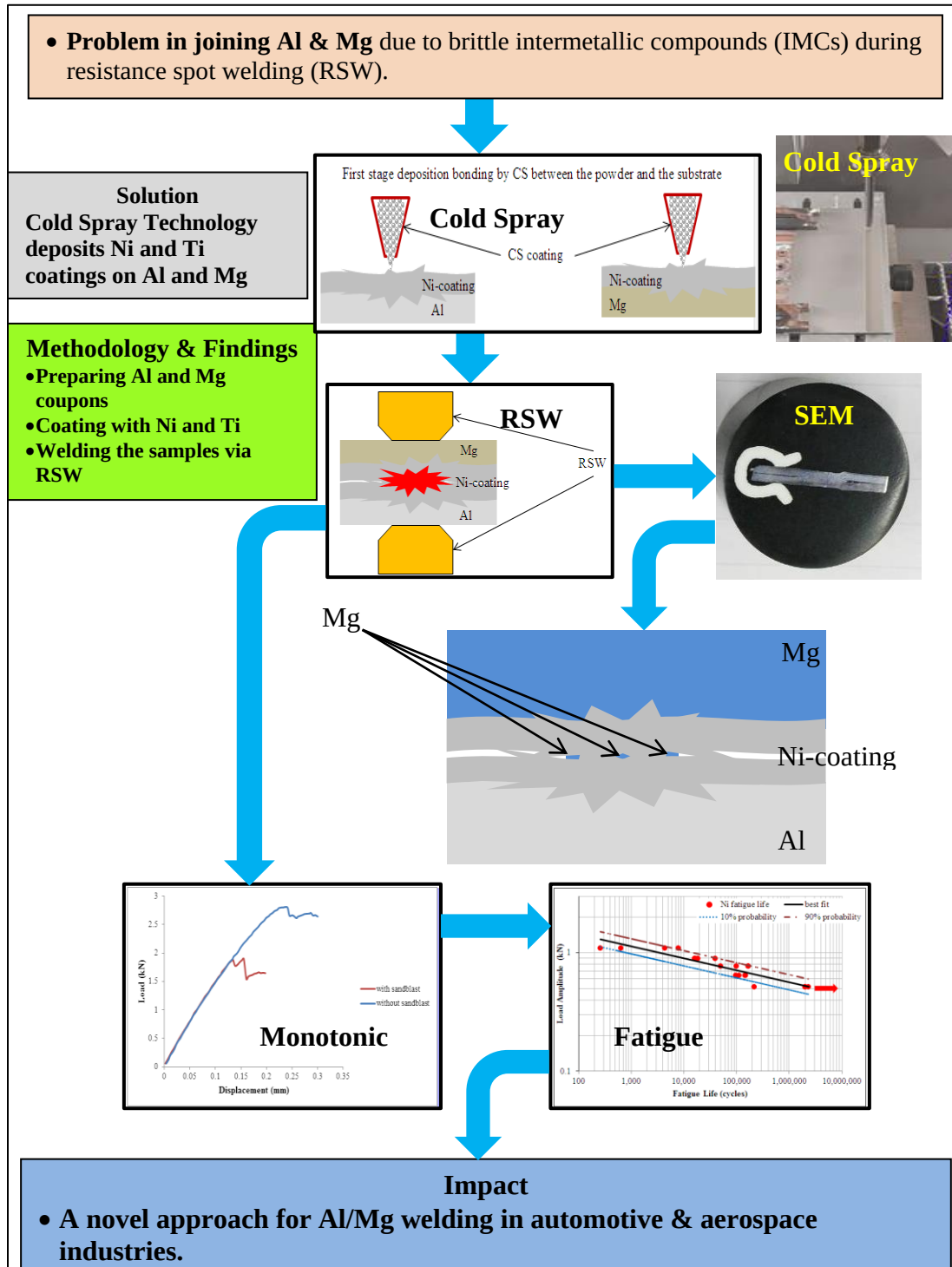


Figure 1:1 Graphical abstract for the current work.

Chapter 2: Background and Literature

Review

2.1. Cold spray (CS) coating technology

Cold spraying is an innovative solid-state deposition technique that emerged as a coating method in the 1980s, but not commercialized until early 2000s. This process involves accelerating solid metal particles to supersonic velocities and directing them toward a substrate [14], [15]. To achieve this, a propulsion gas, such as air, nitrogen, or helium, is pressurized to high temperatures and pressures. The compressed gas is then used to propel metal particles or powders at speeds exceeding 340m/s. Upon impact with the substrate, these particles deform and adhere to it through a combination of mechanical adhesion and metallurgical bonding. It is important to note that the success of cold spraying hinges on the kinetic energy of the particles before impact, rather than their thermal energy. Furthermore, the materials employed in the cold spraying process typically remain in a solid state throughout the coating procedure. The interaction at both the inter-particle and particle-substrate interfaces induces localized plastic deformation, leading to mechanical interlocking and the creation of metallurgical bonds. This results in the deposition of solid particles onto the substrate, forming a durable and effective coating.

There are some parameters that influence the coat quality, such as the size and the velocity of the particles, see Figure 2:1 a. Reliable deposition via cold spraying requires

exceeding the critical impact velocity for the particles of metal [16]–[20]. In general, deposition quality can be improved with higher particle velocity. Depending on the material type, particle size and/or particle temperature, the critical velocity can be changed in the cold spray coat process. Increasing the size of the particles and the temperature can reduce the critical velocity during the cold spray coating process [16], [18], [20], [21]. The acceptable range of the powder size is between 10 and 100 μm in diameter in the cold spray process to ensure there is sufficient particle speed to exceed the critical velocity [19]. Accelerating the particles that are outside the typical size range (i.e. 10 to 100 μm in diameter) is difficult; therefore, efficient deposition is mainly restricted to this range [22]. The effective range that is frequently used is 20 - 60 μm ; however, with low-density materials such as Al and Zn, the useful particle size can increase to 100 μm [19].

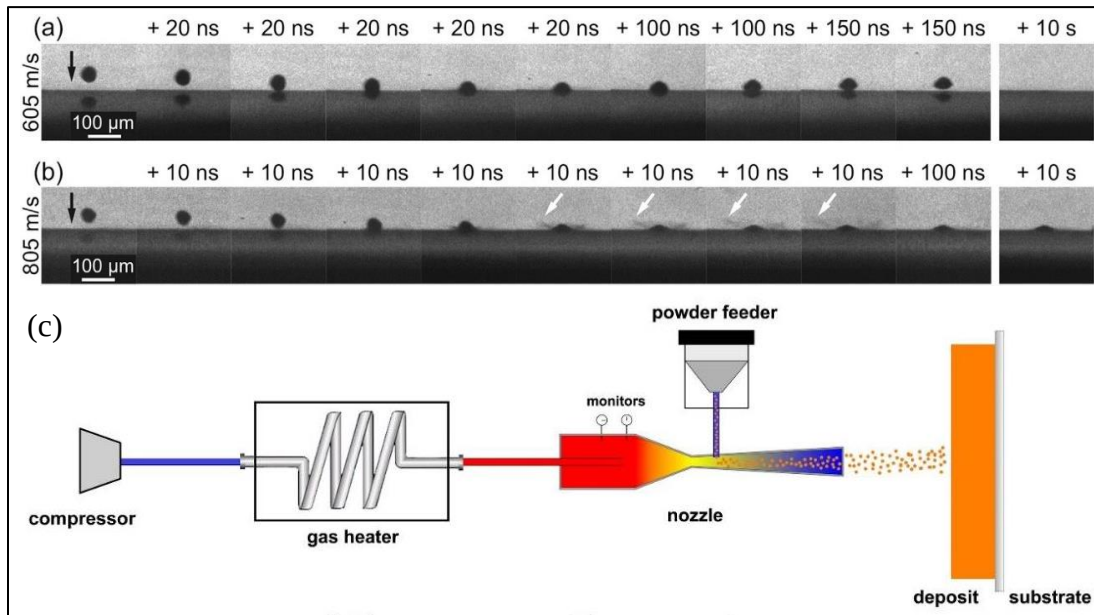


Figure 2:1: a) Particle bouncing due to low velocity and b) Particle adhesion at right critical velocity, c) a low pressure cold spray system[23].

2.1.1. Theories regarding bonding mechanism of CS

Cold spray coating technology can be considered as a relatively new coating method. The principle of cold spray depends on impact and deposition of powder or fine particles in the solid-state, which are accelerated using a compressed gas flow at supersonic velocity towards a substrate material. Initially, Alkimov and Papyrin et al. [14] developed cold spray technology at the Institute of Theoretical and Applied Mechanics of The Russian Academy of Sciences in Novosibirsk in the 1980s [15], [23]–[25]. They found that in the high-velocity impact the fine metallic particles are deposited on the metallic substrate. In the cold spray process, the most important parameter is the velocity of the particles which is well known as critical velocity; the particles can be deposited properly if the velocity of the particles is higher than or equal to the critical velocity. Nitrogen, helium and air are the carrying gases usually adopted to accelerate the fine particles in cold spray device. The cold spray systems can be classified into two types according to the pressure of the gases, namely are high-pressure cold spray (HPCS) and low-pressure cold spray (LPCS) systems, and the pressures in the LPCS variant are usually around 1-2 MPa [25].

The carrying gases are heated by an electrical heater to achieve high particle temperature and high particle velocity. Then the carrying gas and the fine particles, which have a size range between 10 and 60 μm , are injected with high pressure into a convergence-divergence nozzle (or de Laval nozzle) in order to accelerate the small particles up to supersonic velocities through the nozzle. When the small particles impact the substrate with high velocity, they deposit on the substrate and create a coating layer by deforming and bonding to the substrate. The whole cold spray process is performed

below the melting temperature of the powder material, which prevents heat from influencing/affecting the material properties [15], [25], [26].

2.1.2. Powder particle critical velocity

In the context of cold-spray technology, the critical velocity is a key parameter that refers to the minimum velocity required for a powder particle to effectively bond with the substrate during the deposition process. This is the velocity threshold above which the particles impact and adhere to the substrate, forming a strong bond. Below this critical velocity, the particles will not bond effectively, and the coating quality will be compromised. The critical velocity depends on various factors, including the size and material of the powder particles, as well as the properties of the substrate material. It is essential to control velocity in cold-spray applications to ensure proper coating adhesion and quality.

2.1.3. Cold spray particle size

The size of the powder particles used in cold spray process is a crucial factor influencing the coating quality, bonding, and overall process efficiency. Smaller particles tend to have a higher specific surface area and can bond more effectively at lower velocities due to their increased surface reactivity. On the other hand, larger particles require higher energy to reach the critical velocity and achieve proper bonding. The choice of particle size depends on the specific application and the desired coating characteristics. Fine powders are often used for achieving dense and uniform coatings, while larger particles may be chosen for building up thicker coatings or achieving specific applications from the coat. Cold spray processes generally utilize gas-atomized powders with particle sizes ranging from 5 to 50 μm . This size range is optimal for achieving high deposition efficiency and coating quality. For Ni coating, a study

examining cold-sprayed pure nickel coatings utilized powders with median particle sizes of 25 μm , 45 μm , and 67 μm . The coating fabricated with the 45 μm powder exhibited the highest densification and mechanical properties [27]. For Ti coating, research focusing on pure titanium coatings investigated powders with mean particle sizes between 20 and 49 μm . A spherical powder with a 29 μm mean particle size was found to produce coatings with the lowest porosity and best cold spray ability [28].

2.1.4. CS process parameters

The type of gas used in the cold spray process plays a significant role in determining the outcome of the deposition. Common gases used include nitrogen, helium, and air. The choice of gas affects the particle acceleration, velocity, and overall energy transfer during the process. For example, helium, being lighter than air, can lead to higher particle velocities and is often used for applications where high kinetic energy is required for bonding [14][29]. Nitrogen and air are more commonly used due to their availability and cost-effectiveness [30]. The selection of the gas depends on the desired coating properties and the specific material being deposited[20].

The temperature of the gas is another critical parameter in the cold-spray process. Heating the gas can significantly influence the adhesion of powder particles to the substrate. By preheating the gas, it can enhance the plastic deformation and adhesion properties of the powder particles upon impact. the preheating has also reduce the critical velocity [31]. However, gas temperature must be carefully controlled to avoid excessive heating that could lead to undesired thermal effects on the substrate material. The gas temperature is typically selected based on the material to be deposited and the desired coating characteristics [30][32].

Gas pressure, often involving the use of compressed air or other gases, influences the acceleration and velocity of powder particles. Higher gas pressure can lead to increased particle velocity and kinetic energy. This can enhance coating quality by promoting better adhesion to the substrate. However, excessive gas pressure should be avoided as it might lead to excessive particle deformation, causing undesired effects [30][29].

The powder feed rate determines the quantity of powder being introduced into the cold-spray system. Adjusting the feed rate affects the coating thickness and overall quality. A higher feed rate can result in thicker coatings, but it might require higher gas velocity and pressure to maintain coating quality. Lower feed rates may be used for finer control, especially when creating thin or precise coatings. The feed rate should be optimized to balance between coating thickness and quality [30][33].

Nozzle speed refers to the speed at which the nozzle or spray gun is moved over the substrate, and this influences the coating thickness and uniformity. A higher nozzle speed may result in a thinner coating, while a slower speed can produce thicker coatings. The choice of nozzle speed depends on the desired coating thickness and uniformity. Slower nozzle speeds can enhance coating uniformity and adhesion [32][33].

Step-over or overlap, determines the distance between the spray gun passes during the deposition process. Adjusting this parameter affects the overlap of adjacent spray passes. A smaller step-over distance leads to higher overlap, which can improve coating uniformity. Larger step-over distances reduce overlap and may result in uneven coatings. The step-over distance is crucial in achieving consistent coatings across the substrate [30][33].

The stand-off distance is the space between the nozzle and the substrate. It plays a significant role in controlling the coating quality. A smaller stand-off distance typically results in better coating adhesion and denser coatings. However, it requires precise control to avoid nozzle-to-substrate contact. A larger stand-off distance might be chosen for applications requiring a more diffuse coating. The stand-off distance should be optimized for each specific application [29][30].

2.1.5. Research trends

The potential utility of the cold spray coating process allows this technique to be applied in many fields. In general, it can be applied to enhance surfaces properties of mechanical components, such as corrosion and wear resistance, repair of mechanical components and 3D printing production and /or fabrication of complex components. The improvement in corrosion by using cold spray is investigated for the first time by Naveen et al. [34], who, while studying the effect of coating Zn by cold spray process on mild steel substrate, observe enhanced corrosion resistance and an increase in the lifetime of the. Diab et al. [9] adopted the cold spray process to coat Mg AZ31B substrate with pure Al powder to study corrosion fatigue and the corrosion behavior of coated and un-coated coupons in NaCl environment, investigating any corrosion resistance improvement. The results show that an Al coating layer protects the Mg substrate significantly from the corrosion. Another application of cold spray is in the repair of mechanical components. For example, besides the ability of the cold spray to coat open surfaces, Widener et al. [35] successfully demonstrated the repair of an internal sealing bore of a hydraulic valve actuator made of Al-6061 using a high pressure cold spray system with Al powder. The researchers in this work demonstrate the usefulness of the cold spray technology in

repairing mechanical components. The use of cold spray to fabricate complex mechanical components has been demonstrated by the production of many mechanical parts via 3D printing layer-by-layer methods. For instance, the fabrication of a turbine blade with a complex surface profile and more examples of repairing surfaces and fabricating mechanical components using cold spray can be found in the literature; Figure 2:2 illustrates some cold spray applications [23].

Also, there are many other trends of research in the literature such as the formation of the nano-layer intermetallic using Al coating on Mg substrate [26]. In another study Marzbanrad et al. [13] used a multi-layer coating of pure Zn and AA7075 on AZ31B Mg substrate to study the residual stress that is formed in the substrate and coating during the cold spray coating process. Cooper and Smith [25] analyzed the mechanism of impact of single particle during the cold spray process in order to improve coating properties and determine the best coating parameters. Dayani et al. [10] used AA7075 powder to coat Mg AZ31B to investigate the effect of the cold spray coating on the fatigue life of the Mg and they observe that the fatigue life is significantly improved by the coating. The above examples of research trends are just a brief review of studies using cold spray coating technology and there are large number of fields and applications that adopt the process [36]. Yet, the cold spray coating has never been applied in facilitating welding Al with Mg in resistance spot welding process.

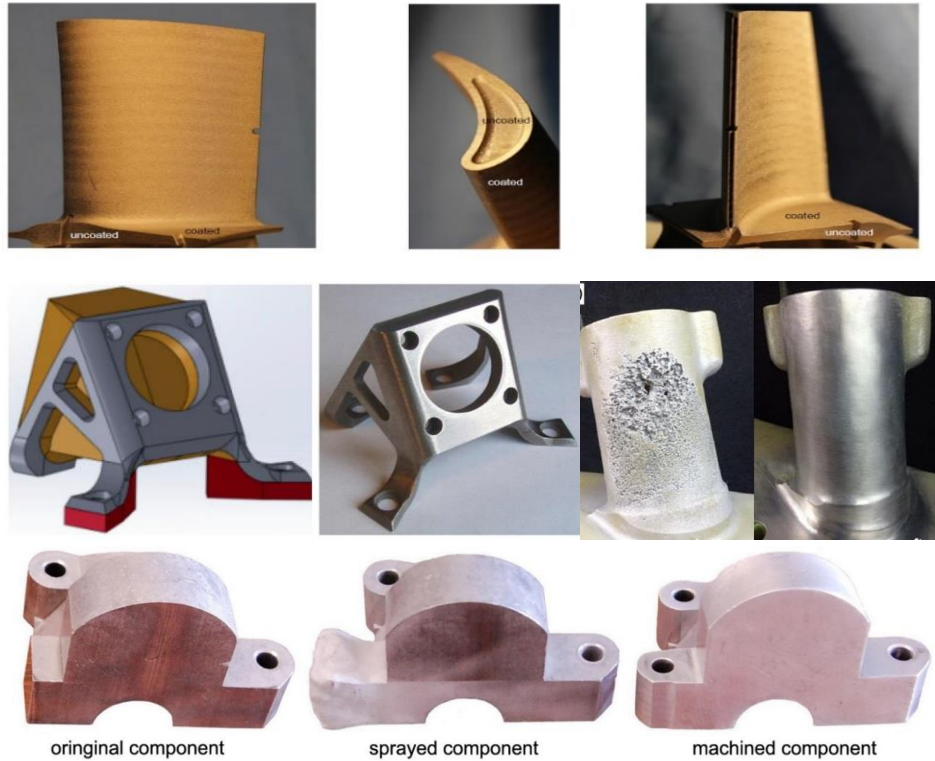


Figure 2:2: Examples of cold spray technology used for various applications [23].

2.2. Resistance spot welding (RSW)

Resistance spot welding is a rapid and effective welding technique used in the metallurgical industry. This process entails sandwiching two or more metal sheets between copper electrodes, which are then subjected to a high electrical current over an exceedingly brief timeframe, typically lasting only a fraction of a second, often measured in cycles. During this brief period, the electrical current generates Joule heat due to the resistance of the metal and the interfacial resistance between the sheets. As a result, the metal sheets are momentarily melted at the interface, effectively welding them together through solidification once the welding current is terminated. Importantly, this method does not necessitate the use of additional filler materials. Given the common electrical supply frequency of 60 Hz, each welding current cycle is equivalent to 1/60th of a

second. This process is a pivotal component of metal joining in various industrial applications [37]–[40].

2.2.1. Process of spot welding

The resistance spot welding (RSW) process hinges on three key parameters: electrode force, welding time, and welding current [37][39]. The manipulation of these parameters can have a significant influence over various aspects of the spot welding process. These factors impact the quality and strength of the spot weld, the size of the grains, the hardness of the weld, the formation of internal porosity, the dimensions of the weld nugget, the amount of expelled metal in the vicinity of the nugget, and the microstructure of both the fusion zone (FZ) and the heat-affected zone (HAZ). The spot welding process involves the following stages: initially, the metal sheets are compressed between the electrodes to ensure they are in close contact. Subsequently, a brief but intense electrical current, often ranging from 1 to 42 kA, is passed through the sheets for a very short duration, typically fractions of a second. The electrical resistance encountered during this process generates significant heat, especially at the point where the sheets are in contact, leading to the localized melting of the metal sheets at the interface. The generated heat can be expressed by following formula [37], [39], [41]: $Q = I^2 R t$, where Q is the amount of heat generated in Joules, I is the welding electrical current in Amperes, R resistance in Ohms, t is the duration time for the welding current in seconds. When the welding current is stopped, the solidification of the fusion zone forms a joint between the sheets upon cooling, which is called the nugget area as shown in Figure 2:3.

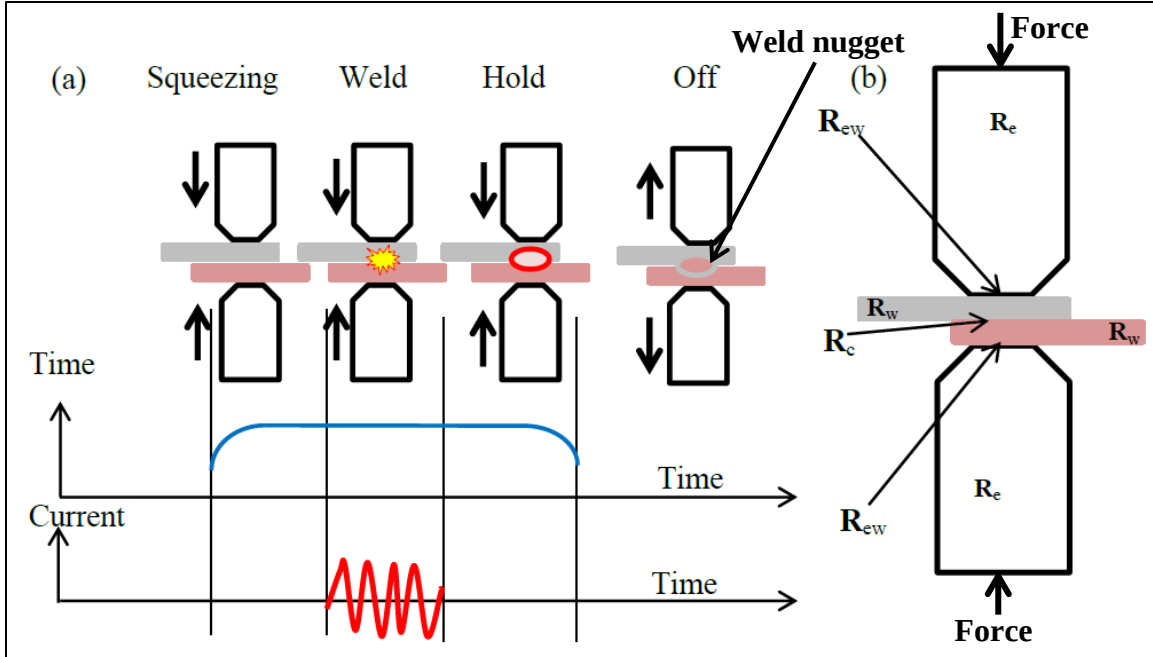


Figure 2:3: a) The resistance welding process, b) the series of resistances to the current consisting of R_e (electrode), R_{ew} (electrode to work-piece interface), R_w (work-piece) and R_c (contact resistance) [42]

This process is simple and effective; making it very useful for a wide range of mechanical components. However, there are many factors during welding which influence the quality and strength of spot weld. The quality and strength of the welded sheets are controlled by the welding parameters, the amount of generated heat at the welded area, cooling rate during solidification, and the alloy composition of the sheets.

2.2.2. RSW process parameters

Welding current and welding time

One of the main requirements for a spot weld is to exceed the minimum nugget diameter that equal to $4\sqrt{t}$, where t is the sheet thickness according to American Welding Society (AWS) Standard D8.1M 2021, page 17 [43]. In order to ensure the nugget diameter is greater than this critical nugget size, increasing the welding current and welding time is required, and this will usually result in a transfer of the failure mode from

interfacial failure (IF) to a pull-out mode (PF) [44]. Increasing the welding current leads to an increase in heat input, which affects the welding area and alters the failure mode due to growth of the FZ [44], affects formation of shrinkage voids [45][46], and promotes softening of the HAZ in high strength alloys [47], and increases electrode indentation depth. Although excessive electrode indentation is not desired, it can promote a change in failure mode to PF [48][49]. Increasing the welding current has some disadvantages such as expulsion due to overheating, which leads to formation of voids in the material.

Electrode force

The electrode force is effective during the welding process when the welded sheets are squeezed and can affect the nugget size as well. When the electrode force is increased, the contact between the sheets being welded increases, reducing the electrical resistance at the contact area. This leads to a decrease in the generated heat and reduced nugget size. Subsequently, the spot welding joint will likely fail by the IF mode, because of decreasing of nugget size [44]. Therefore, to compensate for the decreasing resistance and generated heat, the welding current should be increased with higher force. However, there is an advantage to increasing the electrode force, which leads to reduced shrinkage of voids [44] [50].

2.2.3. Other factors affecting RSW strength

These factors can affect the strength of the spot welding joint and fatigue life of the joint as well; however, they are not welding parameters. These include geometric parameters such as nugget size, sheet thickness and similarity and/or dissimilarity of sheets materials.

Nugget size

After the fusion zone is solidified, the nugget will be formed from this solidification. The nugget size plays a significant role in increasing or decreasing the spot weld fatigue life and failure mode [44], [47], [51]–[55]. The welded sheets are connected with each other via the nugget; therefore, increasing the nugget size leads to improved weld strength due to increased contact area between the sheets [51], [56]–[58]. When the nugget is formed in relatively small size, failure will occur by the IF. The nugget size of a tensile shear specimen is small if $d \leq 5\sqrt{t}$, where: d is the nugget diameter and t is the sheets thickness [44],[51],[59]. The other type of specimen such as coach-peel and cross-tension specimens require a different critical nugget diameter than tensile-shear critical nugget diameter [44], [51], [59]. Additionally, the similarity and dissimilarity of the sheet thickness can also affect the shape and nugget size, because the sheets will have a different resistance, which leads to a different amount of generated heat [60]–[64]. In such cases the nugget will be asymmetrical as shown in Figure 2:4; however, the final solidification line of the dissimilar sheets will be in the geometric center of the thickness of the nugget [44],[65].

Sheet thickness

Regardless of the ratio between the sheets thickness and the critical nugget diameter which is $d \leq 5\sqrt{t}$ and the effect of the nugget size, the sheet thickness itself can affect the fatigue life of the spot welding joint, because the thickness of the sheets can affect crack propagation.

Similarity/dissimilarity of sheets materials

The nugget size is also affected by similarity of sheet thickness which affects the strength of the weld joint; therefore, the dissimilar sheets thickness stack-ups have been

investigated by many researchers to find that the nugget size of dissimilar welded sheets can be influenced by thermal conductivity and electrical resistance of the welded material [60]–[64], [66]. When dissimilar thickness sheets are welded, the shape of the nugget will be asymmetrical due to differences in thermal conductivity, melting point, and electrical resistance of the welded material, as well as differences in the amount of the molten metal and heat that is generated by the welding process in each sheet [44] [65]. However, as previously stated the final solidification line will be in the geometrical center of the thickness of the two dissimilar sheets, particularly with TRIP steel alloys [44][65] as shown in Figure 2:4.

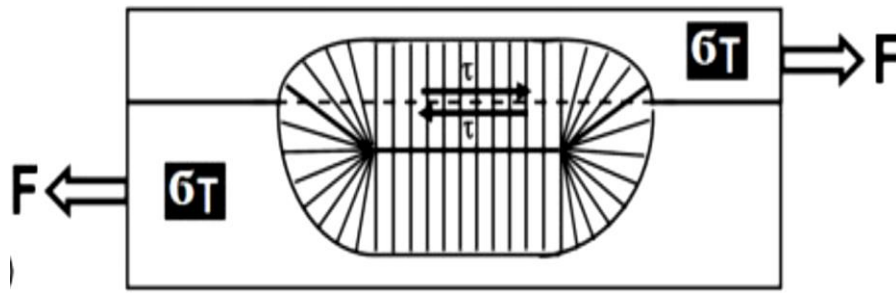


Figure 2:4: The final solidification line in dissimilar thickness welded sheets, σ_T is tensile stress [44].

2.3. Dissimilar RSW of Mg/Al

In the literature, there are a number of studies that focus on dissimilar RSW of Mg/Al [4], [7], [67]–[70]. The researchers highlighted the microstructural characterization of Al/Mg RSW and using different types of interlayers between the Al and Mg substrates. This and use of cold spray process on the sheets before their spot welding are reviewed in the following section.

2.3.1. Using an interlayer in Al/Mg RSW

The direct welding Mg to Al leads to the formation of brittle intermetallic compounds (IMC), which deteriorates the properties of the joint, and may lead to the formation of cracks in the welded material. Improving the strength of Mg/Al joints can be achieved by controlling IMCs and/or by reducing their undesired effects [4]. One approach to joining by placing interlayers has been demonstrated to avoid Al and Mg interactions and thus can limit the generating of IMCs [4], [5], [68]; however, the strength of the joint will be totally dependent on the strength of the intermetallic compounds created in the interlayer and Al interface or the Mg interface. Mg and Al melting points are 650 °C and 660.42 °C, respectively, whereas the investigated interlayers have higher melting temperature such as Ni with a 1455 °C, and steel with a melting point of 1425-1540 °C. Therefore; Ni coatings and steel have been used as an interlayer to restrict the mixing of Al and Mg to form IMCs since they will remain as a solid barrier during welding. Also, Ni has been adopted to promote the formation of Al-Ni and Mg-Ni IMCs which are less brittle than Al-Mg IMCs. These factors make Ni-based interlayers a good candidate as a barrier interlayer with the RSW dissimilar Al/Mg joint.

The possibility of using Ni-based in RSW of Al and Mg has been investigated by Penner et al. [5]. Gold-coated Ni foil and pure Ni foil interlayer were used in an attempt to join AZ31B Mg alloy and 5754 Al alloy. The results show that pure Ni foil as an interlayer did not successfully provide bonded intermetallic compounds between the Al and Mg sheets with the welding parameters used the study. On the other hand, a gold-coated Ni interlayer was successful in bonding the two materials sheets, and it operated

as a barrier to avoid forming Al-Mg IMCs. Since the gold-coated Ni interlayer has a higher melting point than the Al and the Mg substrates, it did not melt during welding. RSW joints withstood an average load of 4.69 kN, which is up to 90% of the strength obtained with similar AZ31B welds [5]. The low heat input applied with a pure Ni interlayer led to failure of the Ni bonding in the Al to Mg joints, as observed by Sun et al. [7]. In their study, AZ31B Mg alloy and 5754 Al alloy were joined with a pure Ni interlayer. In this case, however a higher welding current was applied and different tip electrodes with a flat tip was used on the Al side which was smaller than the Mg side to impose a better heat balance. The weld fracture loads in this case reached about 5.1 kN when the welding current ranged from 32 to 36 kA. The Ni interlayer restricted the formation of Al-Mg IMC by staying un-melted while Al-Ni and Mg-Ni intermetallic layers were created at the Al/Ni and Mg/Ni interfaces, respectively [7].

Penner et al. [69] also tried to substitute a pure zinc foil and zinc-coated HSLA steel as interlayers in RSW of AZ31B Mg alloy to Al alloy 5754 in their study. Al-Mg IMC was formed when using pure zinc foil, resulting in poor joint strength with microhardness values in the nugget zone of 224–304 HV. However, zinc-coated steel, gives a more acceptable weld strength according to the AWS D17.2 standard, reaching up to 74 % of the strength of similar AZ31B RSW joints, since the zinc-coated steel prevented the formation of Al-Mg IMCs [69]. According to Penner et al. [69], placing pure zinc foil as an interlayer did not enhance the strength of Mg / Al RSW joint. However, a thermo-compensated RSW process was suggested by Zhang et al. [68] where zinc interlayer is used to weld AZ31B Mg alloy to AA5052-H12 Al alloy. In this process, more heat can be generated at the weld area, specifically at the Al side, by placing a

stainless steel tape between the Al sheet and the electrode which increases the amount of the melted metal and size of the nugget at the Al side, subsequently enhancing the welded joint strength and mechanical properties. The tensile-shear load resulting from this process was three times higher than that by conventional RSW with the same interlayer, but strengths achieved with the thermo-compensated RSW process with a zinc foil interlayer were low compared with zinc-coated steel and Ni interlayers in studies mentioned above [68]. Sun et al. [70] used a Sn-coated steel interlayer in welding dissimilar joint Al (AA5052) to Mg (AZ31). The tensile test results of this joint were obtained and compared with those of Mg/Mg RSW joints. The strength of the Al/Mg RSW joint with an Sn-coated steel interlayer was 88% of the strength of a Mg similar sheet joint. In another study, Sun et al. [6] performed fatigue test for Al/Mg RSW with an Sn-coated steel interlayer, and the results of the tests indicated that the Al/Mg RSW joint has the same fatigue life as Mg/Mg joints; however, there was a difference in the degradation rate until the final failure where the Al/Mg has a faster degradation rate in life range $N_f < 10^5$ than a Mg/Mg RSW joint.

Table 2:1: Summary of prior dissimilar Mg/Al joining studies that used different interlayers and listed the joint strength with each interlayer [71]

Process	Sheet Materials	Interlayer	Joint strength (kN)	Reference
Conventional RSW	AZ31B Mg / Al 5754	Pure nickel	Metallurgical bond not produced	[5]
Conventional RSW	AZ31B Mg / Al 5754	Pure nickel	5.1	[7]
Conventional RSW	AZ31B Mg / Al 5754	Gold-coated nickel foil	4.69	[5]
Conventional RSW	AZ31B Mg / Al 5754	Zinc-coated HSLA steel	3.86	[69]
Conventional RSW	AZ31B Mg / Al 5052-H12	Zinc interlayer	0.727	[68]
Thermo-compensated RSW	AZ31B Mg / Al 5052-H12	Zinc interlayer	2.199	[68]
Conventional RSW	AZ31B Mg / Al 5052-H12	No interlayer	0.833	[68]

The summary of these results is shown in Table 2:1, where it is clearly observed that using a zinc interlayer did not enhance the strength of the joint [71]. However, applying thermo-compensated RSW process increased the strength of joints produced with a zinc interlayer. A successful Al/Mg RSW joint can be achieved by using a pure Ni interlayer with a high welding current. Also, using gold-coated Ni interlayer can produce acceptable strength of RSW joint; however, the high cost of this interlayer is commercially impractical [69][71].

2.3.2. Use of cold spray coating in RSW

Cold spray coating process has never been used to enhance Al/Mg dissimilar RSW joints; however, it has been applied with ultrasonic spot weld (USW) since the USW method involves lower input energy during welding compared with o RSW process [72]. Panteli et al. [72][73] has evaluated Al to Mg joining using USW and the effect of coating the Mg substrate with a 50 to 100 μm thick layer of Al powder using cold spray coating process before welding Figure 2:5. They observe an improved weld strength that is comparable to Mg-Mg joints.

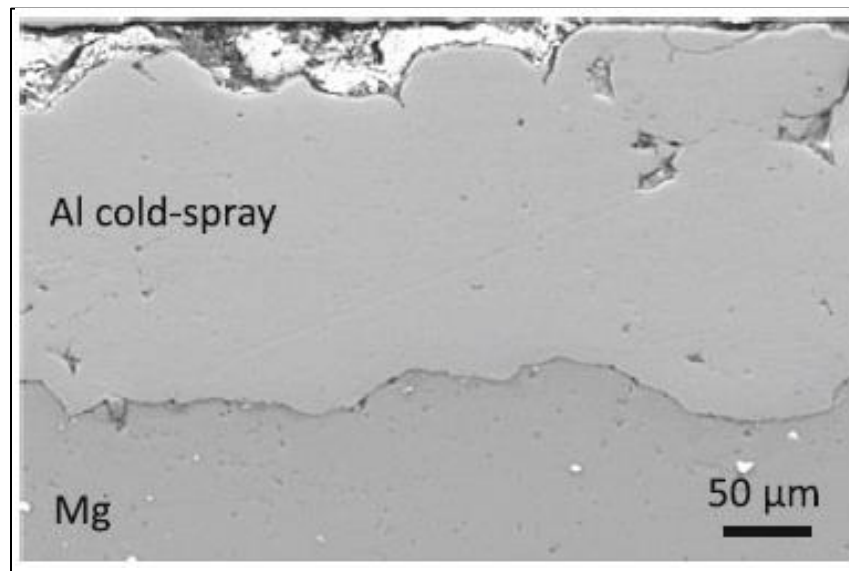


Figure 2:5: Cold sprayed Al-coated on a Mg substrate with ultrasonic welding [73].

The microstructure of the dissimilar Al to Mg USW using cold spray is also investigated by Panteli et al. [73]. It is observed that the cold spray coating layer significantly reduced the formation of the Al-Mg intermetallic between the two sheets to 50% and increased the requested failure energy. Also, they observe an interaction between the Al-coated layer and the Mg surface after the welding process which creates Al-Mg IMCs, see Figure 2:6. The intermetallic compound $Mg_{17}Al_{12}$ is also observed in the study by Shaha et al. [26] where cold spray coating process is used to coat Al AA7075 on Mg AZ31B substrate; the thickness of the IMC is in the nanometer scale. Hou and colleagues [74][75] utilized cold spray to introduce a Ni-coating layer on the Cu side, aiming to enhance the strength of dissimilar friction stir welding butt joints involving Cu and Al. The results were promising, with an approximately 25% increase in the average tensile strength of the joint, rising from 152 MPa to 190 MPa. This enhancement was also accompanied by an improvement in the joint's ductility, which increased from ~5.5% to ~10.5%. Furthermore, a significant reduction in the thickness of the intermetallic compound (IMC) was observed, decreasing from approximately 1.2 μm to just 200 nm. In another study by Kavian et al. [76], a different coating approach was employed to deposit three distinct interlayers between Al and Mg. They individually electrodeposited Ni-TiO₂, Ni, and Ni-Al₂O₃ on the Al side in a lap shear joint configuration. They observe that the addition of nano-sized TiO₂ and Al₂O₃ led to a reduction in grain size within the welding area. This grain refinement played a crucial role in enhancing the shear strength of the Al/Mg resistance spot welding (RSW) joint. However, it is noteworthy that the maximum load achieved in this study was 520 N when Ni-Al₂O₃ was utilized as the interlayer.

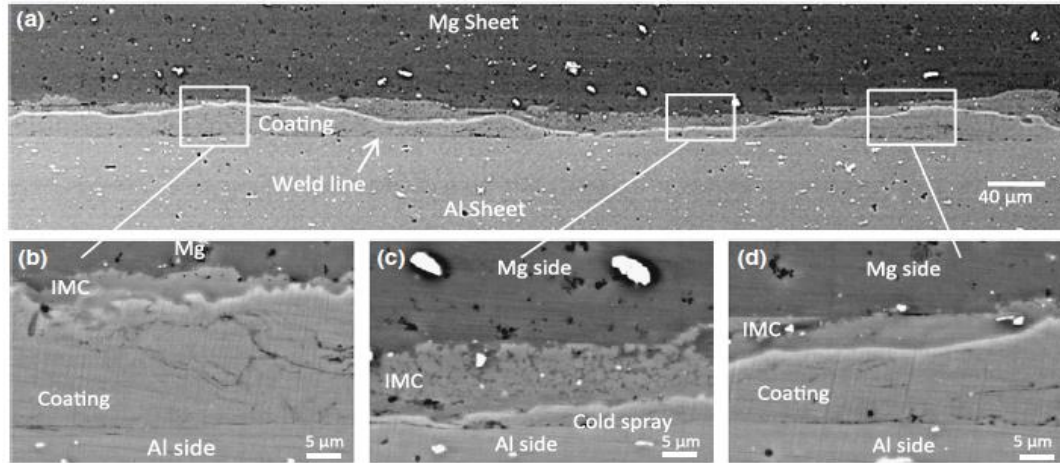


Figure 2:6: SEM results illustrating the formation of IMC reaction layer at the interface between the Al-coating and Mg substrate after USW with a welding time around 0.5 s: (a) welded area and (b) - (d) selected areas at higher magnification[73].

2.4. Crack detection techniques

Several non-destructive tests (NDTs) have been implemented to detect cracks and failures in mechanical components and structures. The most common NDT techniques used in inspection include dye-penetration, magnetic particle, ultrasonic testing, electromagnetic (Eddy current) testing, radiographic (X-ray) testing, thermal/infrared testing (IR), and visual testing. Each NDT technique has some advantages and disadvantages which define their capabilities for detection or limitations of the technique; hence there is no single technique capable of detecting all types of defects or flaws [77]–[79].

Thermal or infrared (IR) testing is a non-destructive evaluation technique that identifies defects by detecting variations in thermal emissions. Infrared cameras capture and visualize heat differences, allowing for the identification of potential flaws in materials or systems. This method is widely used in various fields, including the inspection of metals, composites, and electrical installations, as well as applications in civil engineering and military operations. The advantages of IR testing are numerous. It is

a non-contact and safe method that provides real-time results, making it suitable for inspecting large-scale configurations efficiently. Despite its benefits, there are limitations to this technique. Accurate interpretation of the results requires significant expertise, as the process can be affected by variations in the emissivity of materials, which may impact measurement accuracy. Nevertheless, IR testing remains a valuable tool in a broad range of industrial and technical applications. Researchers have used the infrared technique to detect surface cracks on welding plate with two different IR sources, laser beam and a flash lamp [80].

Also, there are many other techniques which are less common than the above-mentioned NDT methods, or are used to detect special flaws, or applied in special conditions. These techniques are as follows: vibration analysis [81], leak testing [82], laser testing [83]–[85] and acoustic emission test [86]. None of these techniques can detect and measure subsurface defects and even acoustic emission, it can just detect whether there is defect or not in the products; it cannot identify the type of flaw in the product [86]. Therefore, these techniques cannot be applied to detect crack initiation.

2.4.1. Fatigue crack initiation in spot welds

In the literature, many different models of spot welds have been created by researchers based on their observed and spot welding behavior. These observations and models are used for different purposes such as to observe crack initiation and propagation, or modeling for stress analysis, modeling of the stiffness of structures, or modeling to predict fatigue life [87]. The models contribute to developing an understanding of the performance of resistance spot welds without a need to create expensive prototypes for each mechanical configuration [88]. Cyclic stresses are the most

critical and harmful type of stress to expose the spot welded joint to. Even with relatively low fatigue stress levels, the joint might fail below the static design load requirements. Therefore, the life expectancy of a spot welded joint can be designed as a function of fatigue life, which can be predicted by modeling. Total fatigue life of a resistance spot weld can be classified or divided into two or more stages depending on the approach that is followed by the researchers. In general, the crack initiation phase of the fatigue failure represents the majority of the total fatigue life [89]. Therefore, it is an important aspect to measure for design or to predict the duration of the crack initiation stage. Many researchers have observed and predicted the fatigue crack initiation life of spot welds, and their work can be classified into two categories, namely measurement and modeling.

The fatigue life of spot welding joint can be divided into many stages according to the approach or the description of the researchers. In a fracture mechanics approach, for example, there is only a crack propagation stage [90]. Another description for the fatigue life and crack growth considers the total fatigue life in two stages: crack initiation and crack propagation life [91]–[94]. Wang et al. [95] identified fatigue life as having three stages: first stage is the crack initiation, second stage is through-thickness crack propagation, and third stage is crack propagation through the width of the sheets. Other researchers divide the fatigue life into five stages as follows: first stage is the early cyclic slip band formation, second stage is micro-crack nucleation, third stage is short crack propagation, fourth stage is macro-crack propagation, and last stage is final fracture [96].

Some researchers state that the crack initiation stage represents approximately 40–50% of the total fatigue life [89], [93], [96], [97]. The results of Swellam et al. [98] also indicate that the crack initiation stage corresponds to more than 40% of the total fatigue

life. The depth of crack initiation in the first stage of crack growth is discussed by many researchers, and they have estimated the depth of crack initiation to be about 0.25 mm [99]–[102]. Other researchers focus on the location of the crack initiation while ignoring the crack initiation fatigue life or the length of the crack initiation, and they state that fatigue cracks in spot welds initiate near the root of the nugget in the interface between the two welded sheets [90], [93], [97], [103]–[108]. Three modes of crack are recognized by researchers, and they state that the cracks depend on nugget size and type of load as follows: sheet fracture, HAZ cracking, and nugget pull out [93][109].

When finite element modeling is applied to resistance spot welds, there are three main regions are considered, namely base material sheet, heat affect zone (HAZ) and nugget area; and each region has different material properties [88], [94], [99], [110]–[112]. However, the models used to predict fatigue life, especially with local stress/strain approach, require finer meshes than the other models used for other purposes, for example, the finer meshes are needed to capture the local stresses around the crack [87][110][113]. This means that more details are required (such as the gap and extruded metal between the welded sheets etc.) in order to facilitate fatigue prediction from the numerical models [87][88]. When spot welding is modeled to predict the fatigue life with high accuracy and very fine mesh, the computation times will increase. In other words, the models with very fine mesh cannot be used in a whole vehicle model because the spot welds are not often in critical damage locations; Donders et al. [88] showed there is no need to devote considerable computation resources to predict their fatigue life. They used the FE approach for spot weld modeling to suggest a two-step approach in order to obtain higher accuracy results without demanding as much computation time. The idea of in the

first step, one can recognize the spot welds which have a critical location, and then in the second step one can rebuild the models for spot welding that located at critical locations in more detail. Hence, the FE code will not devote unnecessary computation to calculating the fatigue life of spot welds at irrelevant locations [88].

2.4.2. Detection of crack initiation

Many different nondestructive and destructive techniques have been applied to assess crack and damage of spot-welded joints. These techniques differ in their application, physical principals and/or sensitivity for damage. The most common techniques, which are used with spot welding joint and which could be also used in this dissertation are: X-ray, optical microscopy, scanning electron microscopy, and digital image correlation (DIC) techniques. A brief review of other techniques that are used with spot welding measurement is mentioned in this section; however, those techniques will not be used in this study. The techniques include the use of electromagnetic, natural frequency response, ultrasonic and another study [100] suggest modifications to the design of the specimen.

X-ray plays a significant role in measuring the development of a crack, especially when evaluating the invisible crack dimensions which occur around the nugget edge of the spot weld. To study the crack development of a spot weld via this technique, some steps should be followed. In the beginning, the fatigue test should be run while applying load on the welded specimen, and then stopping the test at many stages of the fatigue life, to inspect the internal crack of the specimen by X-ray imaging. The accuracy of the inspection results depends on the number of the stages when the test interrupted. The interruption of the test can be considered as a drawback of using X-ray because it

requires a lot of time and does not provide result in real time. In other words, this technique cannot detect the crack in real time as it is initiated during the test [91], [114]–[116]. In 2006, the process of crack initiation and propagation during spot weld overlap shear testing was investigated using X-ray technique by Wang and Barkey [91]. The study indicates that the crack occurs at a distance of 0.2 to 1.0 mm from the nugget edge of the spot weld for three different crack propagation modes depending on the amplitude of the applied load. The crack initiation stage was also observed and it was determined to be around 50 to 60% of the total fatigue life [117][91].

Optical microscopy and scanning electron microscopy are both destructive tests which are used in most studies on resistance spot welding [103], [112], [118]–[124]. These techniques can be used to observe fatigue crack behavior and location as well as the material properties of the spot weld. The fatigue test must be stopped at a particular stage during the test, and then a cross section of the specimen should be prepared by cutting and polishing the desired zone of the specimen for study. However, the technique cannot observe crack initiation and propagation fatigue life stages in real time as the crack is occurring and growing (because the specimen will be cut to prepare a clear cross section of the spot weld) [108].

DIC has been used to measure the surface strain of spot weld [125]. In 2012, Lacroix et al. [126] used DIC method to quantify crack tip opening angle and to measure the extension of the strain localization. The crack in the study is accessible, and its evolution can be measured using DIC because it is a surface crack; however, the crack in the spot weld joint usually initiates in the interface between the welded sheets at the edge

of nugget, which cannot be captured by the camera until it propagates and reaches the outer surface. Therefore, DIC technique cannot detect crack initiation.

The other available techniques which could not be adopted in this dissertation will be briefly reviewed with their limitations. The electromagnetic techniques, which are Eddy current and magnetic flux leakage method, have been used to detect the defect of spot weld [127] [128], but they have not been used to detect and observe the crack initiation stage. Figure 2:7 shows magnetic flux leakage method. Also, the electric potential drop technique with direct current was applied to study the crack evolution of the spot weld joint [98]; however, the researchers found that the changing of the resistivity has a poor correlation with the crack depth during crack initiation stage. The natural frequency response have been used as a damage parameter to measure the crack development of spot weld [96] [95], but the researchers state that during the crack initiation stage when the crack still has small size, the natural frequency response of the spot welding specimen might not change significantly and during the crack propagation stage when the crack grows, the change in the natural frequency of the spot welding specimen can be noted clearly. The work using ultrasonic [129], was limited to tensile-shear spot welds and the researcher did not discuss the use of an ultrasonic technique with other specimens such as coach-peel or cross-tension. Also, a limitation of the ultrasonic technique is that the transducers, which send and receive ultrasonic pulses or waves, needs to directly touch the spot welding specimen. The pre-sectioned specimen, which was proposed to explore the crack developing zone and the stress hot spot of the spot weld [100] as shown in Figure 2:8, has some limitations such as there are two load paths instead of one load path in the regular specimen, one for each half nugget. These

load paths will be created out when applying the load during the fatigue test. Also, the researchers used a correction factor to reduce the load when they conducted the fatigue test with the pre-sectioned specimen because they indicate that the stress intensity factor of pre-sectioned specimen was greater than the stress intensity factor of regular specimen by a ratio of 1.074 which support the notion that the welding characterizations of the pre-sectioned specimen are not the same as the regular specimen. This can affect the crack initiation life where the crack initiation life stage of the pre-sectioned specimen was shorter than the crack initiation life stage of the regular specimen. The last point which can be adduce for using this specimen is that the location of the crack will be changed from the center of the specimen to the edge which may influence the crack development.

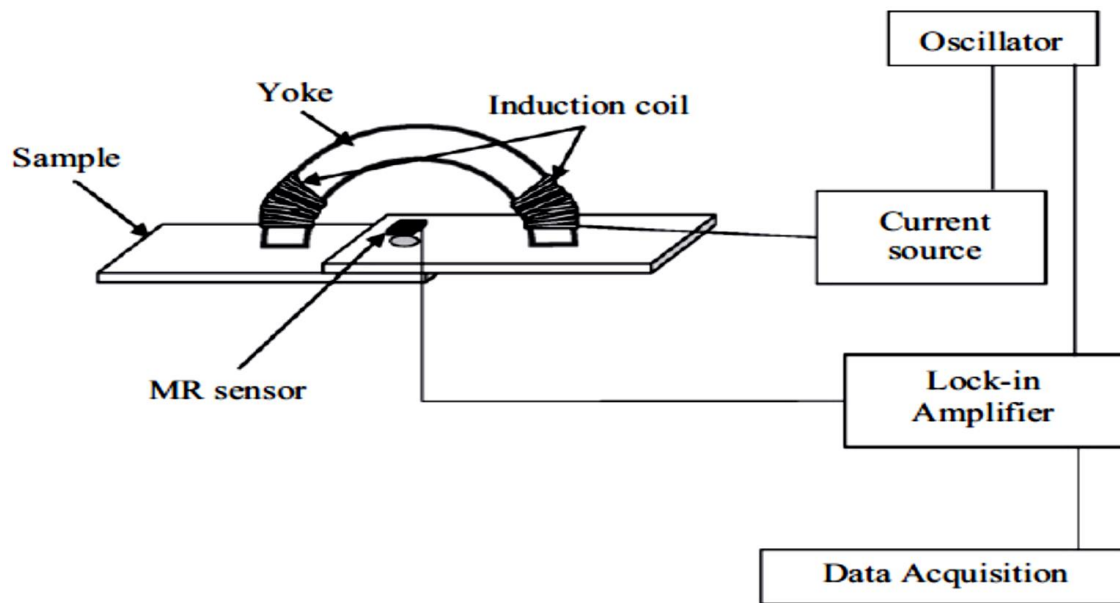


Figure 2:7: Schematic of MFL technique used by Tsukada et al. [128]

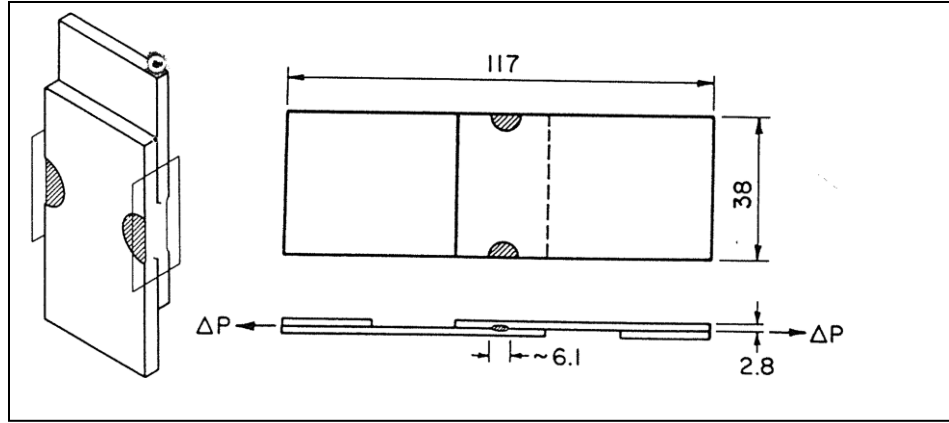


Figure 2:8: Developed specimen dimensions used by McMahon et al. [100]. The nuggets in this specimen have been cut half to exposed side of the nugget edge assuming the load will be handled by welded area that has size of one nugget.

Despite all the information and details in the literature about the measurement of the crack initiation, it remains difficult to accurately recognize the onset and the end crack initiation because the location of the crack initiation of a spot weld is invisible and disappears between the sheets near the nugget as mentioned earlier.

2.5. The knowledge gap

The literature review reveals that the use of cold spray coating technology with suitable material powders has not yet been explored for the purpose of facilitating Al/Mg resistance spot welding (RSW). The novelty of this research lies in its pioneering application of cold spray coating technology to achieve reliable dissimilar spot welds between Mg AZ31-B and Al 6022-T4 alloys. This innovative approach offers the advantage of precise control over the thickness and composition of the cold spray layer. This control enables the creation of an effective interlayer between Al and Mg, facilitating strong bonding while simultaneously mitigating the formation of undesirable intermetallic compounds. As a result, the research effectively addresses the issue of brittle interfacial phases that commonly arise in Al/Mg welds. By employing cold spray coating, this study introduces a novel and promising technique to enhance the quality and

reliability of dissimilar spot welds, ultimately expanding the possibilities for incorporating lightweight materials like Mg into various industrial applications.

Another contribution of this research is developing a new method to detect fatigue crack in spot welds during early stage that allows detecting the crack in real time without interrupting the fatigue test. Also, the crack propagation behavior can be observed and recorded totally until final failure as well as the actual strain around the nugget edge can be measured via the technique. Observing the onset of crack initiation at the nugget edge can help researchers in the future to find some surface treatment to avoid the crack or to improve the surface resistance for the crack, and subsequently improve the fatigue life of the RSW joint.

Chapter 3: Methodology

Several critical parameters related to the cold spray coating process require optimization to make this approach effective. These parameters encompass the type of carrier gas used, gas pressure and temperature, feed rate of powder, nozzle velocity, and stand-off distance. The primary function of the cold spray coating is to deposit the selected powder onto the surfaces of both the Mg and Al sheets, thus establishing an interface layer that facilitates the subsequent resistance spot welding to create a joint between Mg and Al. The experimental work that been followed to verify and obtain the dissimilar welding is summarized in the flow chart in Figure 3:1.

3.1. Material

The cold spray coating process was employed to deposit pure Ni and pure Ti as Ni-coating and Ti-coating layers onto Al 6022-T4 and Mg AZ31B-O substrates. According to the ASTM B90/B90M-21 standard, the chemical compositions of the Al and Mg sheets are detailed in Table 3:1.

Table 3:1: Nominal chemical compositions of Al 6022-T4 and Mg AZ31B-O (wt. %).

Al 6022-T4 (wt. %)								
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.8-1.5	0.05-0.2	0.01-0.11	0.02-0.1	0.45-0.7	≤ 0.1	≤ 0.25	≤ 0.15	Balance
Mg AZ31B-O (wt. %)								
Al	Zn	Mn	Si	Cu	Ca	Ni	Fe	Mg
2.5-3.5	0.6-1.4	≥0.2	≤0.1	≤0.005	≤0.004	≤0.005	≤0.005	balance

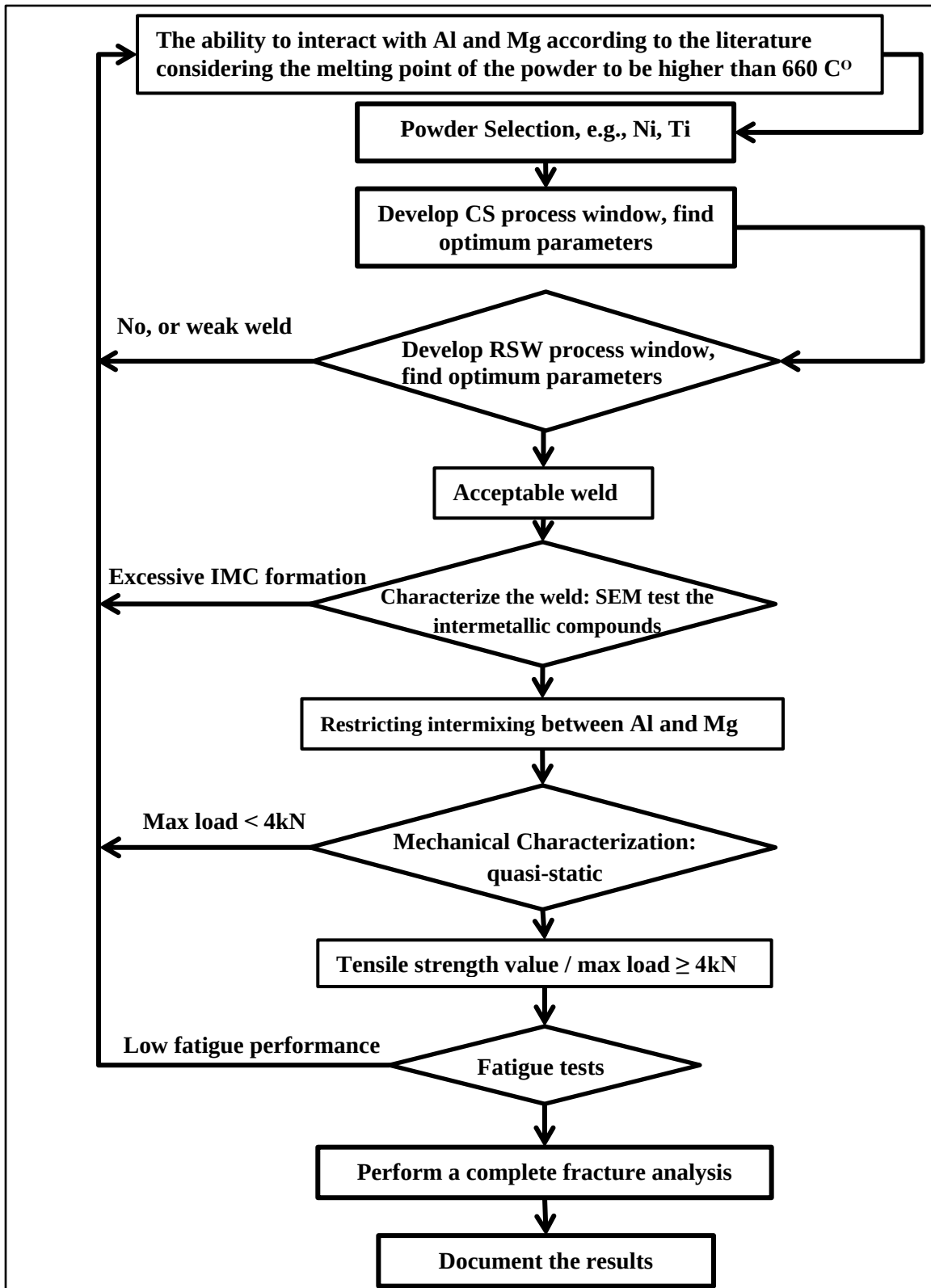


Figure 3:1: Flow chart for experimental work that display the methodology steps that followed from selecting the powder to documenting the results.

3.2. Cold spray coating methods used for interlayer fabrication

Cold spray coating process has been adopted to coat two groups of samples the first group with Ni-coating layer and the second group with Ti-coating layer on Al 6022-T4 and Mg AZ31B-O substrates. The Al sheet dimensions are 25x25x1.5 mm, while the Mg sheet dimensions are 25x25x2 mm. The details and the parameters involving in processes, cold spray coating and resistance spot welding of dissimilar joint are summarized below.

Ni-coating

The Al 6022-T4 and Mg AZ31B-O substrates were coated with Ni powder first group of samples using the parameters summarized in Table 3:2. A commercial cold spray system (SST Series P) manufactured by Centerline was used to deposit pure Ni and pure titanium Ti, which classifies as a low pressure cold spray system. The maximum pressure of the SST series P is 1.72 MPa and the maximum temperature that can be provided with this system is 550 °C. The carrying gas that used during the operation was nitrogen (N₂). Figure 3:2 shows the SST Series P that used for coating the samples.

Table 3:2: parameters summary of cold spray

Coating Materials	Ni on Mg	Ni on Al	Ti on Mg	Ti on Al
Flow Gas	N ₂	N ₂	N ₂	N ₂
Gas Temperature (°C)	485-500	485-500	500	500
Gas Pressure (MPa)	1.5	1.5	1.4	1.4
Powder Feed Rate (gr/min)	8	8	2.24	2.24
Nozzle Speed (mm/s)	25	25	70	70
Step Over (mm)	2.7	3	3	3
Stand-off Distance (mm)	12	12	12	12
Type of Nozzle	de Laval UltiLife™ (L=120mm, d _{orifice} = 2mm and d _{exit} = 6.3mm)			

Ti-coating

In second group of samples, Al 6022-T4 and Mg AZ31B-O substrates coated with Ti using same commercial Cold Spray system with slightly different parameters as summarized in Table 3:2.

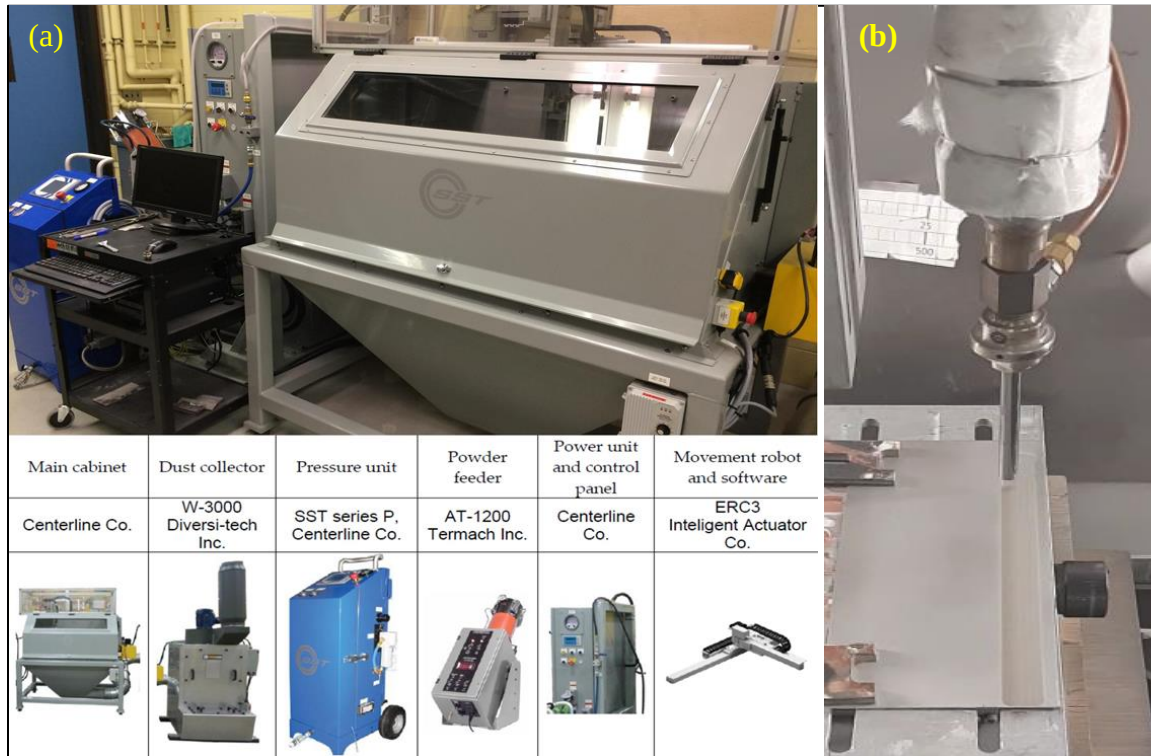


Figure 3:2 : (a) SST Series P cold spray system, the outside of the device and the inside main parts (b) the cold spray gun and nozzle during Ni-coating process where each seven samples were coated simultaneously.

3.3. Roughness of the coating

In this study focusing on Ni-coating and Ti-coating produced through the cold-spray process, surface roughness was meticulously assessed using a Nanovea M1 surface indentation device. This instrument quantifies surface roughness to within 20 nm, offering insights into the topographical features of the coatings. Additionally, 3D scans of the Ni-coating and Ti-coating surfaces were conducted by the Nanovea M1 device, creating detailed topographical maps that encompass parameters beyond Ra, providing a

comprehensive view of surface texture attributes. These assessments play a crucial role in ensuring that coatings produced via cold-spray technology meet stringent quality standards and performance requirements, guiding material selection processes for various applications.

3.4. Resistance spot welding

A medium-frequency direct current (MFDC) spot welder is used to weld the coupons as shown in Figure 3:3. The maximum current of the MFDC is spot welder 60 kA and the maximum electrode force is 25 kN. Figure 3:4 shows the MFDC spot welder used for resistance spot weld.

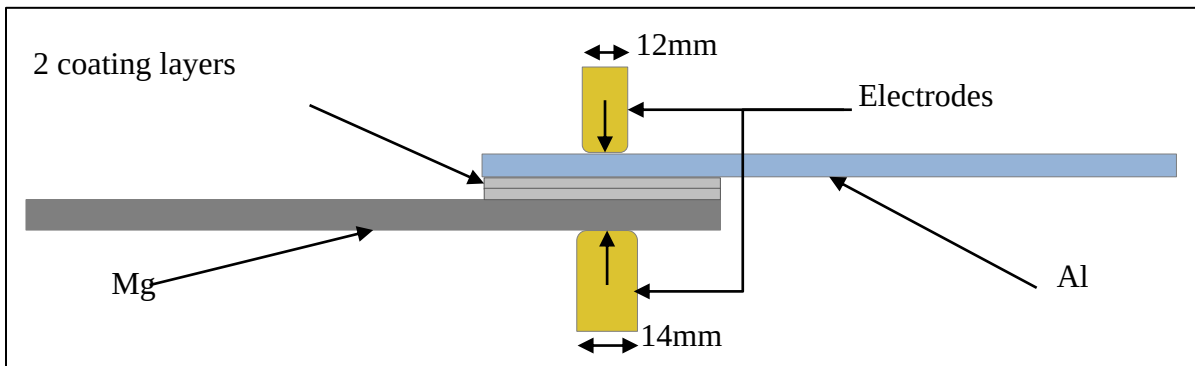


Figure 3:3 : Schematic of sheets and welding arrangements for samples that used in monotonic and cyclic tests.

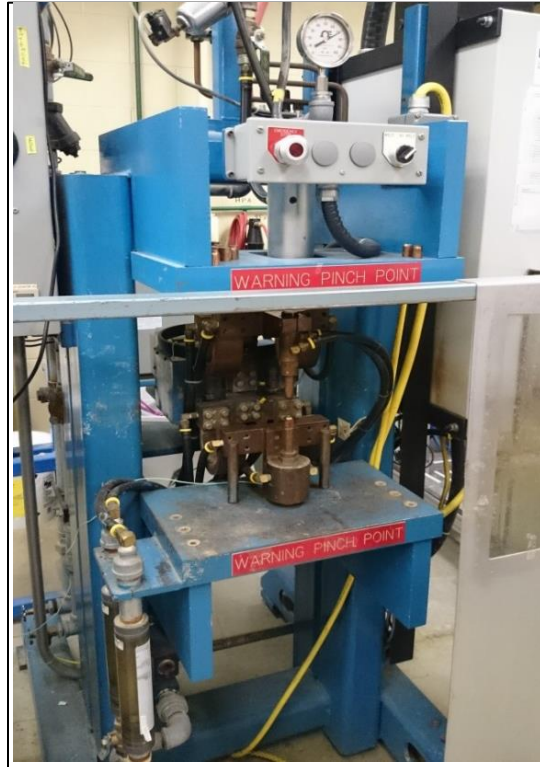


Figure 3:4 : MFDC spot welder (the maximum direct current is 60 kA and the maximum electrode holding force is 25 kN)

3.5. Micro-characterization methods

The preparation of metallographic samples was a critical process aimed at enabling a comprehensive microstructural analysis of various components, including Ni-coated Al, Ni-coated Mg, Ti-coated Al, and Ti-coated Mg, both before and after the welding process. The preparation process encompassed several essential steps:

1. Sample selection and cutting: The process commenced with the careful selection of specific areas of interest within the coated materials. These selected areas were then cut into appropriately sized specimens using cutting tools or saws, followed by hot mounting.
2. Rough grinding: Initial grinding was carried out using coarse-grit abrasive papers or grinding wheels grit from 320 to 800. This coarse grinding step served to remove

excess material and create a flat surface. Grinding continued until the sample achieved the desired level of smoothness and thickness.

3. Fine grinding and polishing: Subsequent steps involved the progression to finer-grit ranged from 1200 to 1 or 2 μm diamond abrasive papers or polishing cloths. This finer grinding and polishing continued, using increasingly finer abrasives, until the desired surface finish was achieved. The samples are mirror finish polished upto 0.04 μm size using colloidal silica suspension in order to facilitate response to etching.
4. Etching: While not extensively used in this study due to the variation in material chemistry, etching was employed once in the examination of welded Ni-coating Al/Mg samples. Etching was utilized with 2% nitric acid in ethanol (Nital) for 5-10 seconds to investigate the bonding between the Ni layers.
5. Rinsing and drying: Following the preparation steps, the samples were rinsed with distilled water to eliminate any residual substances. Drying was carried out using blowers to prevent the formation of water stains or contamination.
6. Final polishing: For samples requiring an exceptionally high level of quality, a final polishing step was conducted. This step utilized colloidal silica or alumina suspension to achieve a mirror-like surface finish.
7. Cleaning: Ensuring that the samples were entirely free of contaminants or debris was of paramount importance. Any necessary cleaning was performed using suitable solvents, such as acetone.
8. Microstructural analysis: The meticulously prepared samples were then subjected to examination under a metallographic microscope or a scanning electron microscope (SEM). The LEO 1530 microscope and the FEI Quanta FEG 250 environmental

scanning electron microscope (ESEM) were used, which was equipped with energy-dispersive X-ray spectroscopy (EDX) capabilities. Micrographs were captured to facilitate the analysis of various microstructural features, including grain structure, phases, and other characteristics, both prior to and following the welding process. Figure 3:5 shows the equipment that used to take SEM images.



Figure 3:5: shows the scanning electron microscope (SEM). The LEO 1530 microscope and the FEI Quanta FEG 250 environmental scanning electron microscope (ESEM) were used, which was equipped with energy-dispersive X-ray spectroscopy (EDX) capabilities

The careful and consistent preparation of these metallographic samples was an indispensable component of the research, as it played a pivotal role in ensuring the accuracy and meaningfulness of the microstructural analysis, particularly when investigating the effects of coating and welding on different materials.

3.6. Joint characterization methods

3.6.1. Monotonic test

Tensile testing was conducted using an 810 MTS frame with a load capacity of up to 50 kN (see Figure 3:6). The specimen configuration was identical in the dimensions for both groups, whether Ni-coated or Ti-coated. The dimensions of the Al coupons measured 39x100x1.5 mm, while the Mg coupons were 39x100x2 mm. As a result, the length of the Al to Mg lap shear samples utilized in the monotonic test after welding was 161 mm. Ni-coating and Ti-coating were applied to the samples via cold spray technology in the area where welding was anticipated. The loading rate employed during the monotonic test was 0.5 mm/min.



Figure 3:6: The MTS 810 material test system with a load capacity of up to 50 kN

3.6.2. Fatigue test

Both sets of samples, the Ni-coating Al/Mg and Ti-coating Al/Mg samples, underwent cyclic tests conducted at room temperature using an Instron 8874 testing machine (see Figure 3:7). This machine was equipped with an axial force capacity of ± 25 kN and a torque capacity of ± 100 Nm, but, all tests were done using axial force. The results obtained from the earlier monotonic tests provided valuable information about the load range in which the fatigue tests should commence. Prior to initiating the fatigue tests, both the Ni-coating and Ti-coating samples were fine-tuned with the Instron 8874 machine shown in Figure 3:7. The fatigue tests were load-controlled, with a load ratio (R) of 0.2. The maximum load ranged from 1.28 to 2.72 kN for the Ni-coating samples and 1 to 2.72 kN for the Ti-coating samples. Data collection during these tests occurred at a rate of 50 data points per cycle. The results derived from these fatigue tests are presented and thoroughly discussed in Chapter 7 of the thesis.



Figure 3:7: Instron 8874 machine. This machine is equipped with an axial force capacity of ± 25 kN

Chapter 4: Novel crack detection in RSW lap-shear samples

4.1 Introduction

The study of resistance spot welds (RSW) has led to the development of numerous models and observations aimed at understanding their behavior under fatigue stress, which is a primary cause of joint failure. These models focus on predicting crack initiation and propagation, stress analysis, structural stiffness, and fatigue life, reducing the need for costly physical prototypes [87], [88]. Fatigue life prediction is critical, as even low-stress levels can cause joint failure. It is generally accepted that the crack initiation phase constitutes the majority of a weld joint's fatigue life, emphasizing the need to measure or predict its duration accurately [130].

The fatigue life of spot welds is divided into stages based on the employed approach. The fracture mechanics approach identifies a single crack propagation stage [90], while others classify it into two stages—crack initiation and propagation [91]–[94] or three stages, including through-thickness and width propagation [112]. More detailed descriptions include up to five stages, from early slip band formation to final fracture [96]. Studies estimate that crack initiation accounts for 40-50% of the total fatigue life [93], [96], [97], [130], with cracks typically forming near the nugget root at the interface of welded sheets [90], [93], [97], [103]–[108]. Crack initiation depth is generally about 0.25 mm [99]–[102], and three failure modes—sheet fracture, heat-affected zone (HAZ) cracking, and nugget pull-out are observed based on nugget size and loading type [93][109].

Finite element (FE) modeling is a popular tool for predicting fatigue life, particularly using localized stress/strain approaches. These models require a fine mesh and additional details like extruded metal and gaps to improve prediction accuracy, increasing computational time [87], [110], [111], [113]. Therefore, high-detail models are usually limited to critical weld locations. To optimize computational efficiency, researchers have proposed a two-step FE approach: identifying critical welds in the first step and refining models for these areas in the second step, saving time without compromising accuracy for non-critical welds [88].

From the literature review, it is evident that crack initiation and subsequent stages in spot welding configurations have not been detected in real time; instead, researchers have focused on predicting crack initiation after its occurrence. Therefore, the objective of this chapter is to introduce and to develop a technique to nondestructively detect crack initiations in spot welded specimens during fatigue test in the real time.

4.2 Materials and test specimens

The material used for experimental test to establish and validate the new technique for detecting crack initiation is steel JAC 270F, which is classified as deep-drawing mild steel. The configuration of spot welded specimens tested in this study is tensile shear (TS) specimen and the modified specimen which is weld-cut tensile shear specimen (WCTS). The specimen in this test is modified via cutting unnecessary part from the regular specimen as shown in Figure 4:1. This cut exposes the hot-spot zone around the nugget where the crack initiates, and the crack can be detect without interruption of the test by using a camera system with a digital image correlation (DIC) software. This method also provides the opportunity to study the deformation in the overlapping zone in

a TS specimen, and observe how the cracks behave there. The sheet thickness of the specimen is 1.34 mm, the width is 25 mm, and the length of each coupon is 100 mm with an overall specimen length of 175 mm as shown in Figure 4:1. More than 50 specimens were manufactured for the initial experimental work. Many investigation steps have been followed in coordination, including finite element (FE) modeling and experimental work, to make sure the proposed method is consistent, and these two phases will be discussed in detail.

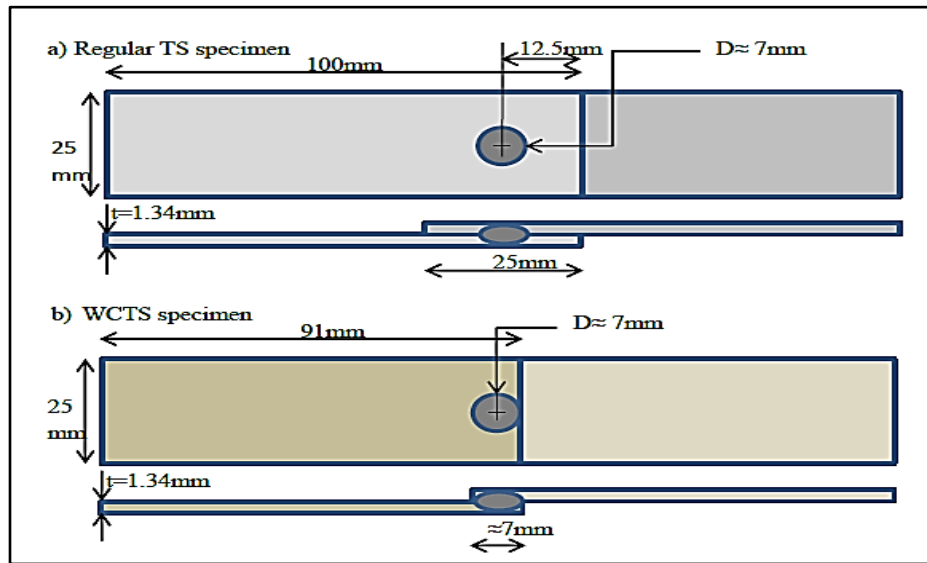


Figure 4:1: (a) the dimensions of regular tensile shear and (b) weld-cut specimens and the location of the cut around the nugget.

4.3 Finite element model of lap shear test

Finite element FE modeling of the lap-shear specimens was conducted using ABAQUS software (version 6.12- and 6.13). To reduce computational cost, while maintaining accuracy, only half of the specimen geometry was modeled, taking advantage of the symmetry along the longitudinal axis. The half 3D models developed for both specimen types are presented in Figure 4:2.

The model utilized 20-node quadratic brick elements (C3D20R) to capture the stress distribution with high fidelity. Around the weld nugget region where stress gradients are

highest 15-node wedge elements (C3D15) were applied to better represent the complex geometry and contact conditions. The overall mesh of each model consisted of 6804 elements, ensuring adequate resolution to capture stress gradients near the nugget periphery. The number of nodes 30947 and since each node has 3 degrees of freedom the total degree of freedom is 92841.

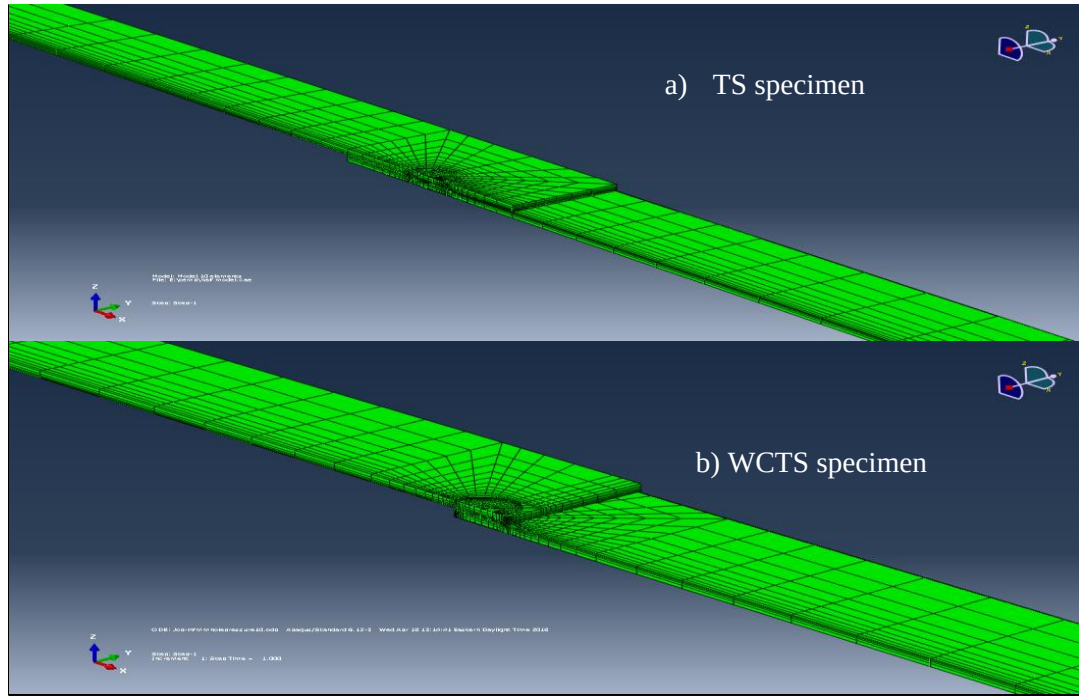


Figure 4:2: FE modeling of the specimens a) 3D model of regular TS specimen. b) 3D model of WCTS specimen. Each 3D model represents longitudinal half of the specimens due to their symmetry.

Convergence test

Convergence test is a method used to ensure that the results of a simulation are reliable and accurate. A convergence test is performed in Abaqus to obtain the minimum number of elements required around the nugget. To verify that the solution has stabilized and is not significantly affected by changes to the model's numerical parameters and/or the mesh density, the convergence test confirms that the calculations have reached a point

where further iterations or refinements will not produce a meaningful change in the results, such as stress, strain, or displacement (see Figure 4:3 - 4:5)

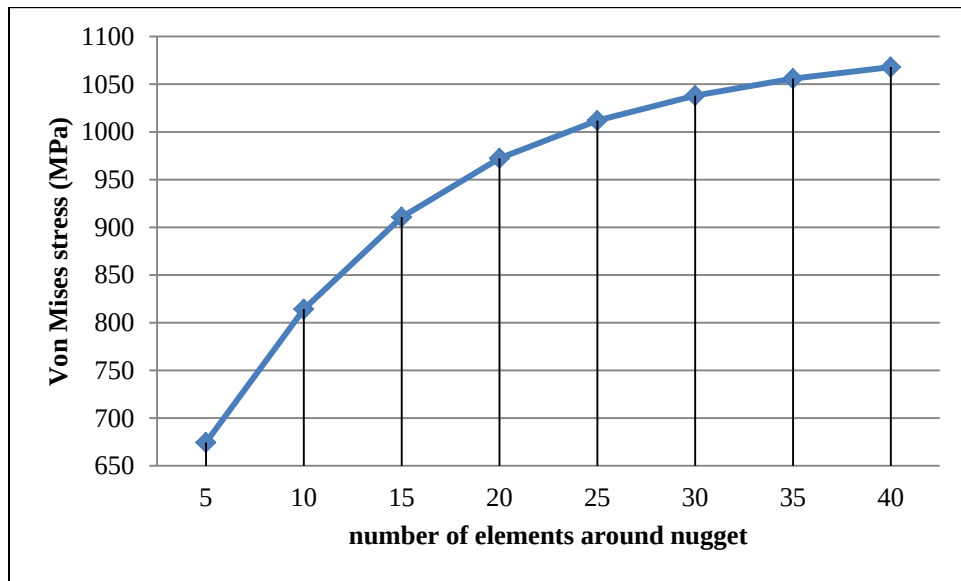


Figure 4:3: number of elements around the nugget vs. von-Mises stress

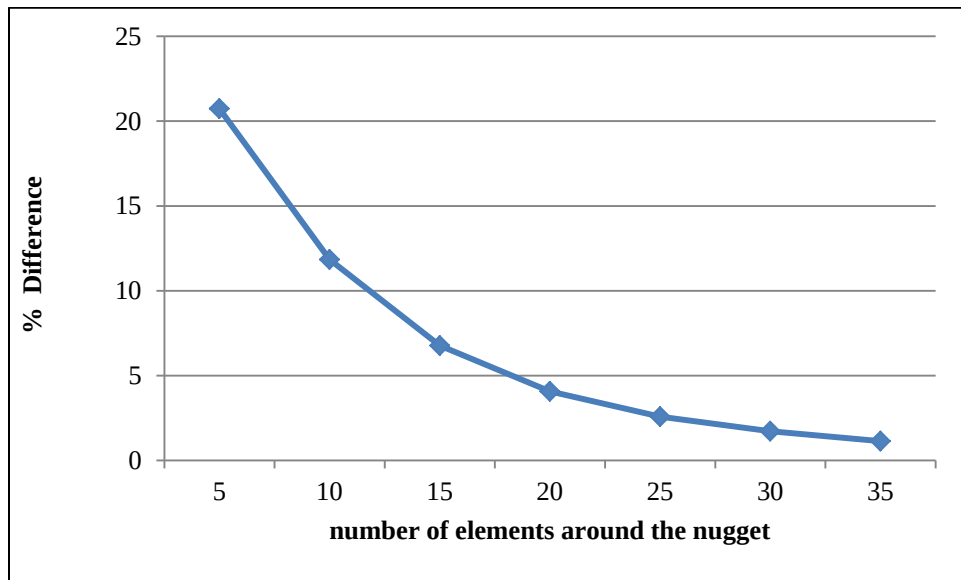


Figure 4:4: number of elements around the nugget vs. the difference percentage

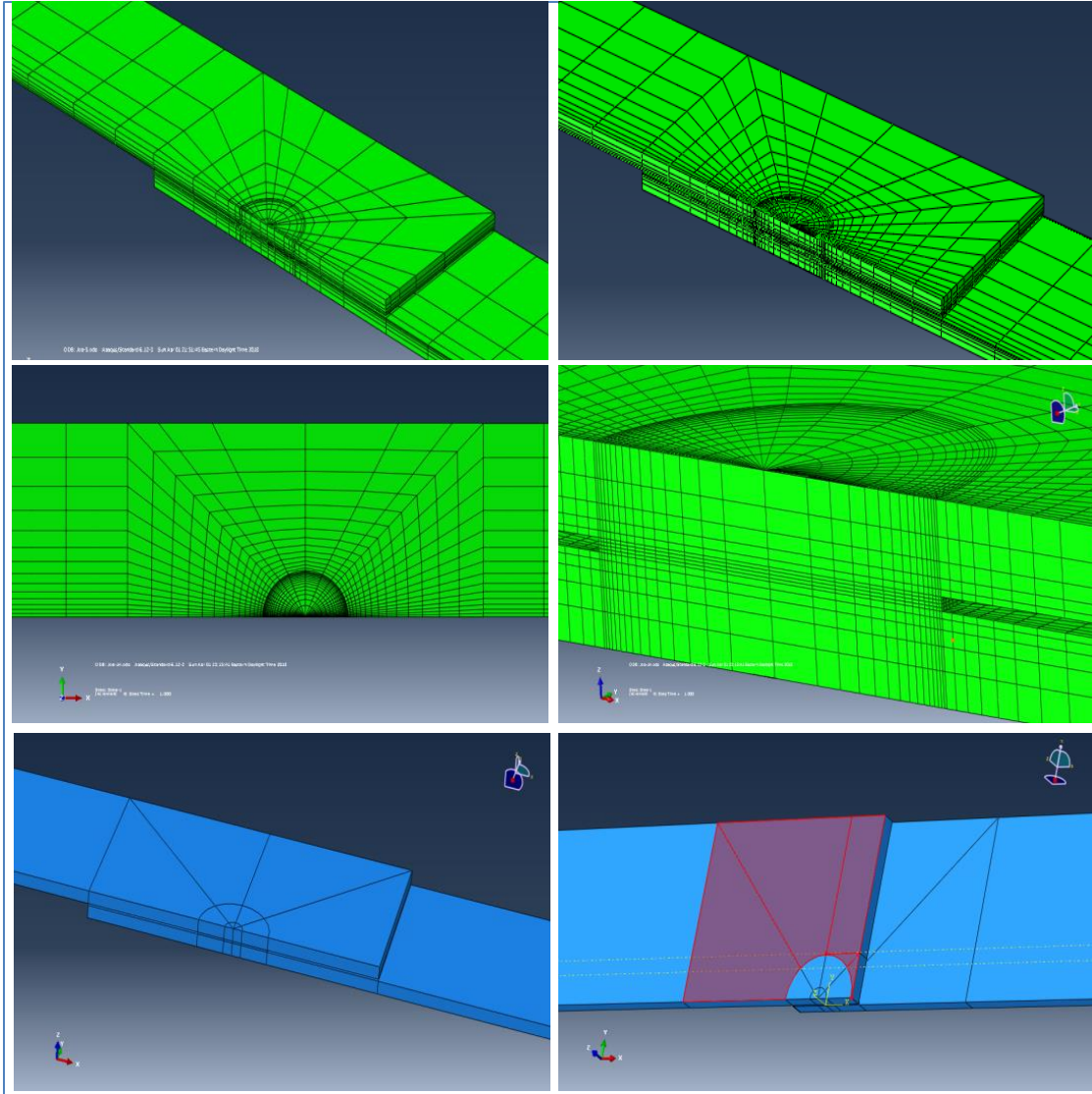


Figure 4:5: close look to the nugget zone and the model with deferent number of elements around the nugget

Boundary Conditions and Material Properties

Typical mechanical properties of mild steel were assumed for the modeled specimens, including a Young's modulus of $E = 210 \text{ GPa}$ and a Poisson's ratio of $\nu = 0.3$. The nugget diameter was set to 6 mm, with each sheet having a thickness of 1 mm. A small gap of 0.156 mm was modeled between the overlapping sheets to replicate the actual setup.

For the TS specimen model, the individual test piece length was 100 mm, while for the WCTS specimen model, the length was 90.55 mm. Both models shared a total specimen length of 175 mm. The clamping distance from each end—representing the spacer position in the experimental setup—was 25 mm in both configurations.

The FE models were designed to compare stress distribution at the nugget edges before and after trimming the unnecessary section of the WCTS specimen. This comparison was intended to determine whether such cutting would influence the mechanical strength of the WCTS configuration.

Initial Results of the FE Model

The simulations examined the effect of varying displacement and applied load on both models, comparing the resulting von Mises equivalent stresses. The displacement and/or the load are applied on one end of the sample while the other end has been fixed. The percentage difference between the two specimen types remained constant across all tested load and displacement conditions. The highest stresses were consistently observed at the nugget edges locations typically associated with crack initiation in resistance spot welds.

As shown in Table 4:1, stress differences between TS and WCTS specimens were negligible for both displacement-controlled and load-controlled cases. For instance, at a displacement of 0.15 mm, the TS specimen exhibited a stress of 2442.64 MPa, while the WCTS specimen showed 2457.4 MPa, a difference of only -0.604%. Similarly, for a 2000 N applied load, the stress difference was approximately -5.42%.

Table 4:1: FEM results, comparing the von Mises stress at the edge of the nugget where the crack initiated between TS and WCTS specimens under deferent displacement and load

Displacement (mm)	TS stress (MPa)	WCTS stress (MPa)	Difference % (TS – WCTS)/TS ×100%
0.05	814.214	819.132	-0.604
0.1	1628.43	1638.26	-0.604
0.15	2442.64	2457.40	-0.604
applied Load			
1000	1543.66	1627.32	-05.42
2000	3087.32	3254.64	-05.42

Mechanical Interpretation

These results confirm that removing the unused portion of the WCTS specimen does not significantly alter the stress state in the weld nugget region. The similarity in stress distribution between TS and WCTS can be attributed to two key mechanical factors:

Dominance of localized nugget stress fields; in lap-shear RSW specimens, the highest stresses are localized near the nugget periphery due to the combination of shear and peel stresses. Since the nugget geometry, sheet overlap, and boundary conditions remain unchanged, the localized stress fields are essentially unaffected by trimming the external sheet portions.

Minimal influence of removed sections on load path; the trimmed regions in WCTS are located away from the primary load-transfer path. In lap-shear specimens, the majority of the load is transferred across the weld nugget and its immediate surrounding material. Therefore, the removal of material outside this zone has little influence on global stiffness and nugget loading.

From an FE modeling standpoint, this finding is important because it validates the use of WCTS geometry as a mechanically equivalent alternative to TS specimens for studying nugget-level stresses, while potentially reducing sample size and material waste.

4.4 Specimen design and test matrix

Based on the sheet thickness used in the experimental work (1.34 mm), the recommended electrode tip diameter is 7 mm. The welding parameters are selected according to the AWS D8.1 [43]; however, the welding current was selected after conducting a stabilization test for the electrode caps. Also, peel tests for the welded coupons were conducted to ensure that the nugget diameter is acceptable in the standard range of $d \geq 4\sqrt{t}$ [43]. After determining appropriate weld parameters, three groups of samples were prepared. A number of metallographic samples were prepared in order to measure the the nugget diameters of each group, and then monotonic and fatigue tests for these samples were performed with and without the use of DIC to detect the crack. The welding parameters were applied as summarized in Table 4:2.

Table 4:2 : Summary of resistance spot welding parameters used for joining steel samples

Welding parameters	
Welding current	14.5KA
Electrodes force	4.4 KN
Number of welding cycles	16 cycles
Electrode diameter	7 mm
Cooling rate	6 L/min
Nugget diameter	(6.5 -7) mm

4.4.1 Welded specimens

The samples were prepared in three groups. The first group was the regular tensile shear TS specimens. The second group was weld-cut tensile shear WCTS specimens. The cut dimensions were according to the measurement of the nugget diameters which have been performed on metallographic samples. The last set of samples was pre-cut tensile shear (PCTS) specimens, which have the same dimensions as the WCTS, but have been cut before the weld process. The micrographs of these three sets of samples are shown in Figure 4:6. The sample test procedure included three steps: Step one was monotonic test

to compare the load capacity of WCTS and PCTS with regular TS specimen under static load. Step two was fatigue testing to compare the fatigue life of WCTS and PCTS with regular TS specimen under cyclic load. After these two sets of tests, the results showed that WCTS is closer in results to the TS than the PCTS specimen. Step three involved testing WCTS specimens in fatigue tests with the DIC camera and dyeing the area where the crack expected to be occurred in order to detect the crack initiation and record the crack growth stages.

The method used to determine the number of cycles at which crack initiation occurs involves synchronizing the fatigue testing setup with the DIC system. The frequency of the fatigue test is predetermined during the setup, and the framing frequency of the DIC camera is also known. By running the DIC system simultaneously with the fatigue test, the camera captures a continuous sequence of images throughout the entire fatigue life span of the specimen. Once the test is complete, the images are reviewed to identify the exact frame in which the crack initiation first appears. Knowing both the image number and the DIC capture rate allows for the precise calculation of the number of fatigue cycles corresponding to crack initiation. This synchronized approach ensures accurate and real-time monitoring of early damage development in the welded joint.

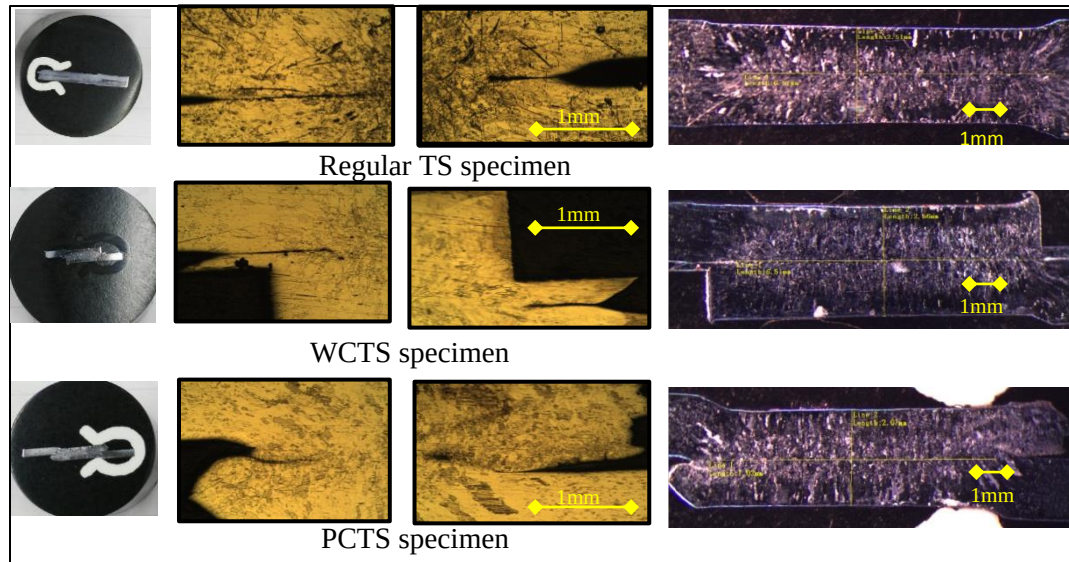


Figure 4:6: Micrographs of the nuggets and their edges for the three types of joint test specimens after cross-sectioning.

4.4.2 Test matrix

In order to prove the concept of using the new method to detect the crack initiation in real time the following test matrix was followed. In step one and two of the test procedure, 11 samples were tested from each group. Two specimens from each group were used to prepare the metallographic samples and measure the nugget diameters. Three specimens from each group were tested in monotonic test. Six samples from each group were tested in fatigue at three load levels, with two samples at each level as shown in Table 4:3. After confirming that the WCTS geometry is suitable to detect the crack, the fatigue tests are conducted in two stages, with the initial stage without DIC, just to compare the fatigue life of the three sets of specimens.

Table 4:3: Test matrix and number of samples that was used with each type of specimen and number of samples in each test

TS specimen 175 mmx25 mm	Coupons dimensions	Monotonic test	Fatigue test	Microstructure test
TS 11 samples	100 mmx25 mm	3 samples	6 samples	2 samples
WCTS 11 samples	100 mmx25 mm	3 samples	6 samples	2 samples
PCTS 11 samples	90.55 mmx25 mm	3 samples	6 samples	2 samples

4.5 Results

The results of the fatigue tests show that the WCTS specimens are more comparable to the regular TS specimens than the PCTS specimen. The second stage utilized DIC and the whole growing stages of crack were recorded. The concept of detecting the crack initiation by the new method has been successfully proved. Figure 4:7 b) and c) shows the crack and how it can be detected and recorded.

However, in relation to crack initiation and its duration percentage of the total fatigue life, DIC camera observations revealed distinct differences in crack behavior between high cycle and low cycle fatigue. The initiation and propagation of cracks follow different duration percentage depending on the applied load and fatigue life conditions.

For high cycle fatigue, where the applied load is relatively low, cracks tend to initiate earlier than expected at around 20% of the total fatigue life. However, these cracks remain undetectable on the outer surface for an extended period, spending approximately 60% of the total fatigue life propagating through the sheet thickness before becoming visible. This process results in three distinct stages of crack development. The first stage, referred to as the no-crack stage, extends from the beginning of the fatigue test until about 20% of the total fatigue life, at which point the crack is initiated within the material. The second stage involves the propagation of the crack through the sheet thickness, which occurs from around 20% to 80% of the fatigue life. During this phase, the crack gradually progresses through the material but remains hidden from the surface. The transition to the final stage occurs when the crack finally emerges on the visible side after spending roughly 60% of the fatigue life growing internally. The third and final stage involves crack propagation across the sheet width, consuming the remaining 20% of the fatigue life before complete failure occurs.

In contrast, the behavior of cracks in low cycle fatigue, where the applied load is significantly higher, follows a different pattern. In these conditions, a larger percentage of the fatigue life is spent solely on crack initiation. The crack does not appear until around 80% to 90% of the total fatigue life has elapsed. However, once the crack has formed, its propagation through both the sheet thickness and width occurs at an accelerated rate due to the high applied load and the resulting stress concentrations at the crack edges. As a result, the final stage of crack propagation, encompassing both the thickness and width of the sheet, takes only 10% to 20% of the total fatigue life.

These observations indicate that in high cycle fatigue, crack initiation occurs earlier but propagates slowly, while in low cycle fatigue, crack initiation is delayed but its rapid propagation leads to faster failure. Understanding these distinct behaviors is crucial for assessing fatigue performance and predicting the failure modes of welded joints under cyclic loading conditions.

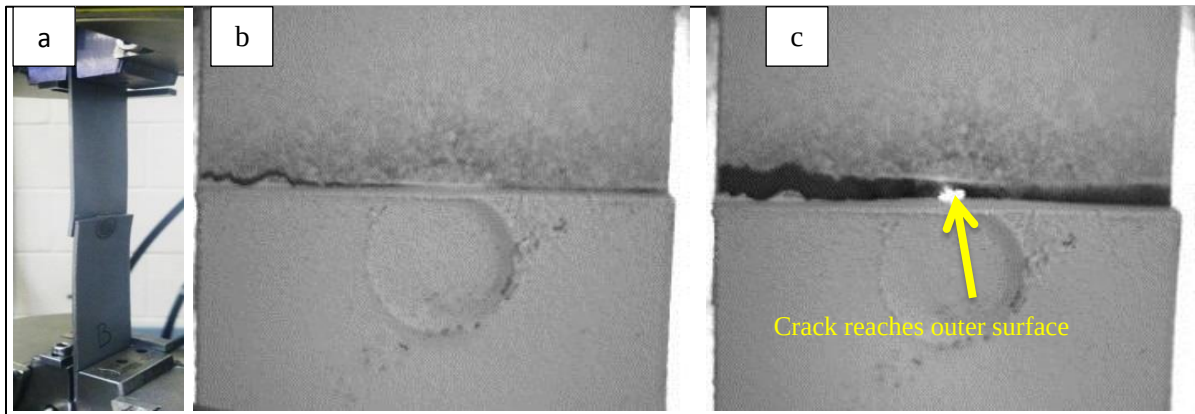


Figure 4:7: Crack detection of modified lap shear weld-cut specimen by DIC, a) the WCTS sample during the fatigue test, b) the sample before crack, c) crack propagation through the thickness of the sheet and light show up from other side of the sample. Please see the video at: <https://youtu.be/s3uzCkkgk9g> .

Chapter 5: Development and characteristics of the Ni-coating interlayer for Al/Mg RSW

5.1. Introduction

The development and characterization of CS-assisted dissimilar resistance spot welding between Al and Mg involves evaluating various aspects to ensure a successful and reliable weld. Due to the differences in material properties and the challenges associated with joining dissimilar metals, thorough characterization is essential. Here are some key aspects considered in this chapter about characterizing the resistance spot welding of Al and Mg:

- Selection of an interlayer material that can suppress intermetallic formation between Al and Mg.
- Developing CS process for coating weld coupons with the selected material.
- Developing RSW process window and obtain the best parameters for CS-assisted RSW of Mg/Al
- Intermetallic compounds: Dissimilar metal welding can result in the formation of intermetallic compounds at the joint interface, which can affect the weld's properties. Characterization should include analyzing the type and amount of intermetallic compounds present in the weld.
- Microstructure: Examining the microstructure of the weld zone and base materials to understand changes in grain structure, crystallography, and potential defects. Optical microscopy and electron microscopy techniques are useful for this purpose.

- **Weld strength:** Assessing the mechanical strength of the weld joint, including tensile strength and shear strength. This helps determine the joint's structural integrity and its suitability for the intended application.

The aim of this chapter is to develop and characterize CS-assisted RSW of dissimilar Al/Mg in order to ensure the quality and reliability of the weld joint in various engineering applications. The characterization helps identify potential issues, refine the welding process, and make informed decisions about the selected material, which are Al and Mg in this dissertation. Furthermore, it plays a vital role in understanding how these materials behave when subjected to Ni-coating through the cold spray process, as well as in determining the best welding parameters.

5.2. Characterization of Ni powder

The Ni powder was selected for the study. This selection was based on the following requirements for welding Al and Mg in dissimilar resistance spot welding:

1. **Enhanced bonding:** Ni coating can promote better bonding between Al and Mg. When coated with Ni, the Al and Mg surfaces exhibit improved adhesion, reducing the likelihood of voids or gaps in the joint [131]. This enhanced bonding contributes to the overall strength and integrity of the dissimilar spot weld.
2. **Material compatibility:** Ni has been extensively studied and used in various welding processes [74], [75], [132]. Their compatibility with Al and Mg makes them suitable for application in dissimilar resistance spot welding.
3. **Thermal conductivity:** Ni has good thermal conductivity that fall within the range 88-91W/m.k. This is important in dissimilar spot welding because it helps distribute heat evenly during the welding process, reducing the risk of overheating or melting one of the

base materials. Controlling heat is essential for achieving a high-quality joint without undesirable defects.

4. Bi-metallic transition materials: Ni is often chosen as a transition material in dissimilar welding because they possess intermediate properties between Al and Mg [131]. The Ni acts as a bridge between the two dissimilar base materials, which helps prevent the formation of brittle intermetallic compounds. These intermetallic compounds can form when Al and Mg are directly welded together and they compromise the joint's mechanical properties.

5. Process optimization: Researchers have optimized cold spray parameters, such as powder feed rate, nozzle velocity, and standoff distance, to achieve the desired coating thickness and quality with Ni powder [133]. This process optimization is crucial for ensuring the effectiveness of the coating as an interlayer in the dissimilar spot welding process.

In summary, the choice of Ni powder in cold spray technology for dissimilar resistance spot welding of Al and Mg is based on their ability to act as an effective transition material, enhance bonding, and provide good thermal conductivity. Researchers can leverage these properties to create high-quality dissimilar spot welds that meet the industry's demands for lightweight, efficient, and environmentally friendly automotive structures.

5.3. Cold spray coating of Ni on Al to Mg sheets

The first group of samples has been coated. Ni-coating was applied to Al and Mg substrates using a cold spray system. Prior to coating, the sample surfaces were prepared through sandblasting and thoroughly cleaned with acetone. The Ni powder, formally

known as SST-N5001, supplied by Centerline Company, featured irregularly shaped particles with sizes ranging from 5 to 45 μm with high purity composition $\geq 99.7\%$ of Ni. Deposition was carried out using an SST-P low-pressure cold spray machine equipped with a 4000 series powder feeder from Centerline Company. Nitrogen was utilized as the carrier gas, delivering the Ni particles through a 120 mm-long convergent-divergent DeLaval nozzle with a 2 mm orifice diameter. To ensure optimal coating quality, the process parameters were precisely controlled, including a gas pressure of 1.5 MPa (217.5 psi) and a gas temperature between 485 and 500°C, while additional parameters are detailed in Table 5:1. The average thickness of the Ni coating layer obtained with the coating process is 100 μm on each substrate, for a total Ni coating average thickness of 200 μm between the two coupons. The SEM image in Figure 5:1 shows the size and the shape of the Ni powder particles and their size distribution, indicating they are mostly agglomerated. As mentioned in the specifications of the Ni powder, which is provided by the producer of the powder that the Ni powder has irregular shape and the average particle size is 5- 45 μm [134].

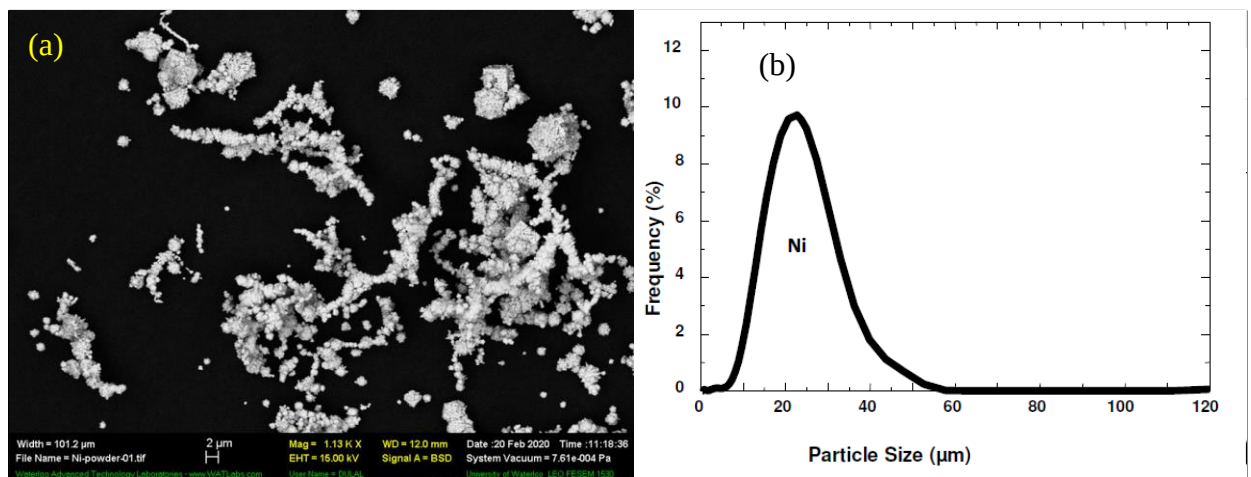


Figure 5:1: (a) SEM image showing the particle shape and size of Ni powder and (b) size distribution[135].

Surface roughness was assessed using a Nanovea M1 surface indentation device, which provided a comprehensive view of surface texture attributes. Figure 5:2 shows the 3D scan that was performed for 1x1 mm of the Ni coating on Al side and Figure 5:3 shows that on the Mg side. The reason for performing the roughness test and capturing the 3D image of the surface is to study the contact surfaces at the welded area to understand how the voids are created at the interface between the welded coated Ni layers as shown in Figure 5:5 (a-e). Scanning electron microscopy (SEM) was utilized for the characterization of the cold spray-coated Ni and for examining the weld region between Mg and Al, with a specific focus on evaluating the presence of intermetallic compounds. This analysis was carried out using two advanced microscopes: the LEO 1530 microscope and the FEI Quanta FEG 250 environmental scanning electron microscope (ESEM), which were equipped with energy-dispersive X-ray spectroscopy (EDX) capabilities.

Table 5:1: Cold spray coating parameters of deposition of Ni on Al and Mg substrates

Coating Materials	Ni on Mg	Ni on Al
Flow Gas	N ₂	N ₂
Gas Temperature (°C)	500	500
Gas Pressure (MPa)	1.5	1.5
Powder Feed Rate (gr/min)	8	8
Nozzle Speed (mm/s)	25	25
Step Over (mm)	2.7	3
Stand-off Distance (mm)	12	12
Nozzle Length (mm)	120	120
Nozzle Orifice Diameter (mm)	2	2
Nozzle Exit Diameter (mm)	6.3	6.3
Type of Nozzle	a converging–diverging de Laval UltiLife TM	

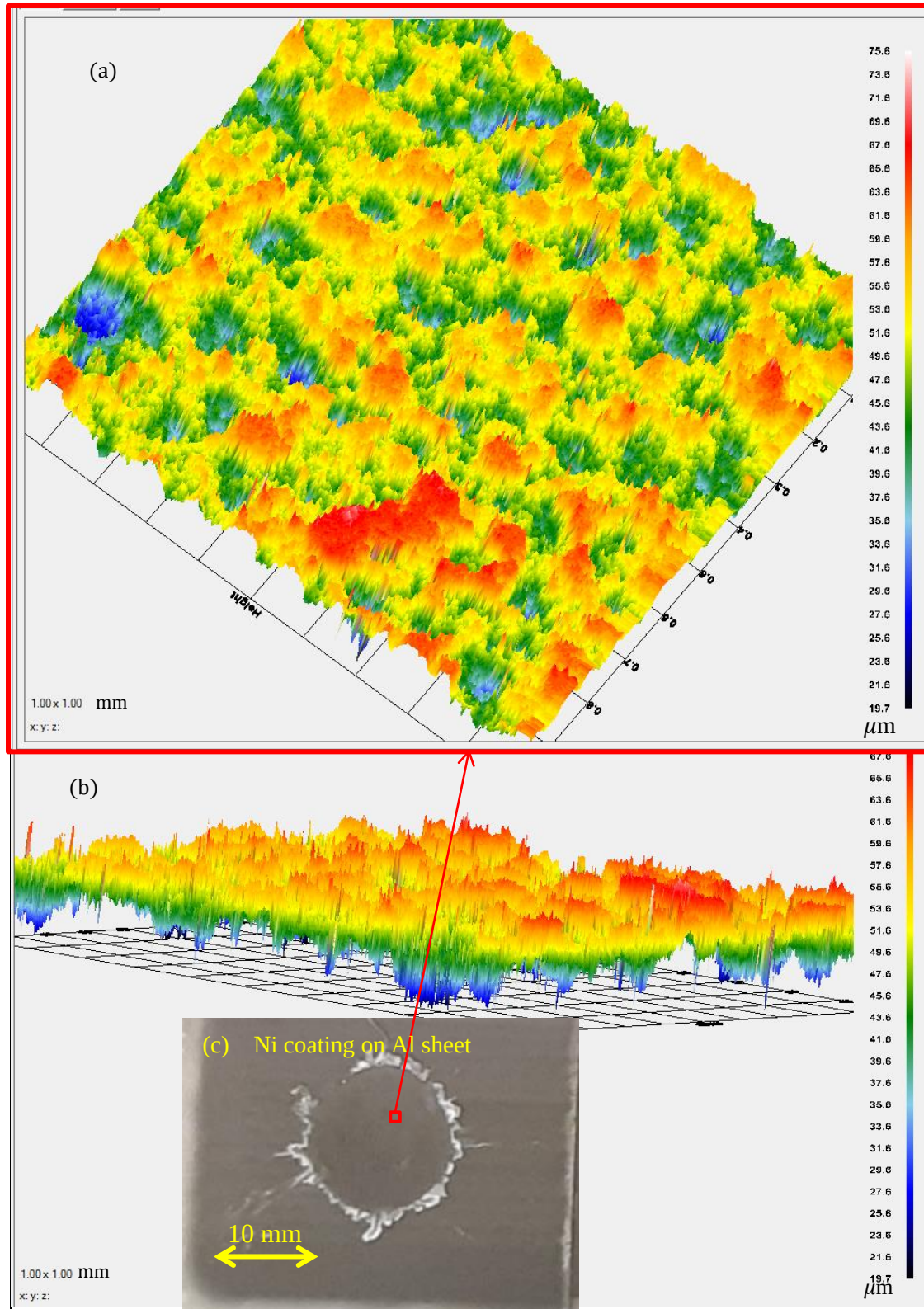


Figure 5:2: 3D scan of 1x1 mm of Ni coating on Al substrate that shows the roughness of 1mm^2 of the coating surface. (a) Top view of the 3D scan, (b) side view of the 3D scan (c) Ni coating on Al sample, that shows the test position before the weld.

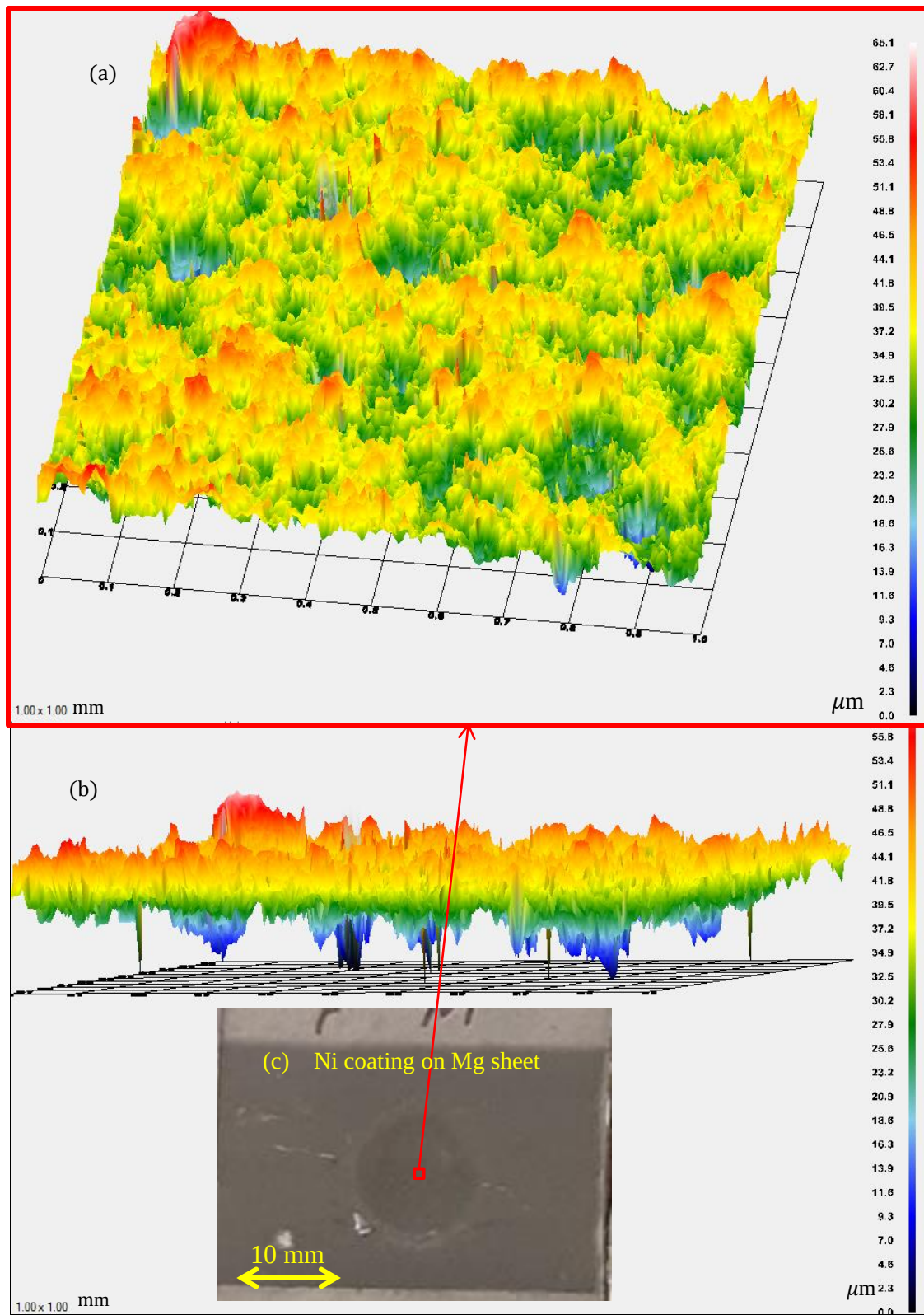


Figure 5:3: 3D scan of 1x1 mm of Ni coating on Mg substrate that shows the roughness of 1mm² of the coating surface. (a) Top view of the 3D scan, (b) side view of the 3D scan (c) Ni coating Mg sample, which shows position of the test before the weld.

Figure 5:4 provides a visual representation of the coated Al sheet with Ni, both before and after welding. Notably, in the initial analysis, it was observed that the Ni coating layers contained micro-porosity, as demonstrated in Figure 5:4 (a)-(c). However, it is worth mentioning that this micro-porosity diminished after the welding process, as evidenced in Figure 5:4 (d)-(f). A comparative analysis of the results before welding (Figure 5:4 (a)-(c)) with those after welding (Figure 5:4 (d)-(f)) revealed a significant observation – the Ni coating had penetrated in to the Al substrate side. The presence of Ni in the Al was further corroborated through elemental analysis, as depicted in Figure 5:4 (e) and (g-h).

In a broader context, these images shed light on the fact that the Ni coating layer effectively prevented the formation of intermetallic compounds between Al and Mg after the welding process, as illustrated in Figure 5:5 (c)-(e). However, an intriguing feature that emerged in the SEM results was the presence of voids that had formed between the two welded Ni-coated layers after the welding process, as presented in Figure 5:5 (a)-(e). It is important to note that this region included Mg. The presence of Mg, positioned between the welded Ni coating layers, can be attributed to the penetration of Mg through the coating's porosity and the thinner Ni coating layer, as observed in Figure 5:4 (c).

The bonding of the Ni layers indeed took place. Therefore, the explanation for the phenomena observed during welding should take the following facts and considerations into account:

- The presence of Mg between the welded Ni coating layers.
- The presence of coating porosity.
- The melting points of Ni, Mg, and Al.
- The forging temperature of Ni.
- The boiling point of Mg.

The steps that occurred during the welding processes become evident with closer examination of the cross sections which can explain how Mg became integrated into the Ni coating layers. As the Ni coating layers were effectively bonded together during the RSW process, the temperature during welding fell within the range between the forging temperatures (when the metal starts to soften), which is 1095 °C for pure Ni and the melting point of Ni, which is 1455°C. In contrast, the boiling temperature of Mg is 1091°C, slightly lower than the welding temperature range. Therefore, it is plausible that some Mg vaporized at the interface with the Ni coating layer during welding. This vaporized Mg may then infiltrate the interface between the two Ni coating layers through the coating's porosity, micro-cracks, and thin voids within the coating, as observed in Figure 5:4 (c) and Figure 5:5 (b). The surface roughness of the Ni coating, as depicted in Figure 5:2 and Figure 5:3 facilitated the creation of voids between the two coating layers at the interface where the rough coating surfaces meet, which subsequently became filled by Mg. With the conclusion of the welding process, the cessation of the current, and the solidification of Ni, the Mg that had infiltrated the Ni coating layers remained trapped within the coating. Figure 5:6 visually presents the sequence of these processes, depicting the formation of Mg voids or cavities within the welded Ni coating layers. In the alternate scenario, if one argues that the Mg did not evaporate, that has one meaning which is the temperature during the weld did not reach 1091 °C (the boiling temperature of Mg). That will lead to unsuccessful welding, because the Ni in this assumption will remain in the solid phase and cannot create a bonding region.

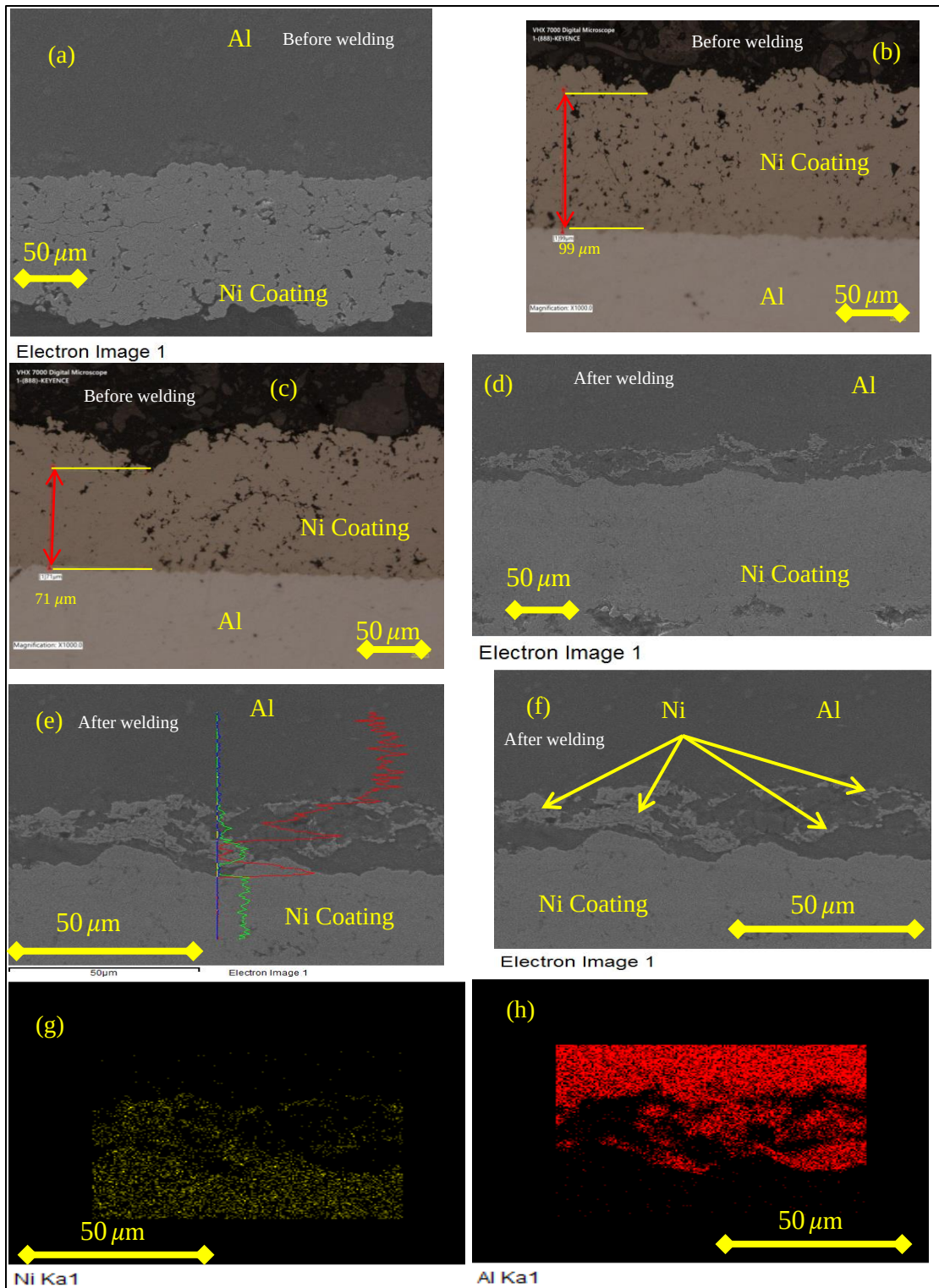


Figure 5:4: SEM images of the Al coated sheet before (a-c) and (d-f) after welding. (a-c) show clear interface between coating and the substrate, porosity in coating, and uneven thickness of coating. (d-f) show a mixed Al-Ni region between coating and substrate, no porosity in the coating, and even thickness of Ni layer. (g-h) show clear presence of both Ni and Al in a 30 μm thick region between Ni coating and Al substrate.

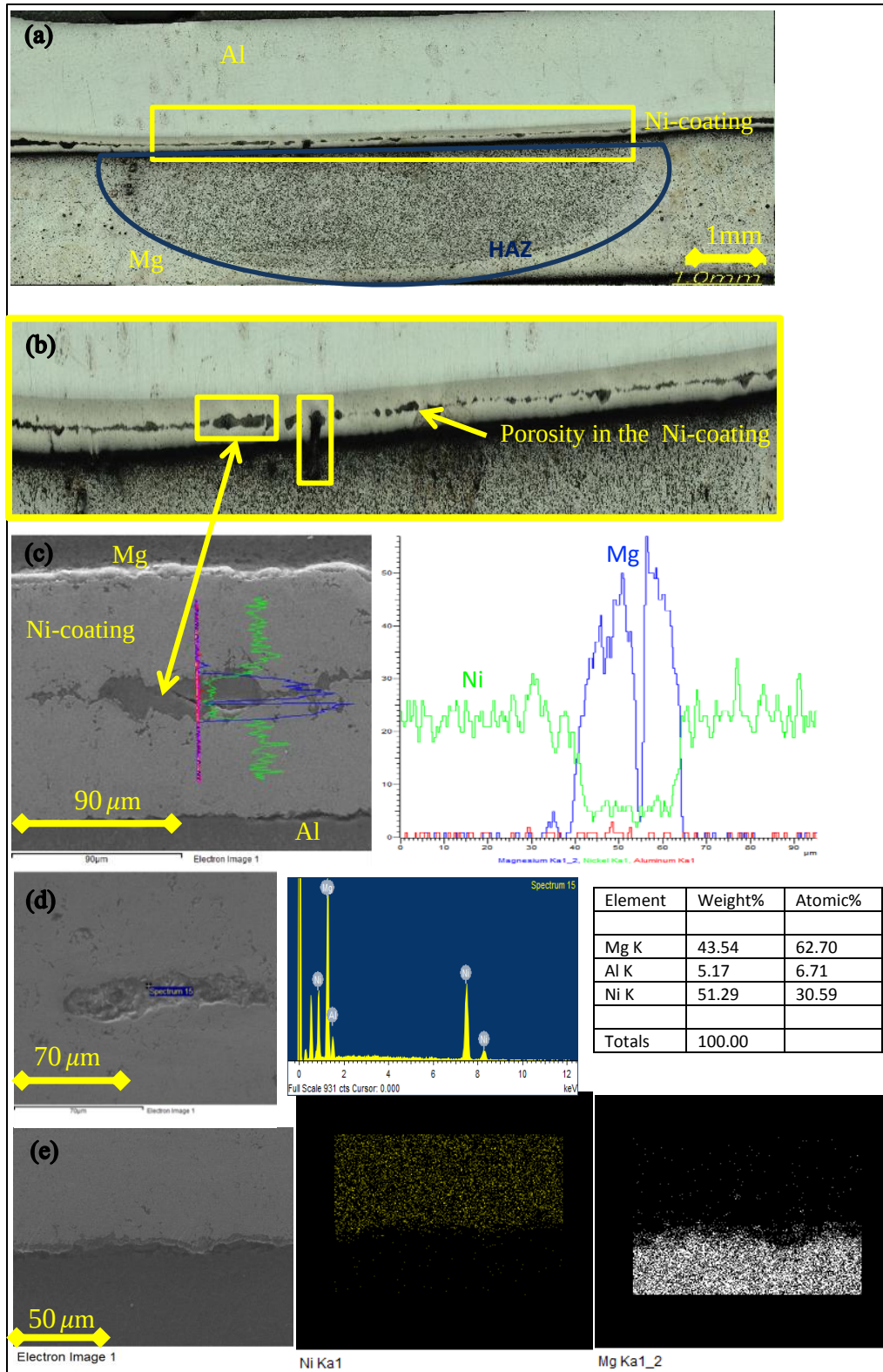


Figure 5:5: Sample after welding showing (a) details of the weld area and (b) images of porosity at welded Ni-coated layer, (c) details of one of the areas in the middle of Ni showing presence of Mg, (d) element analysis using EDX in areas with significant Mg content. (e) SEM image of Ni and Mg interface

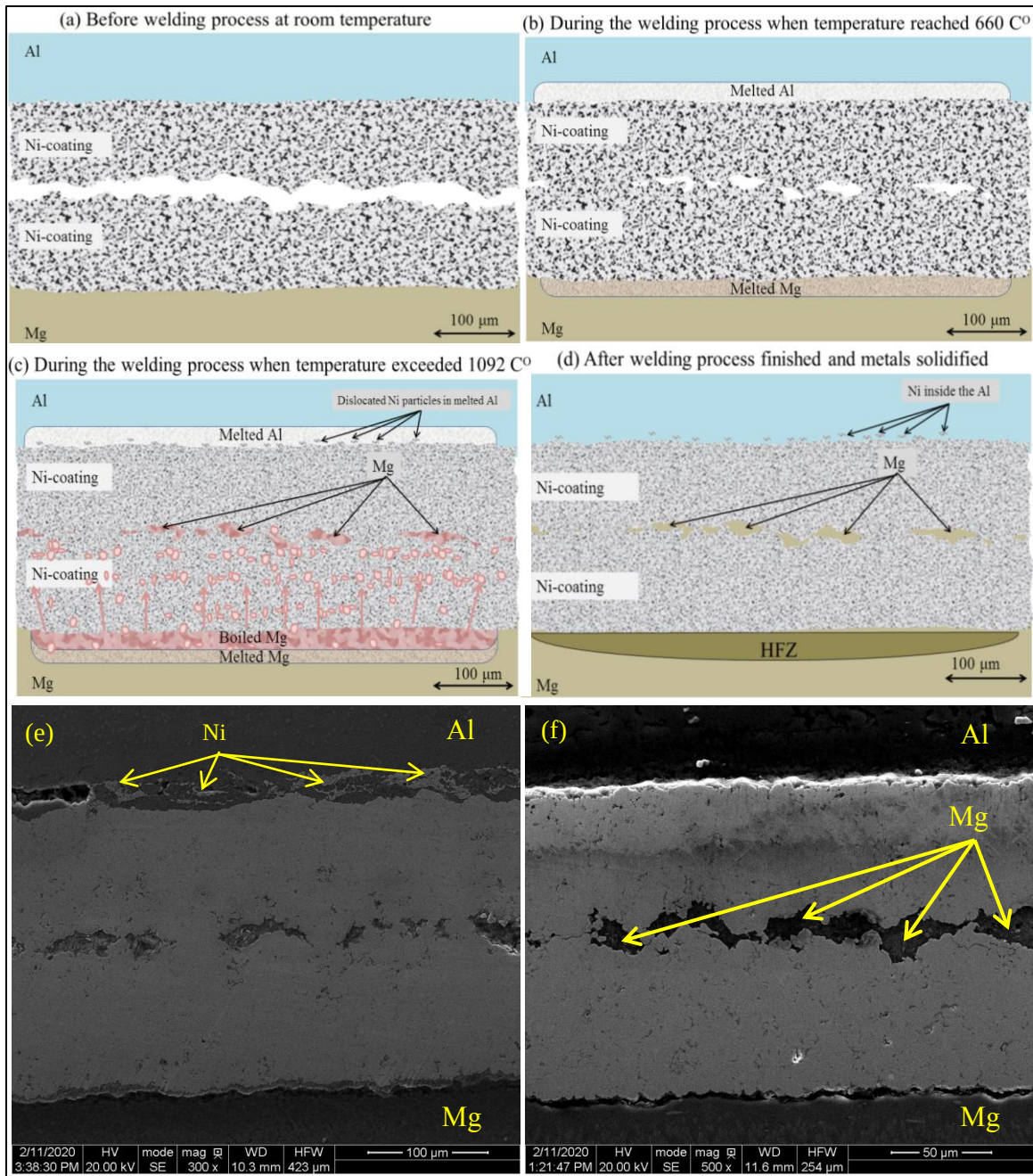


Figure 5:6: Schematic representation of the joining mechanisms occurring at critical temperatures during the resistance spot welding process, highlighting the interaction behavior of Ni, Al, and Mg. (a) Initial positioning of the specimen for welding; (b) Progression as the interfacial temperature reaches the melting points of Al and Mg; (c) At the boiling point of Mg (~1092 °C) and the forging temperature of Ni (~1095 °C), vaporized Mg migrates through the inherent porosity of the Ni coating, accumulating within interfacial voids between the opposing Ni layers; (d) Final stage illustrating the completion of the welding process and formation of the bonded joint, (e-f) SEM images of the final results (e) shows Ni powder inside the Al substrate and (f) show the Mg at the Ni/Ni coating interface

5.4. Characterization of resistance spot welds of Ni-coating

Al/Mg

Ni coating was applied to the samples via cold spray, as discussed in the previous section, in the area where welding was anticipated, as depicted in Figure 5:7 (a). Also, Figure 5:7 (b) shows the coated area after failure in the monotonic test. The weld process was performed on the Ni-coated Al and Mg coupons and the best weld features were obtained at 27 kA and 15 cycles 2 pulses and the delaying time between the pulses was 5 cycles. In resistance welding, the current frequency is typically 60 Hz, which corresponds to 60 alternating current (AC) waves per second. Each wave is considered one cycle, and the duration of a single cycle can be calculated as $1000/60$, giving approximately 0.0167 seconds per cycle. In contrast, direct current (DC) does not possess actual electrical cycles. Instead, the cycle count under DC conditions is represented by the equivalent time duration. For instance, 30 cycles of DC current corresponds to a weld duration time of 0.5 seconds. Table 5:2 summarizes the welding parameters for Ni group of samples.

Table 5:2 summary of welding parameters for Ni-coating Al/Mg group of samples

Welding parameters		Ni-coating Al/Mg
1	Welding current (kA)	27
2	Welding time (cycles)	15
3	Holding time after welding (cycles)	30-45
4	Number of pulses	2
5	Delaying time between the pulses (cycles)	5
6	Electrode force (kN)	4
7	Water flow rate (L/min)	7
8	Electrode diameters on Al side (mm)	12
9	Electrode diameters on Mg side (mm)	16

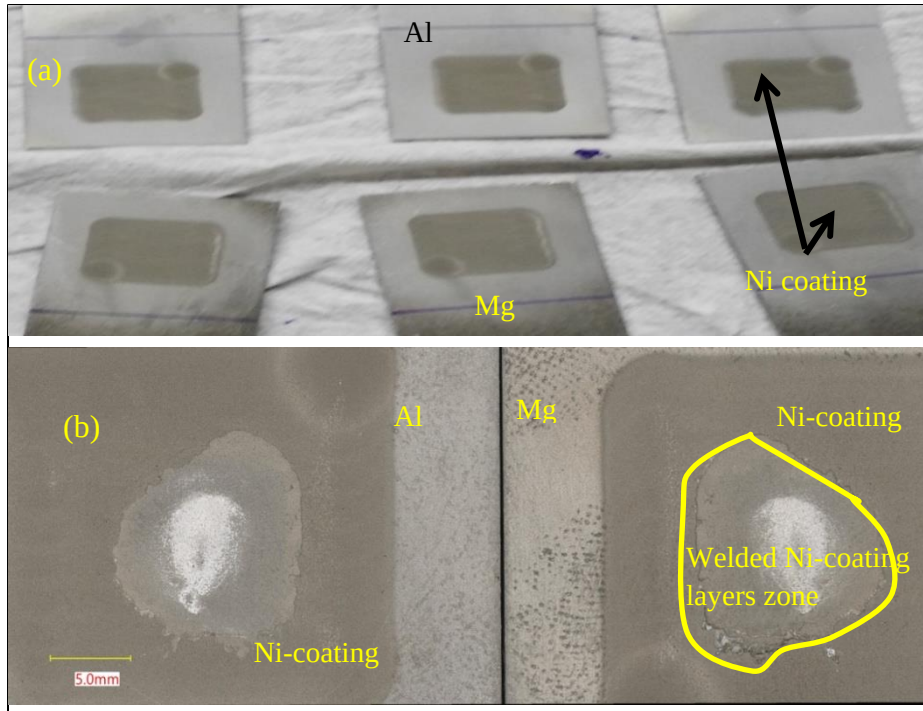


Figure 5:7: (a) Al and Mg coupons before the welding process and (b) image shows nugget size or welded area after failure in monotonic test on the separated sheets.

As It is logically and widely recognized that an increase in weld nugget size corresponds to an improvement in joint strength [136]. This relationship was also observed in the coated weld samples of the present study, where enlarging the welded area resulted in enhanced mechanical performance of the joints. Consequently, the strategy employed to identify the best and more suitable welding parameters focused on adjusting the welding current and welding time to achieve the maximum possible welded area that maximizes the joint strength. In that way, there is no need for preparing samples for monotonic test until the largest and most suitable welded area is obtained and then monotonic test take place to find the highest strength. As mentioned before the best features of RSW for Ni-coated Al and Mg coupons were obtained at 27 kA and 15 cycles 2 pulses and the delaying time between the pulses was 5 cycles. However, different levels

of current and weld time have been applied in order to select those welding parameters.

Figure 5:8 shows the effect of different welding parameters on the welded area.

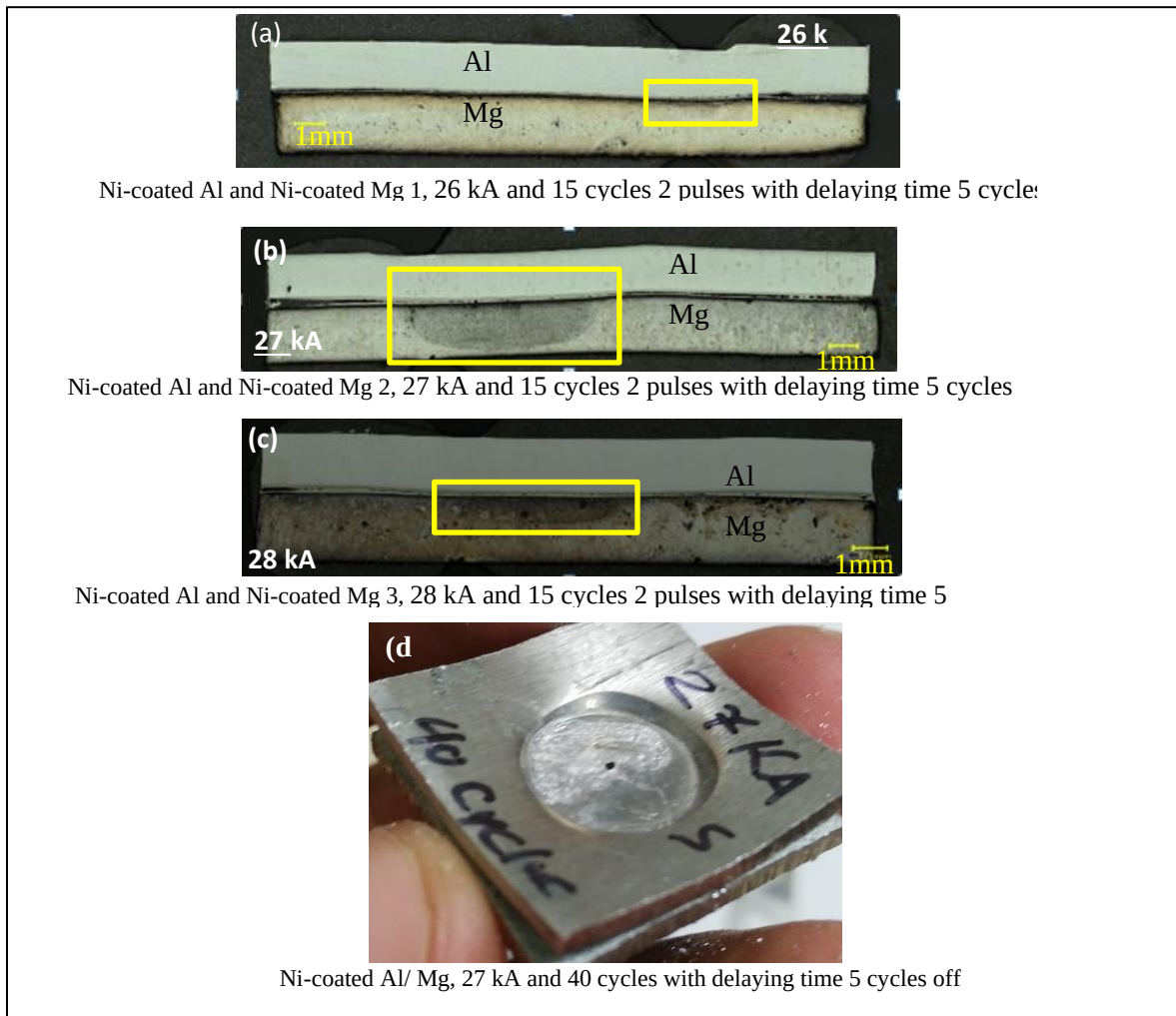


Figure 5:8: Metallography of cross-sectioned welds between Ni-coated Al to Ni-coated Mg produced with varying currents. (a) Welded at 26 kA, (b) welded at 27 kA that show the largest bonding area and (c) welded at 28 kA (d) shows the indentation in the welded samples with 40 cycle welding time.

Welding parameters have been adjusted as follows: initially with one pulse, coated samples were welded with five levels of welding currents, 26, 26.5, 27, 27.5 and 28 kA, and three different welding times, 25, 30 and 35 cycles. The range of welding currents spans from conditions resulting in either no welding or weak welds, typically observed around 24 kA, to scenarios of expulsion accompanied by high indentation at

relatively elevated welding currents, approximately 29 kA and above. In same way the welding time range have been determined. With all samples through welding process, the electrode force was 4 kN, cooling water flow rate was 7 L/min and electrode diameters were 16 mm on the Mg side and 12 mm on the Al side. The dimension of the samples used to obtain the best welding parameters were 25 x 25 x 1.5 mm for Al and 25 x 25 x 2 mm for Mg. All the samples with the above range of welding currents and times successfully bonded together. However, to determine which parameters are best suited to weld, the samples were pulled apart and the bonded areas are measured to compare the diameter of the welded area of the Ni-coat for different levels of welding current and welding times. Following trials with a single pulse, it was found that the diameter of the welded area and the strengths were insufficient for overlap testing, and subsequently, two pulses with 15 to 20 cycles each have been implemented as shown in Table 5:3. The samples were examined by peel test and then the welded area of the coat was measured for each test by using imageJ software.

Table 5:3: Summary of welding parameters examined by peel test, with conditions highlighted that achieved superficial bonding.

Welding current (kA)	Two pulse welding time (cycles)			delay time (cycles)
	15	18	20	
26	Test 1	Test 7	Test 13	5
27	Test 2	Test 8	Test 14	5
28	Test 3	Test 9	Test 15	5
26	Test 4	Test 10	Test 16	10
27	Test 5	Test 11	Test 17	10
28	Test 6	Test 12	Test 18	10

Attempts number 1, 2, 3 and 10 produced suitable results in terms of superficial bonding at the peel test and large welded area. Also, when tensile test is applied for samples that welded in same parameters, the best during the tensile test was sample that welded with parameter of test 2 in Table 5:3. Subsequently, five samples of lap shear test have been welded according to the parameter of attempt 2 and tested by monotonic test.

Based on these results, a comprehensive evaluation of welding parameters was carried out using two distinct groups of samples. In the first group, substrate surfaces underwent sandblasting to achieve a more uniform roughness, which is known to enhance the coating's performance [137]. The second group of samples had their surfaces meticulously cleaned with acetone before the coating process. The two groups are shown in Figure 5:9 (a) and (b). Both sets of samples were then subjected to coating using the parameters of Ni-coating that detailed in Table 5:1. It is worth noting that all samples successfully formed strong bonds or sound welds, irrespective of the variations in welding current and welding time. However, to pinpoint the best welding parameters for joining the coated Al to coated Mg, the samples were subjected to tensile testing and the sandblasting shows better performance. Figure 5:10 and Table 5:4 display the improvement in the strength of the coating samples after sandblasting.

Table 5:4: Max load for samples tested under same conditions to examine the effect of the sandblast on the strength of coated samples.

Without sandblast Sample number	Max load (kN)	With sandblast Sample number	Max load (kN)
2	1.89	2S	2.80
3	2.01	3S	2.76
5	1.82	5S	2.51
8	2.52	8S	2.38
Average	2.06	Average	2.61

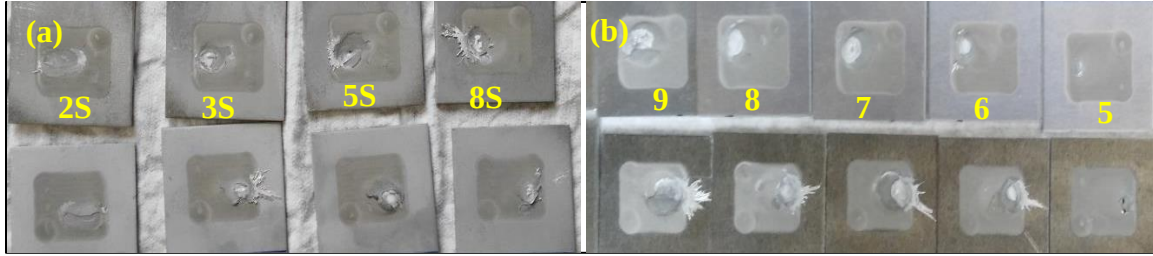


Figure 5:9: (a) Ni coating samples with sandblasting that show acceptable bonding area in sample 2S and expulsion occurred in sample 8S (b) Ni coating samples without sandblasting, but cleaning surface with acetone that show smaller bonded area is formed such as shown in sample 5

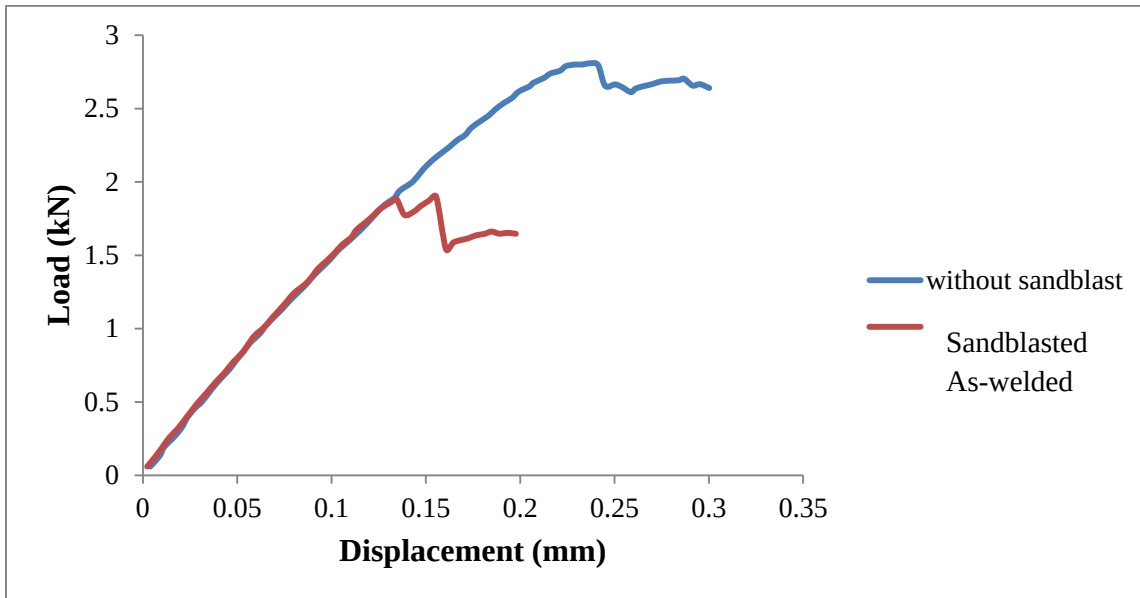


Figure 5:10: Joint strength comparison of sample #2 for surfaces that were as-welded versus sample#2S after sandblasting the sheets for Ni-coating samples, and welded in same conditions using the parameters shown in Table 5:2

According to Table 5:4 more samples with sandblast were prepared and tested in monotonic test as listed in Table 5:5 but with slightly different preparation. The difference being the coating area became larger to cover 30 mm x 39 mm at the edge of the coupons as show in Figure 3:2 (b) where seven samples were coated in same time with Ni instead of coating sample by sample with 25 mm x 25 mm as show in Figure 5:7 (a). Additional steps were taken to ensure that the electrodes made flat contact with the samples during the welding process. Samples for fatigue testing were prepared in the same condition in Table 5:5.

Table 5:5: The max load for more monotonic test results of Ni-coating samples that sandblasted with extra preparations

Sample number	Max load (kN)	Sample number	Max load (kN)
3	4.069	8	3.438
4	3.747	9	4.309
5	3.443	10	4.283
6	2.521	11	4.273
7	4.104		

During the tensile test, a direct correlation was identified between the diameters of the welded Ni-coated area and the strength of the welded samples. Therefore, bonded areas were meticulously measured. The results, as presented in Table 5:6 and Table 5:7, provide insights into the ideal welding conditions. After considering the indentation and the expulsion that occurred in the welded samples as show in Figure 5:8 (d), the samples that were welded with 40 cycles welding time were eliminated. The samples welded with 20 cycles welding time have relatively smaller welded area than the other samples in the group that processed by sandblasting. According to these findings, the most favorable range of welding current in this experimental work falls between 26.5-27.5 kA, while the welding time is found to be within the 25-30 cycles range as show in Figure 5:11. These parameters facilitate the formation of the largest welded area or nugget, signifying their effectiveness in achieving robust welds between coated Al and coated Mg surfaces.

Table 5:6: Equivalent welded nugget diameters in (mm) of the samples that were cleaned with acetone.

Welding current (kA)	Welding time (cycles) for both two pulses			
	20	25	30	40
28	9.9	12.9	14.8	15.2
27.5	9.4	12.6	13.4	14.8
27	11.4	10.1	12.6	15.2
26.5	12.4	13.0	12.6	15.1
26	10.2	8.8	12.7	14.5

Table 5:7: Equivalent welded nugget diameters in (mm) of the samples that were processed by sandblasting.

Welding current (kA)	Welding time (cycles) for both two pulses			
	20	25	30	40
28	11.2	13.4	14.1	----
27.5	3.5	12.0	12.0	----
27	12.8	12.5	15.0	16.4
26.5	11.7	12.9	13.5	15.8
26	4.3	13.2	13.5	18.9

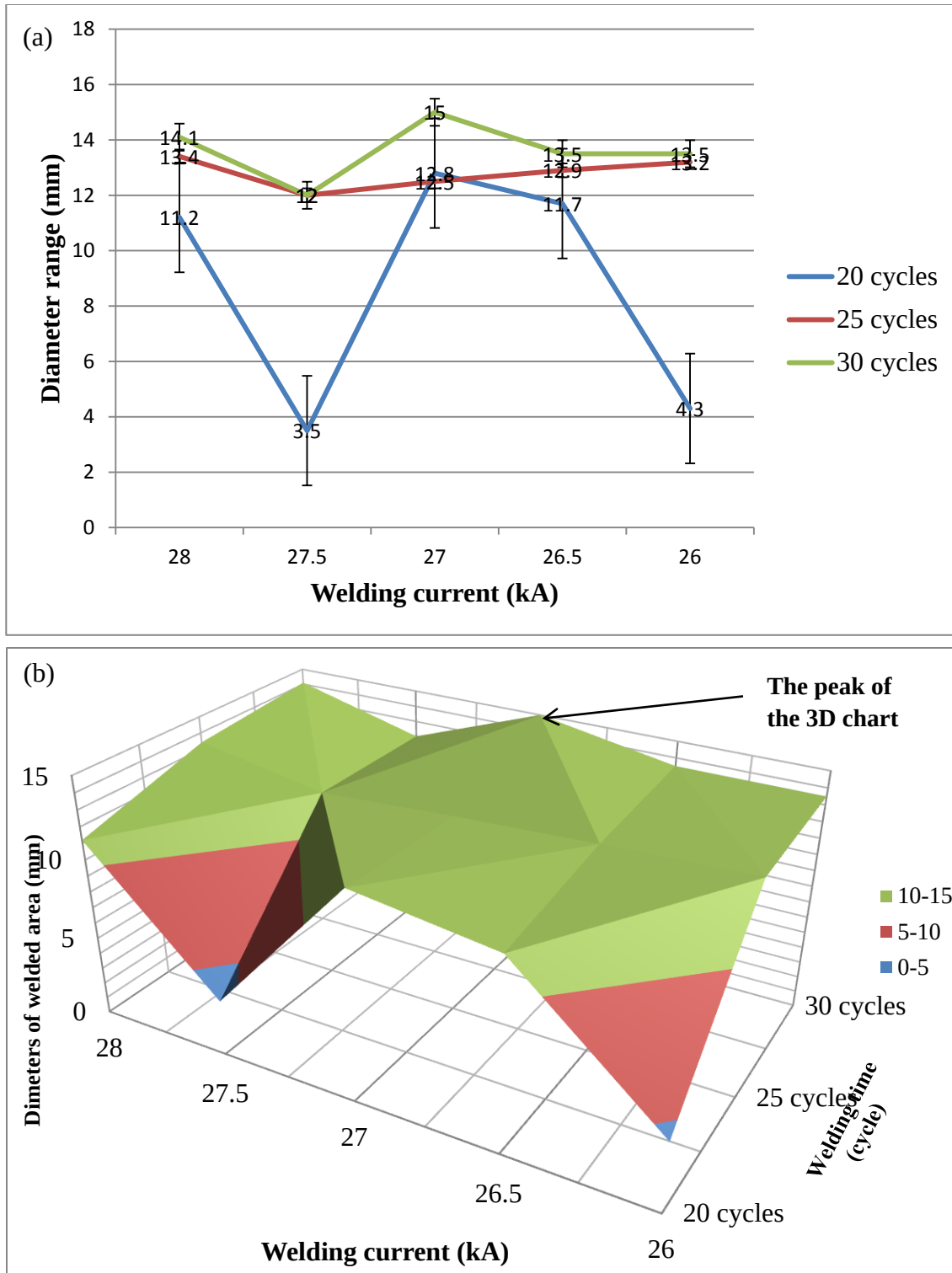


Figure 5:11: 3D plot for equivalent welded diameters of the samples that were processed by sandblasting. The 15 mm welded diameter shows at the peak at 27 kA welding current and 30 cycles welding time the 30 cycles represented in two pulses and 15 cycles each pulse

5.5. Joining adhesion in the coated dissimilar RSW Al/Mg

The joining process in this study can be delineated into two primary phases as how in Figure 5:12. Initially, bonding occurs between the coating layer and the respective substrates, and subsequently, the second phase involves the joining of the two coating layers at the interface. The bonding between the coating and the substrate primarily takes place during the cold spray coating process when powder particles are deposited onto the substrate. The mechanism of mechanical interlocking, a well-documented phenomenon in cold spray technology, significantly contributes to the effective bonding of the powder to the substrate surface. This is depicted in Figure 5:4 (a)-(c) and is supported by prior research [1], [21], [29]. Additionally, following the welding process and at the interface between Al and Ni, there is evidence of Ni penetration into the Al side. The Ni that infiltrated the Al side is the initial row or layer of powder deposited directly onto the Al surface during the cold spray process. Subsequently, when the Al melts at the Ni/Al interface during welding, the Ni particles disperse within the molten Al and remain embedded after the Al solidifies, as illustrated in Figure 5:4 (d)-(f).

Furthermore, after the cold spray coating, both substrates with Ni-coating exhibit the same material at the interface. Essentially, the dissimilar joint between Al and Mg transforms into a similar joint composed of Ni/Ni at the interface. The coupons featuring coating layers on the Al and Mg sides are subsequently subjected to the resistance spot welding process. Given that the Ni-coated layers are not perfectly flat, as depicted in Figure 5:2 and Figure 5:3, where the coating surfaces exhibiting peaks and valleys ranging from 19 to 75 μm , contact at the interface of the two Ni-coating layers on the Al and Mg sides primarily occurs among the peaks of the coated surfaces. This results in

micro-gaps at the interface, which subsequently give rise to voids after the welding process, as seen in Figure 5:5. Therefore, these voids can be attributed to the surface roughness. Simultaneously, the coating porosity, which arises during the powder deposition phase, and the voids at the interface play a crucial role in enhancing the heat generated at the interface between the coated layers during the resistance spot welding process. Notably, air gaps typically possess high resistance to welding current, leading to an increased softening rate or even partial melting at the contact areas on the peaks of the Ni-coating, both on the Al and Mg sides. This phenomenon is due to the maximum heat being generated at the contact areas between the surfaces being welded in the resistance spot welding process. As illustrated in Figure 5:6, the peaks of the Ni-coating bonded at the interface between the coated Al and coated Mg. This bonding is significant as the temperature reaches a range between the forging temperature of Ni, which is 1095°C, and its melting point at 1455°C. If the temperature of the Ni-coated layers did not fall within this range on both sides, the Al and Mg sheets would not effectively join and withstand relatively high loads during the subsequent monotonic test.

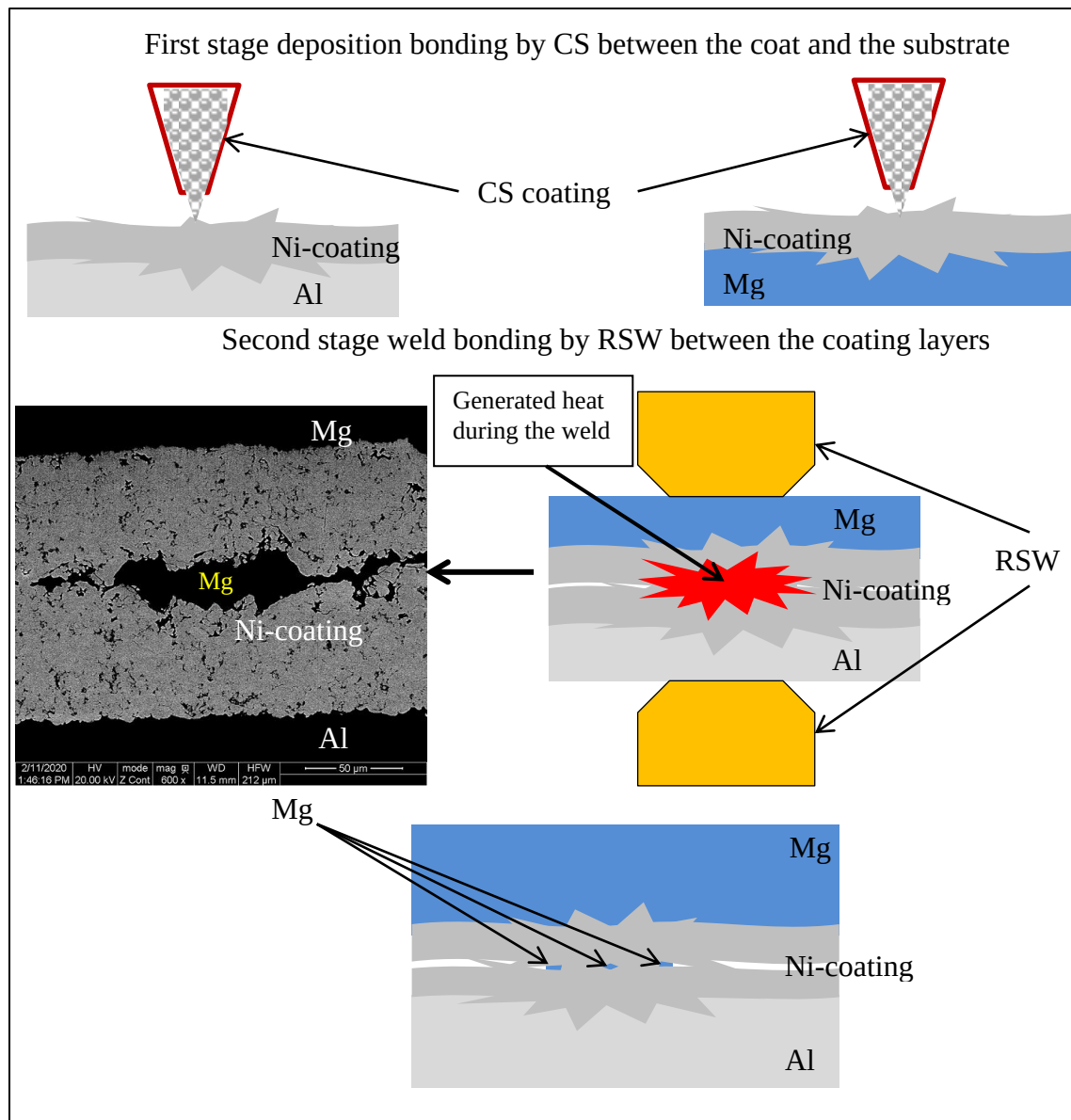


Figure 5:12: A visual schematic to show the two different mechanisms/processes that lead to final adhesion joint of the coating Al/Mg. The first stage is bonding between coating layer and substrate during CS process by interlock phenomena. The second stage is joining the coating layers from Al side with Mg side together during RSW process by welding the coating layers

5.6. Failure mechanism in CS-assisted lap-shear

Upon examining the fracture surfaces of the monotonic lap-shear test samples, it was evident that no Al/Mg intermetallic compounds were present. This observation confirmed that the coating interlayers introduced through the cold spray process effectively

prevented the formation of undesirable intermetallic compounds. As a result, the samples exhibited a high ultimate load of 4.3 kN for coating samples. However, the cause of failure in both groups of samples was attributed to the presence of voids and porosity at the welded coated areas. The porosity, which contained a notable percentage of Mg, provided a crack initiation point and then propagation progressed within the welded coated layers.

To evaluate the failure mechanism, the Ni-coated samples were selected for an extensive examination using SEM after fracture. SEM images in Figure 5:13 illustrate how these cracks propagated along the porous regions that retained traces of Mg. In Figure 5:13(a), a cross section of the welded area following failure in the monotonic test is visible. Figure 5:13 (b) and (c) show SEM evaluations of the fracture surface, with spectrum 2 at (b) revealing a 43.7 weight percent of Mg in the welded Ni-coated area. The penetration of Mg through the Ni coating was attributed to the porosity resulting from the powder deposition process, as well as the valleys on the Ni-coated surface and any thin-coated regions. Figure 5:13 (d)-(g) depict the fracture surface on the Al side, with (d) showing the Al substrate and two welded Ni-coating layers following failure in the monotonic test. Both Figure 5:13 (e) and (f) reveal the presence of Al and Ni, respectively. Examination of the Al side of the fracture surface in Figure 5:13 (g) indicated the presence of Mg; however, the amount was negligible and insufficient for intermetallic compound formation. Nevertheless, this limited presence of Mg contributed to crack propagation and failure in the Al direction. The majority of sample failures in the monotonic test occurred on the Mg side, specifically between the Mg and the welded Ni-coating layer.

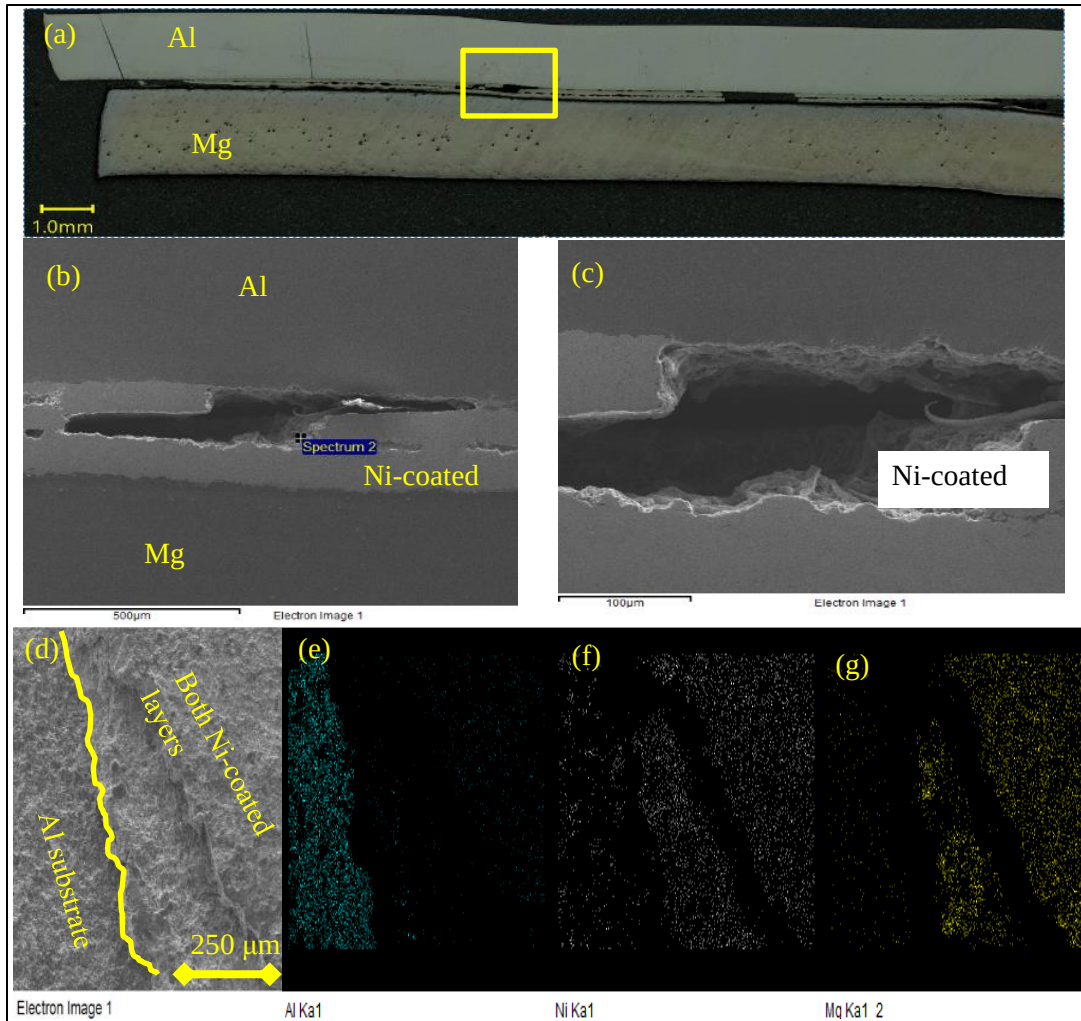


Figure 5:13: Fracture surface and failure caused by porosity and indicating the fracture surface contains a relatively high percentage of Mg. (a) is the optical microscopy image of the cross section after failure in monotonic test, (b)-(c) are SEM images, (d) is SEM for the Ni-coating layers, (e)-(g) element analysis results in and around the porosity containing Mg.

To potentially reduce or eliminate the penetration of Mg through the coating layers, optimization of the cold spray parameters for coating on the Mg side is necessary. This optimization could involve increasing the density and/or thickness of the coating layers, which may aid in minimizing Mg penetration during RSW.

Chapter 6: Development and characteristics of the Ti-coating interlayer for Al/Mg RSW

6.1. Introduction

The development and characterization of cold spray CS-assisted dissimilar resistance spot welding RSW between Al and Mg require a comprehensive evaluation to achieve a reliable and high-quality weld. Given the significant differences in material properties and the challenges associated with joining dissimilar metals, detailed characterization is essential. This chapter focuses on several key aspects to ensure the effectiveness of the welding process:

- **Interlayer Material Selection:** Choosing a suitable interlayer material that can effectively minimize the formation of intermetallic compounds IMCs at the Al-Mg interface.
- **Cold Spray Coating Development:** Establishing the CS process for depositing the selected material onto the weld coupons.
- **Optimization of RSW Parameters:** Defining the process window and determining optimal welding conditions for CS-assisted RSW of Al/Mg joints.
- **Intermetallic Compound Formation:** Investigating the presence, type, and distribution of IMCs at the weld interface, as these compounds can influence mechanical properties and weld reliability.
- **Microstructural Analysis:** Examining the weld zone and base materials to assess grain structure, crystallographic changes, and potential defects using optical and electron microscopy techniques.

- **Mechanical Performance:** Evaluating the weld joint's mechanical strength, including tensile and shear strength, to assess its structural integrity and suitability for engineering applications.

This chapter aims to establish a well-characterized CS-assisted RSW process for Al-Mg dissimilar joints to enhance weld quality and reliability. By conducting in-depth analyses, potential challenges can be identified, and the welding process can be refined to improve performance. Additionally, this study investigates how Ti coatings applied through the cold spray process influence material behavior and helps determine the optimal welding parameters for improved joint durability.

6.2. Characterization of Ti powder

Ti powder was chosen for this study due to its suitability for dissimilar resistance spot welding RSW of aluminum Al and magnesium Mg. This selection is based on several key requirements that enhance the welding process and improve joint performance:

1. **Improved Bonding:** The application of a Ti coating enhances adhesion between Al and Mg, reducing the presence of voids or gaps at the interface. This improved bonding significantly strengthens the weld and ensures structural integrity [131].
2. **Material Compatibility:** Ti has been extensively studied in welding applications due to its compatibility with both Al and Mg, making it a viable option for dissimilar RSW [138].
3. **Thermal Conductivity:** Ti exhibits favorable thermal conductivity, which facilitates uniform heat distribution during the welding process. This helps prevent localized overheating or melting of either base material, ultimately contributing to a defect-free weld. Proper heat management is critical for producing high-quality joints.

4. **Bi-Metallic Transition Properties:** Ti is often utilized as a transition material in dissimilar welding due to its intermediate properties between Al and Mg. Acting as a bridge, Ti minimizes the formation of brittle intermetallic compounds that can otherwise weaken the joint when Al and Mg are directly welded [131].
5. **Process Optimization:** Studies have optimized cold spray parameters including powder feed rate, nozzle velocity, and standoff distance to achieve the desired coating thickness and quality when using Ti powder [133]. This optimization is essential for ensuring the effectiveness of Ti as an interlayer in dissimilar spot welding.

In brief, the use of Ti powder in cold spray technology for Al-Mg dissimilar RSW is driven by its ability to enhance bonding, serve as a transition material, and provide efficient thermal conductivity. Leveraging these properties enables researchers to develop high-quality welds that align with the industry's needs for lightweight, durable, and environmentally sustainable automotive structures.

6.3. Cold spray coating of Ti coated Al to Mg sheets

In second group of samples, Al and Mg substrates were coated by Ti using Cold Spray system with slightly deferent parameters. The surfaces of samples were prepared for coating by sandblasting and thorough cleaning with acetone. Pure titanium powder, characterized by a spherical morphology and a particle size ranging from 20 to 80 μm , was sourced from TLS Company for the coating process. A low-pressure cold spray machine (SST-P) with a 4000 series powder feeder from Centerline Company was used for deposition. Nitrogen served as the carrier gas, propelling titanium particles through a 120 mm-long convergent-divergent DeLaval nozzle with a 2 mm orifice diameter. To achieve an optimal coating, the cold spray process parameters were carefully adjusted:

gas pressure of 1.4 MPa (203 psi), gas temperature of 500°C and the rest of the parameters are listed as show in Table 6:1. The thickness of Ti-coating layer is 300-400µm on each substrate, for a total Ti coating thickness of 600-800 µm between the two coupons. Note that in coating the Al side with Ti, the Ti powder was mixed with a 3% wt pure Al powder to enhance the strength of the weld. The percentages of powder mixing have been optimized where higher than this percentage of Al powder, the Al/Mg intermetallic compounds will be formed after weld. And lower than the percentage range of Al powder, lower improvement in load capacity will be obtained.

Table 6:1: Cold spray coating parameters that applied for deposition of Ti on Al and Mg substrates

Coating Materials	Ti on Mg	Ti+3%Al on Al
Flow Gas	N ₂	N ₂
Gas Temperature (°C)	500	500
Gas Pressure (MPa)	1.4	1.4
Powder Feed Rate (gr/min)	2.24	2.24
Nozzle Speed (mm/s)	70	70
Step Over (mm)	3	3
Stand-off Distance (mm)	12	12
Nozzle Length (mm)	120	120
Nozzle Orifice Diameter (mm)	2	2
Nozzle Exit Diameter (mm)	6.3	6.3
Type of Nozzle	a converging–diverging de Laval UltiLife TM	

Scanning Electron Microscopy (SEM), specifically using the LEO 1530 and FEI Quanta FEG 250 ESEM microscopes with EDX, was also employed to characterize the Ti-coated samples, assess the weld region between Al and Mg, and detect intermetallic compounds. This analytical approach offers high-resolution imaging and elemental analysis, delivering essential insights into sample microstructure and composition. The SEM image in Figure 6:1 shows the size and the shape of the Ti powder particles and the size distribution.

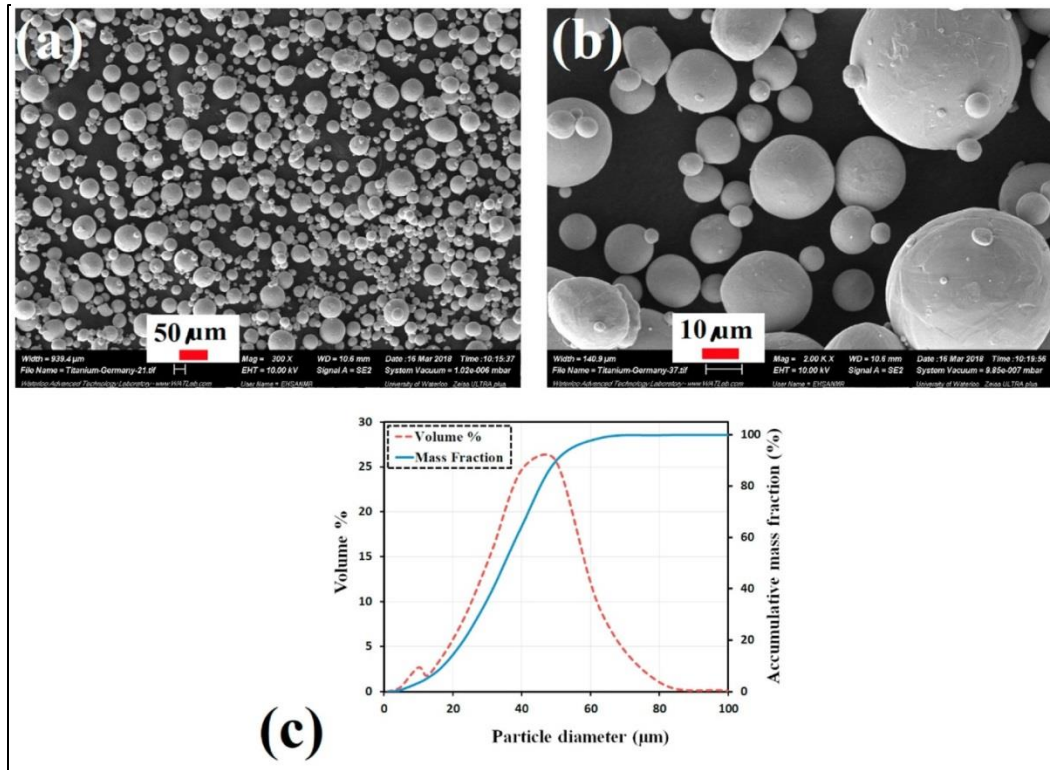


Figure 6:1: (a) and (b) SEM images of the Ti powder particles and (c) their size distribution [133]

Roughness test was performed to capture the 3D image of the surface to study the contact surfaces at the welded area which can explain the existence of voids at the interface between Ti-coated layers at the welded area as shown in Figure 6:8 (a). Figure 6:2 shows 3D scan image of Ti coating on Mg side and Figure 6:3 shows the 3D scan that was performed for 1x1 mm of the Ti coating on Al side.

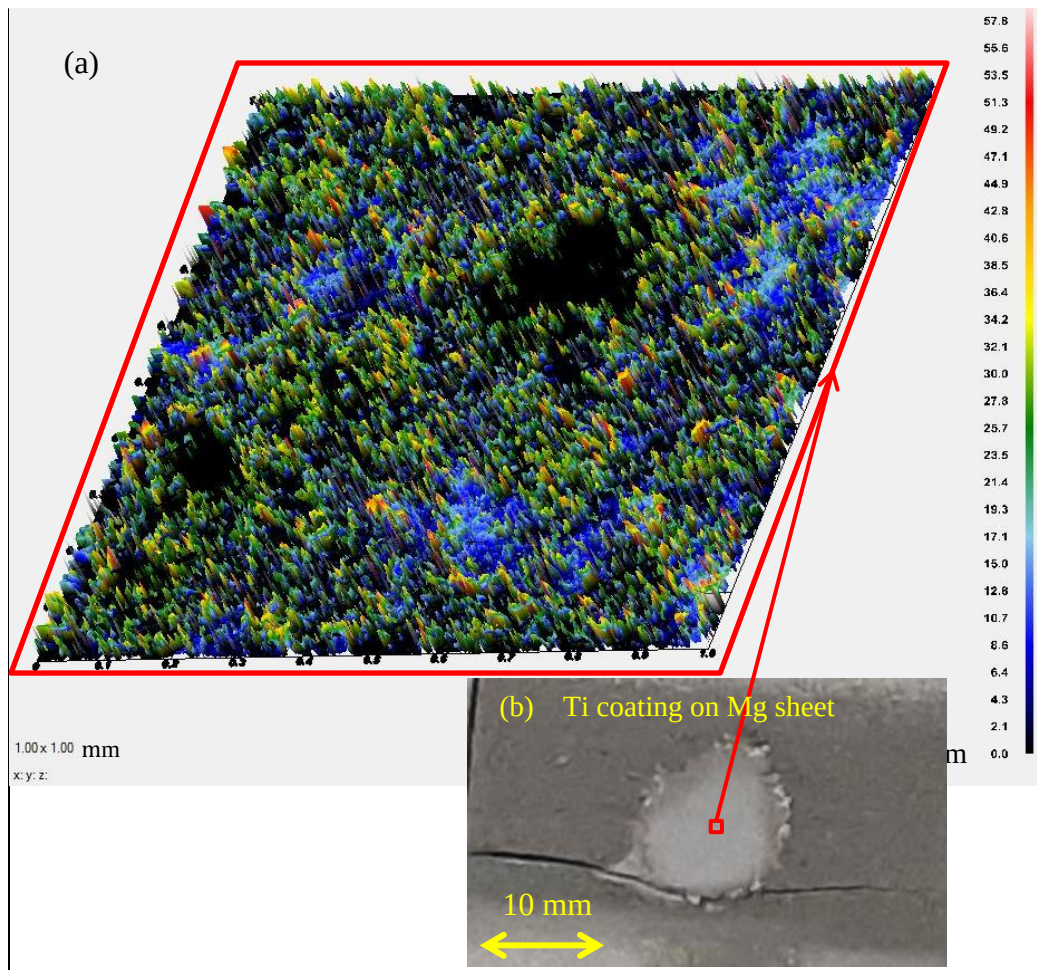


Figure 6:2: (a) Top view of the 3D scan of 1x1 mm of Ti coating on Mg side that shows the roughness of the coating surface (b) Ti coating Mg sample that shows the test position

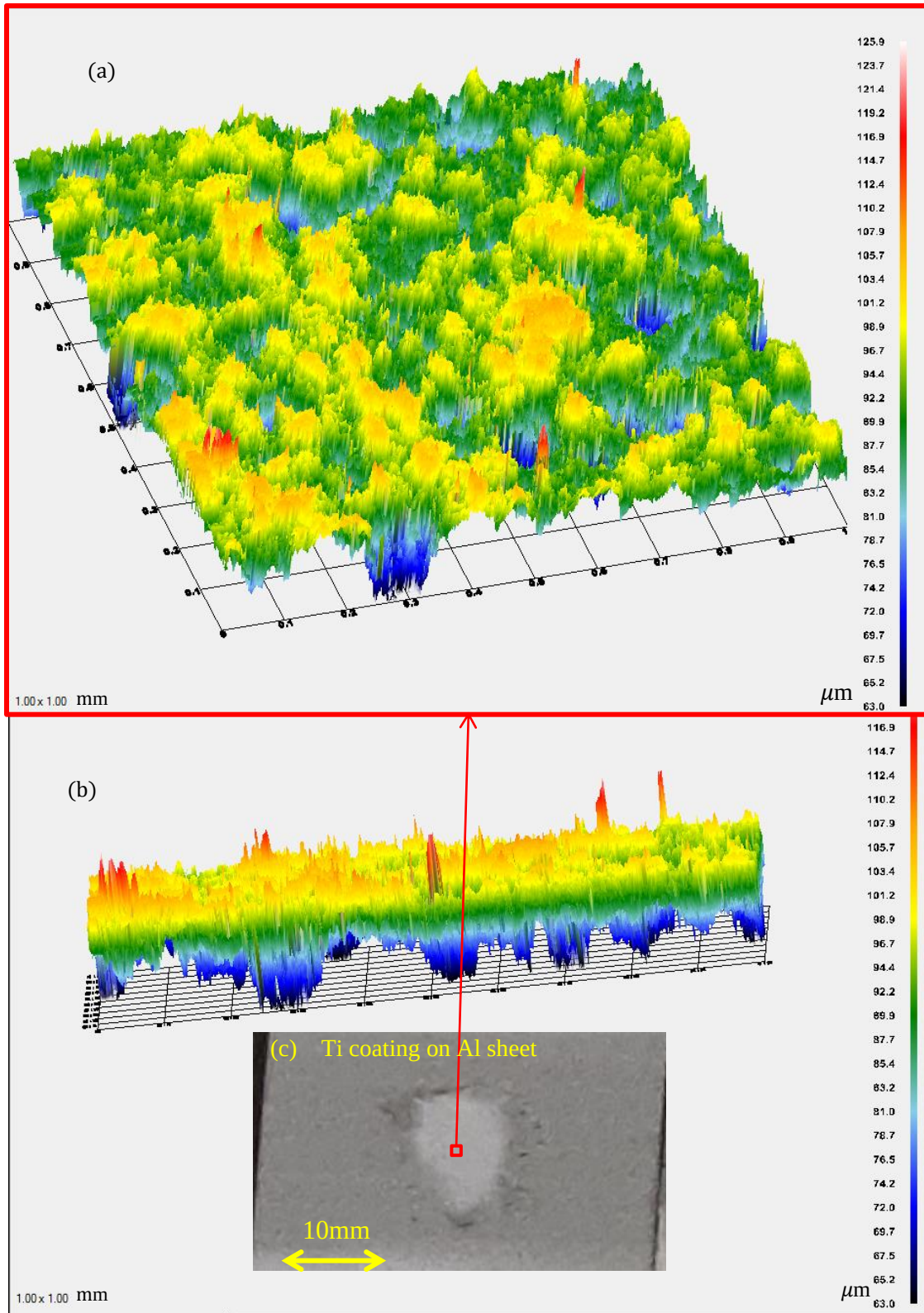


Figure 6:3: 3D scan of 1x1 mm of Ti coating on Al side that shows the roughness of 1mm^2 of the coating surface. (a) Top view of the 3D scan, (b) side view of the 3D scan (c) Ti coating Al sample that shows position of the test before the weld.

In further examination of the SEM images, see Figure 6:7 (d)-(f), it was evident that the Ti-coating on the Mg side did not contain Mg before the welding process. Conversely, on the Al side, an analysis of results before welding in Figure 6:7 (a)-(c) and Figure 6:9 (e) showed that about 3% Al, added during the cold-spray process, acted as cement-like filler, effectively mitigating the porosity in the Ti coating. This contributed to enhanced strength in the Al/Mg RSW joint by improving the adhesion between Ti and Al. The Al powder was evaluated from values of 0% to 12%, and was optimized during the cold-spray process based on the strength and elongation of the joints during tensile tests. It is important to note that the percentage of Al powder added during the cold-spray process is critical; too low a percentage results in insufficient adhesion and strength improvement, while too high a percentage can lead to undesirable intermetallic compounds formation with Mg during welding, Thus weakening the joint.

To optimize the Al powder percentage, Al powder was initially added to Ti powder at a concentration of 12% by weight, which resulted in the formation of brittle intermetallic compounds during the welding process, adversely affecting joint strength. To address this issue, the Al powder content was reduced to just 1% and the mixture was thoroughly blended with Ti powder. After welding five samples with this composition, tensile testing revealed some improvement in joint strength. However, to further improve the mechanical properties, additional tests were conducted with varying Al powder concentrations. Subsequent experiments included Al powder additions of 2%, 3%, and 5% by weight to the Ti powder. At 5% Al powder, the formation of brittle intermetallic compounds began to negatively impact the welding strength. The best results were observed with Al powder concentrations of around 3% by weight, which provided an

optimal balance between strength and structural integrity. It is important to note that these percentages were determined by weight rather than volume due to the significant difference in density between Al and Ti. Table 6:2 and Figure 6:4 show the results that informed the conclusion that 3% of Al powder is the optimal percentage to be added to the Ti powder before coating the Al substrate. Figure 6:5 represents the improvement of the strength before and after adding the 3% Al powder.

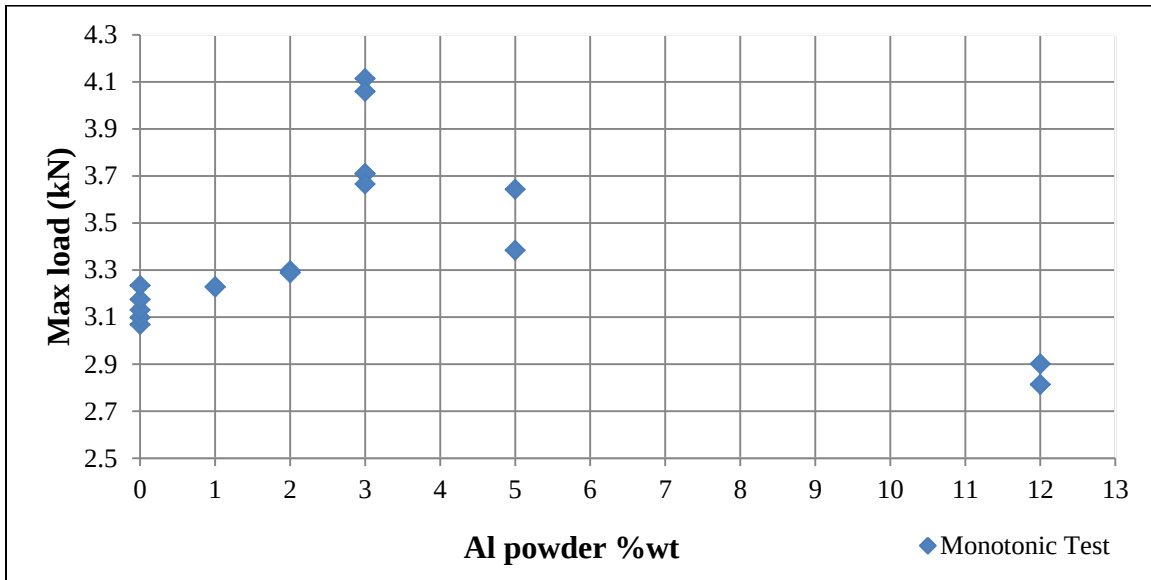


Figure 6:4: Represent that the highest improvement of the strength can be obtain by adding 3% Al powder to Ti powder. 18 monotonic tests have been performed to optimize the Al percentage. With each Al powder percentage, numbers of tests are shown in Table 6:2.

Table 6:2: Max load of the Ti-coated samples that tested in monotonic test with different Al powder percentage, that mixed with Ti powder before the CS coating process just on Al substrate side.

Test #	Max load (kN) with Pure Ti	Max load (kN) with 12% Al	Max load (kN) with 1% Al	Max load (kN) with 2% Al	Max load (kN) with 3% Al	Max load (kN) with 5% Al
1	3.13	2.90	3.22	3.29	4.11	3.64
2	3.23	2.81	3.23	3.28	3.67	3.38
3	3.06				3.71	
4	3.09				4.06	
5	3.17				3.70	

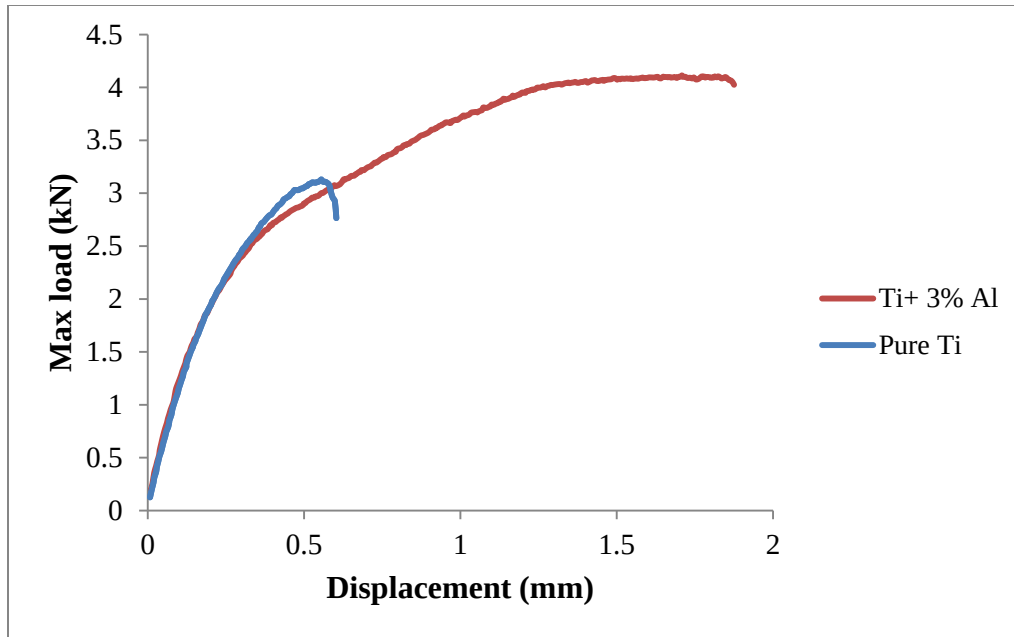


Figure 6:5: load-displacement curves showing the effect of mixing 3% Al powder with Ti powder before CS coating process on the strength of the Ti-coating samples.

Figure 6:6 – 6:9 offer a visual depiction of the Ti-coating on Al and Mg sheets, both before and after the welding process. Initially, micro-porosity can be observed within the Ti-coating layers, as highlighted in Figure 6:6 (a)-(b). Interestingly, micro-porosity notably decreased after welding, as seen in Figure 6:8 (a).

The bonding of the Ti layers did indeed occur as can be seen in Figure 6:8, although a similar explanation to that of the Ni-coating thermal cycle can be applied to understand the phenomena observed during welding. It is important to note that Ti has a lower forging temperature, typically ranging from 790 to 1065°C, compared to Ni [138]. When considering several factors, including the presence of Mg between the welded Ti coating layers, the existence of coating porosity, and the melting points of Ti, Mg, and Al, along with the forging temperature of Ti and the boiling point of Mg, one can elucidate the processes that took place during the welding procedure, clarifying how Mg became integrated into the Ti coating layers.

As the Ti coating layers were effectively bonded together during the RSW process, the temperature during welding fell within the range between the forging temperatures and the melting point of Ti, which spans from 790 to 1668°C. In contrast, the boiling temperature of Mg is 1091°C, placing it within the Ti forging temperature range to the melting point of Ti. This is further substantiated by SEM evidence showing a gas bubble at the interface between Ti and Mg after welding, as displayed in Figure 6:9 (a)-(d). Consequently, it is plausible that the welding temperature exceeded 1091°C, causing some Mg to vaporize at the interface of the Ti coating layer during welding. This vaporized Mg subsequently infiltrated the interface between the two Ti coating layers through the coating's porosity, micro-cracks, and thinner sections within the coating, as observed in Figure 6:6 (a)-(b) and Figure 6:8 (a)-(h). The surface roughness of the Ti coating facilitated the formation of voids between the two coating layers, which were later filled by Mg. With the completion of the welding process, the termination of the current, and the solidification of Ti, the Mg that had infiltrated the Ti coating layers remained trapped.

Given that both Ti and Ni experienced the same thermal cycle, Figure 5:6 provides a visual representation of the sequence of these processes. It is important to note the slight difference in forging temperatures between Ti and Ni, which influences the size and characteristics of the Mg voids or cavities within the welded Ti coating layers. The relatively low forging temperature of Ti, ranging from 790 to 1065°C for Ti, allows Ti to deform more readily under the pressure exerted by the welding electrodes during the welding process. Consequently, the voids created in the Ti coating are squeezed after welding process, primarily due to the forging temperatures and material behaviors.

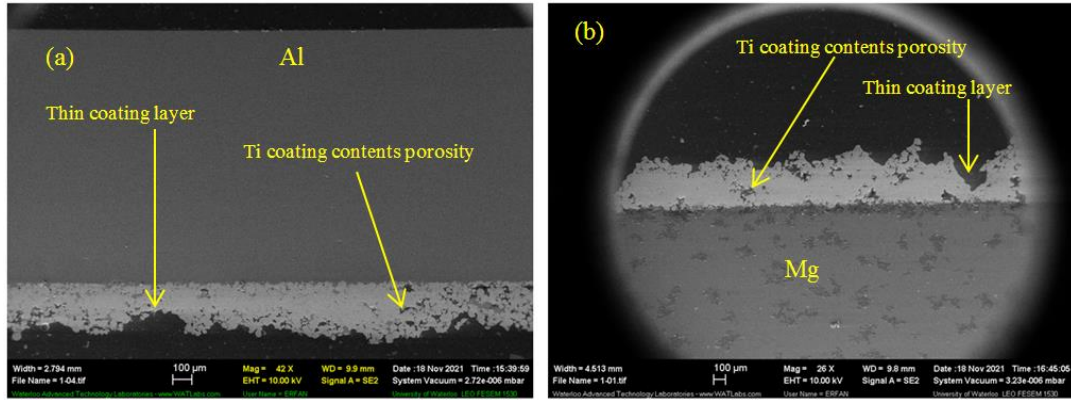


Figure 6:6: (a) Ti coating on Al side, (b) Ti-coating on Mg side. Both (a) and (b) shown the porosity in the coating and some thinner layers in the coating and rough interface of the Ti coating layer among different places in the Ti-coating

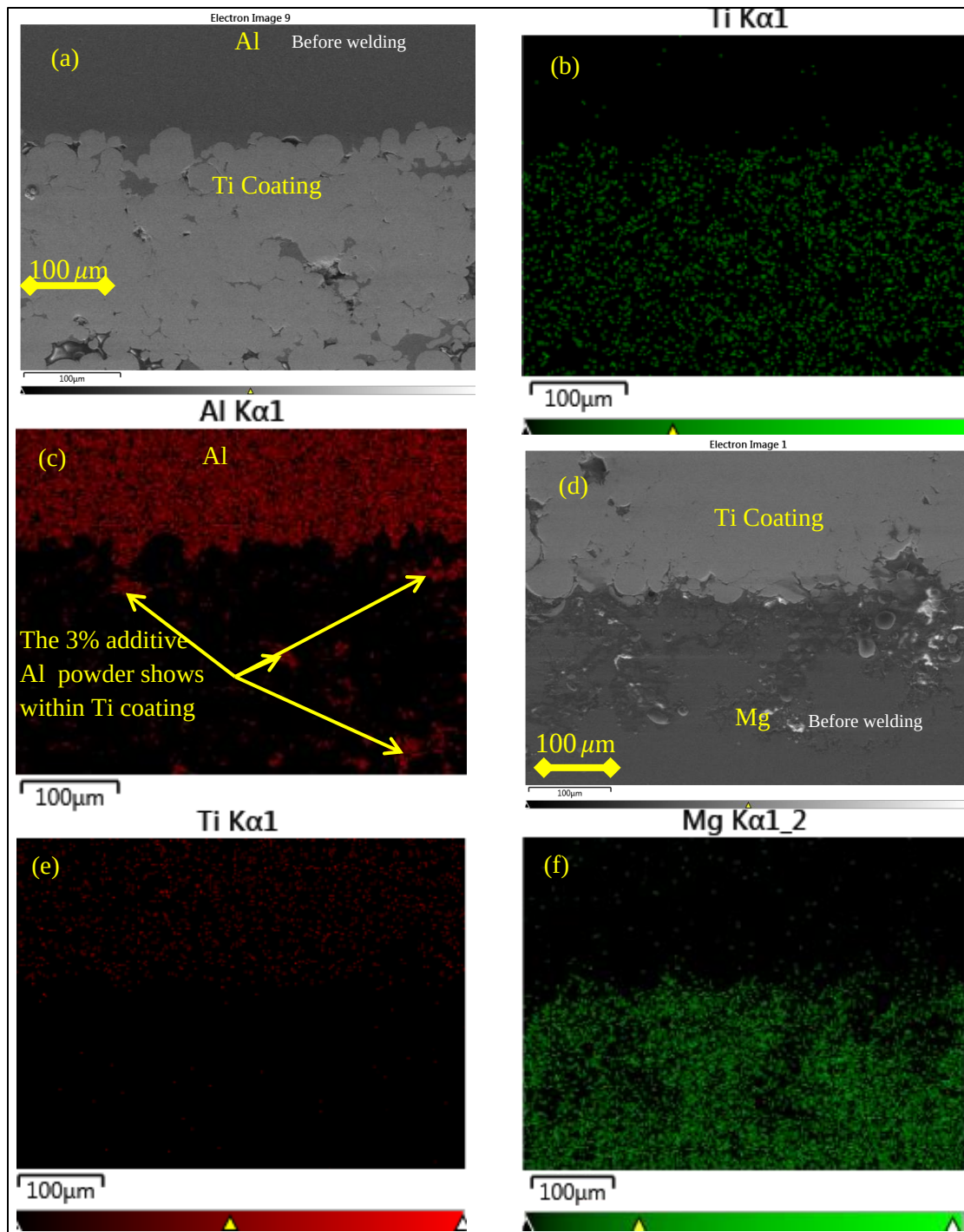


Figure 6:7: SEM images of the coated sheets by Ti before welding, (a-c) on Al sheet where (b) shows the Ti and (c) shows the Al distribution through the Ti-coating just in the Mg side, (d-f) on Mg sheet where (e) shows the Ti deposit on the Mg sheet and (f) shows the Mg.

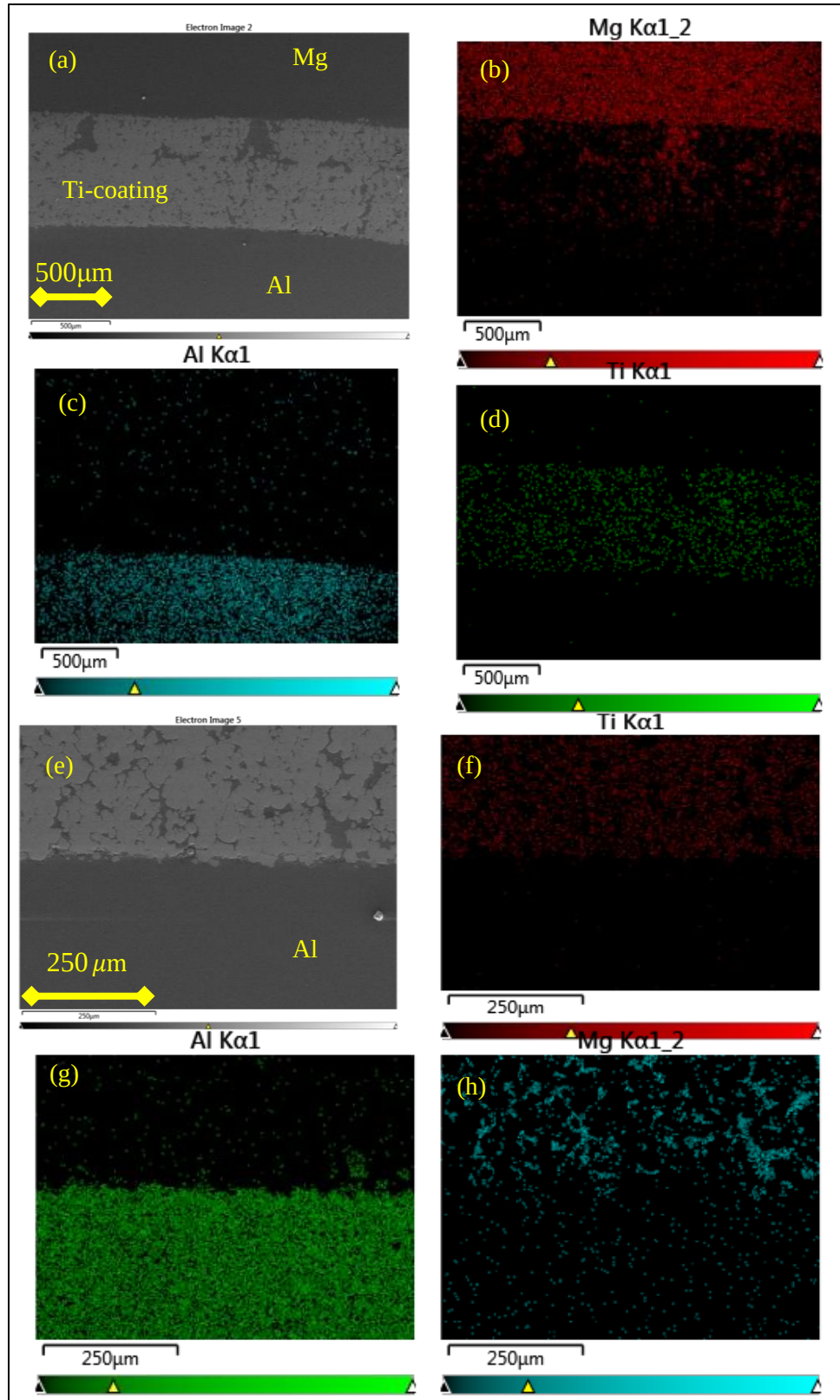


Figure 6:8: SEM images of the sample after welding showing (a)-(d) details of the weld area and (e)-(h) images of porosity at welded Ti-coated layer on Al sheet side and show the presence of Mg at welding area.

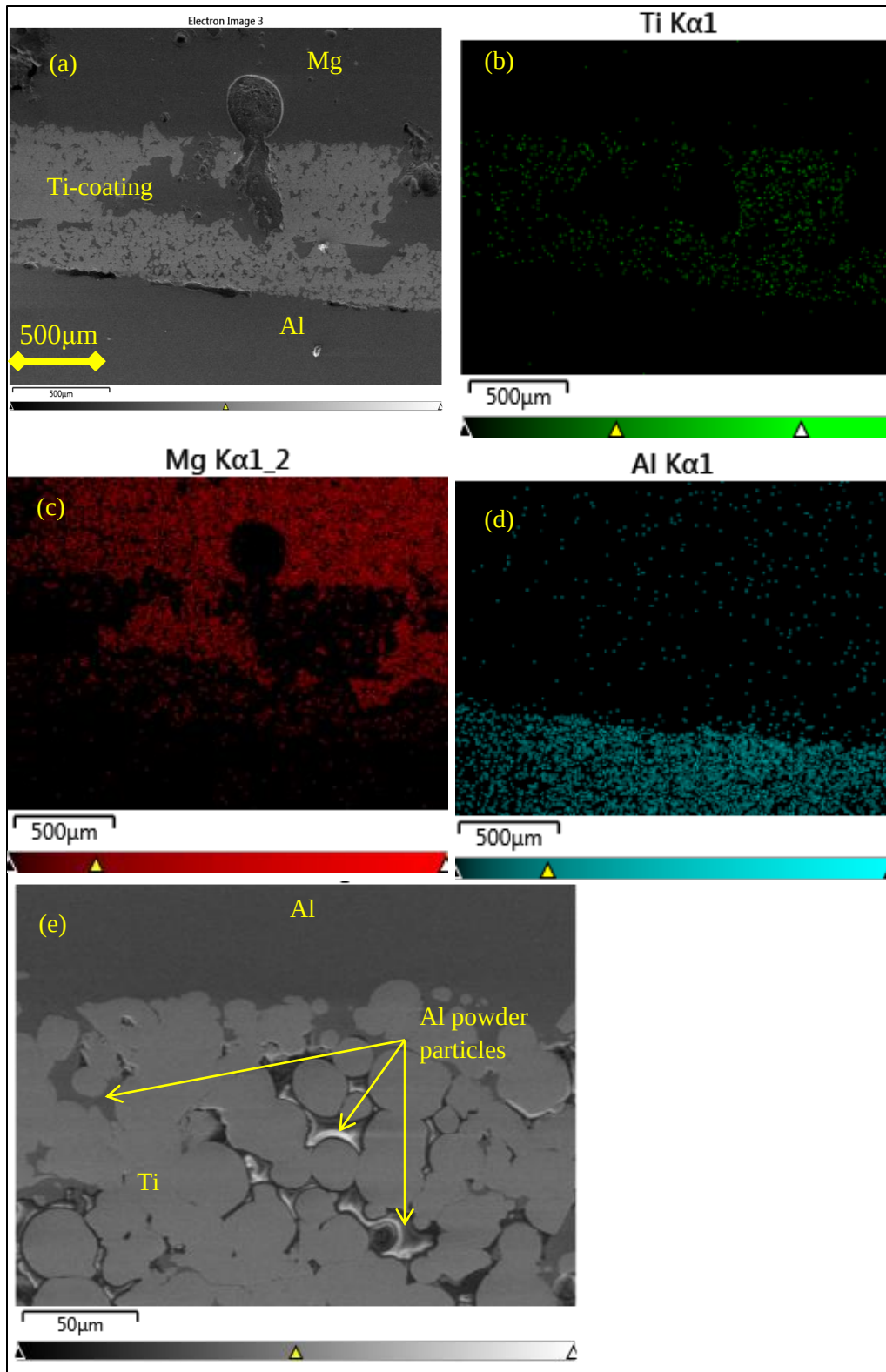


Figure 6:9: SEM images of the sample after welding showing (a)-(d) images of porosity at welded Ti-coated layer on Mg sheet side and show the presence of Mg at welding area and interesting form of bubble at the interface of Ti/Mg after welding. (e) SEM image that shows the Al powder co-deposited with Ti during the cold-spray.

6.4. Characterization of resistance spot welds of Ti-coating Al/Mg

Ti-coating was applied to the samples via cold spray, as discussed in the previous section, in the area where welding was anticipated, as depicted in Figure 6:10 (a). Also, Figure 6:10 (b) shows the coated area after failure in the peel test. The weld process was performed on the Ti-coated group of samples, the best weld features were obtained at 20 kA and 15 cycles 2 pulses and the delaying time between the pulses was 5 cycles. Table 6:3 summarizes the welding parameters for Ti group of samples.

Table 6:3: summary of welding parameters for Ti-coating Al/Mg group of samples

Welding parameters		Ti-coating Al/Mg
1	Welding current (kA)	20
2	Welding time (cycles)	15
3	Holding time after welding (cycles)	15-21
4	Number of pulses	2
5	Delaying time between the pulses (cycles)	5
6	Electrode force (kN)	4
7	Water flow rate (L/min)	7
8	Electrode diameters on Al side (mm)	12
9	Electrode diameters on Mg side (mm)	16

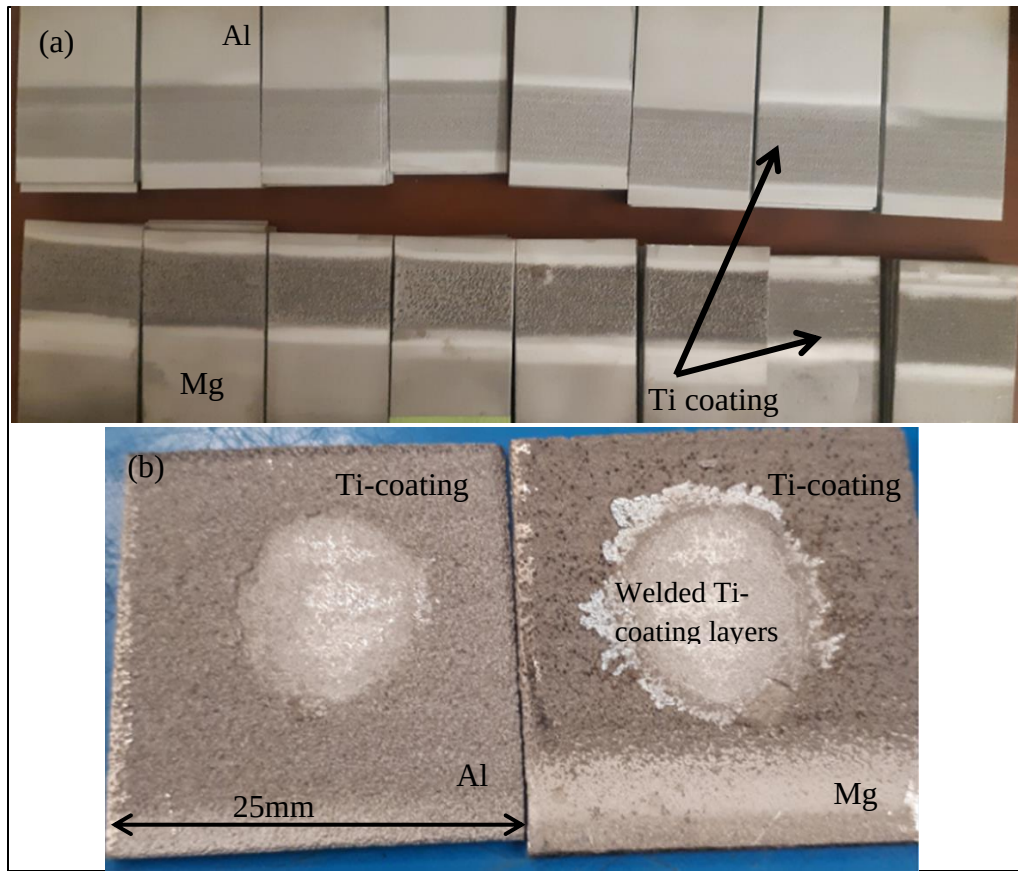


Figure 6:10: (a) Al and Mg coupons that coated with Ti before the welding process and (b) image shows nugget size on the separated sheets after welding and peel test.

To weld Ti-coated Al/Mg, the method for preparing Ni samples was replicated with Ti. The Al and Mg samples, measuring 25x25x1.5 mm and 25x25x2 mm, respectively, are coated using the parameters outlined in Table 6:1. The welding parameters have been finely tuned as follows: initially, coated samples were subjected to welding using five levels of welding currents, specifically 18, 19, 20, 21, and 22 kA, along with three different welding durations, namely 15, 18, and 20 cycles. Throughout the welding process for all the samples, an electrode force of 4 kN was applied, water flowed at a rate of 7 L/min, and electrode diameters measured 16 mm on the Mg side and 12 mm on the Al side. The samples successfully formed bonds in this range of welding currents and durations. To identify the optimal welding parameters, the samples were

pulled-out, and the bonded regions were measured to compare weld nugget sizes across various welding currents and times. Following peel test, the parameters that yielded the best welding results, as well as tensile test loads, are presented in Table 6:3. Subsequently, 24 lap shear test samples were welded using those parameters and subjected to monotonic and cyclic tests.

6.5. Comparing Ni coating and Ti coating and the factors affecting bond strength

In the realm of cold-spray technology, selecting the right coating material can significantly impact the performance and characteristics of coated surfaces. Ni and Ti are selected in this study for their potential promising properties and they both successfully bonded the Al to Mg sheets and prevented the undesired intermetallic compounds. In this comparison, several critical factors and considerations that differentiate these coatings were investigated, including their porosity, thickness, melting points, forging temperatures, deformation during welding, and how these features depend on the Al powder in the Al substrate.

Porosity: One of the primary distinctions between Ni-coating and Ti-coating is their porosity levels. Ti-coating is often characterized by higher porosity when compared to Ni-coating. This increased porosity can impact the integrity and strength of the coating, making it an essential consideration when selecting the appropriate coating for specific applications.

Coating Thickness: The thickness of the coating is another significant factor that can affect the bending moment during the monotonic test. Ni-coating is typically thinner, ranging from 0.25 to 0.4 mm, while Ti-coating tends to be thicker, with a thickness range

of 0.5 to 0.7 mm. The choice between the two coatings depends on the desired coating thickness and its compatibility with the substrate material.

Melting Points: Ni and Ti coatings also differ in their melting points. Ni has a relatively low melting point of about 1,455°C, while Ti exhibits a higher melting point of 1,668°C. This variation in melting points is crucial when considering the operating conditions and potential exposure to elevated temperatures considering the heat generated during the RSW process.

Forging Temperatures: In terms of forging temperatures, Ti and Ni exhibit distinct behaviors. Ti has a lower forging temperature, which ranges from 790 to 1,065°C, while that of Ni is slightly higher, which ranges from 980 to 1140 °C. This variation can influence the deformability and malleability of these coatings during welding processes.

Deformation during Welding: During welding, the deformation of the coating material is an essential consideration. Observations indicate that Ti tends to deform more during the welding process compared to Ni, which is attributed to the lower forging temperature of the Ti as confirmed by the SEM images before and after welding when showing the porosity been influenced/reduced due the generated heat during the RSW process. This propensity for deformation can impact the structural integrity and overall performance of the coating and the joint it forms.

Electrical Conductivity and Resistance: In addition to the factors mentioned, electrical conductivity and resistance play a pivotal role in selecting Ni-coating and Ti-coating due to their effect during the resistance spot welding process. Ni, known for its excellent electrical conductivity, means a low electrical resistance, with a typical electrical resistivity of approximately 6.99×10^{-8} ohm-meters. This characteristic makes Ni-

coating an ideal choice for applications where electrical conductivity is crucial. On the other hand, Ti exhibits moderately higher electrical resistance compared to Ni, with an approximate electrical resistivity of 4.51×10^{-7} ohm-meters. Therefore, when electrical conductivity is a primary consideration, Ni-coating often takes precedence, offering superior conduction properties and lower electrical resistance. This can be a deciding factor for applications where both electrical performance and protective coating are essential.

Dependence on Al Powder: A unique characteristic of Ti-coating is its reliance on Al powder that was added to the Ti powder during the cold spray process when Ti coated at the Al substrate side. This added Al content, around 3%, plays a crucial role in filling the porosity within the Ti-coating and enhancing adhesion between Ti coating and Al substrate. In contrast, Ni-coating does not require this additional Al powder for bonding.

The surface roughness of the coating: One of the key differences between Ni-coating and Ti-coating lies in their surface roughness levels. Ti-coating generally exhibits a higher surface roughness compared to Ni-coating. This heightened roughness can influence the coating's overall integrity and strength, making it a critical factor in determining the most suitable coating for specific applications. However, in the current study, the addition of Al powder to the Ti powder effectively reduced the surface roughness of the Ti-coating applied to the Al substrate.

In summary, the choice between Ni and Ti coatings depends on several key factors. While Ni-coating is characterized by lower porosity, thinner thickness, and a lower melting point, Ti stands out with a thicker coating layer and a higher forging temperature. Additionally, Ti-coating exhibits greater deformation during welding and often

necessitates the inclusion of Al powder in the Al substrate for optimal adhesion, whereas Ni-coating does not require this modification. An essential and overriding consideration may be electrical conductivity. Ni-coating, known for its exceptional electrical conductivity and lower electrical resistance, takes precedence in applications where electrical performance is vital. In contrast, Ti-coating, with its moderately higher electrical resistance, may be preferred for applications where electrical conductivity is not a primary concern. Therefore, the selection between these two coatings should be driven by a comprehensive evaluation of the specific requirements and priorities of the intended application.

6.6. Powder selection method for cold spray-assisted RSW of Al/Mg

Based on the behavior exhibited by Ni and Ti when used as coating materials on Al and Mg substrates to facilitate RSW, a set of selection criteria can be established to guide the identification of suitable powders for future applications. These criteria are derived from the successful implementation of Ni and Ti coatings, which demonstrated the ability to suppress the formation of intermetallic compounds, improve joint strength, and withstand the thermal and mechanical conditions of both the cold spray and RSW processes. Therefore, by examining the key thermal, chemical, and mechanical properties that made Ni and Ti effective in this context, a structured approach can be followed in selecting new candidate powders.

1. The first criterion in selecting a suitable powder for cold spray-assisted resistance spot welding RSW of Al/Mg joints involves evaluating the thermal properties of the candidate materials. Specifically, materials should have a forging temperature in the range of 600 °C to 900 °C or a melting point between 700 °C and 1000 °C. These

temperature thresholds ensure that the material remains stable and does not deteriorate under the thermal conditions encountered during cold spray deposition and the subsequent welding process.

2. Next, the chemical reactivity of the candidate powder with both Al and Mg substrates must be assessed using available literature. Preference is given to powders that exhibit minimal IMC formation when in contact with Al or Mg, as excessive IMC formation can lead to brittle joints and compromised mechanical performance. A material that reduces or eliminates the formation of undesirable IMCs is therefore favored to ensure better bonding and improved structural integrity.
3. The third step involves verifying whether the selected material can be successfully deposited using cold spray coating technology. This assessment is also based on literature, focusing on factors such as deposition efficiency, coating adhesion, and structural soundness when applied to Al or
4. Once a material is found to be chemically and thermally suitable and shows promise in cold spray performance, the next step is to ensure the commercial availability of that powder. It is important that the powder is readily available in the appropriate particle size and composition suitable for cold spray systems. This practical constraint ensures the feasibility of experimental and industrial implementation.
5. Finally, the electrical properties of the powder are considered, particularly its electrical resistance. A higher electrical resistance is generally preferred because it facilitates localized heat generation during the RSW process, leading to more effective nugget formation. If a suitable powder has low electrical resistance, it may

be blended with a second powder that has higher resistance to enhance its performance during welding.

6.7. Summary of Ni coating and Ti coating

When either Ni or Ti are coated on to the Al/Mg sheets, the cold spray coating process, followed by welding, has proven to be successful in achieving strong bonding while effectively preventing the formation of undesirable intermetallic compounds between Al and Mg after welding. The use of advanced analytical techniques such as SEM and EDX provided a comprehensive characterization of the microstructural features and compositional aspects of these materials. Initial observations revealed the presence of micro-porosity within both Ni and Ti coating layers, which significantly diminished after the welding process. The welding process facilitated the relocation of a thin layer of Ni into the Al substrate, while the inclusion of a small percentage of Al powder during the cold-spray process mitigated the porosity in Ti coatings on the Al side, improving the adhesion between Ti and Al. For both Ni and Ti-coating, the temperature during welding fell within the appropriate range, preventing the formation of intermetallic compounds.

A notable difference arises when considering the deformation characteristics of the two coatings during welding. Ti, with a lower forging temperature than Ni (ranging from 790 to 1065°C for Ti), exhibits higher deformation under the pressure exerted by the welding electrodes. As a result, the porosity remaining in the Ti coating weld is smaller compared to those in the Ni coating, influenced by differences in forging temperatures and material behaviors. Additionally, the electrical properties of Ni and Ti coatings must be considered. Ni-coating offers superior electrical conductivity and lower electrical resistance, making it the preferred choice in applications where electrical performance is

a critical factor. In contrast, Ti-coating presents moderately higher electrical resistance, which may be favored in applications where electrical conductivity is not the primary concern. In conclusion, the selection of Ni or Ti coatings should be driven by a comprehensive evaluation of specific application requirements, with both coatings demonstrating their efficacy in ensuring strong bonding and inhibiting intermetallic formation in Al/Mg joints.

The joining process in this study comprises two primary phases: initial bonding between the coating layer and the respective substrates and the subsequent joining of the two coating layers at the interface during the welding process. Effective bonding between the coating and substrate takes place during the cold spray coating process, utilizing mechanical interlocking, the well-known phenomenon in cold spray technology. Subsequently, with the coating/coating interface, the formation of voids and micro-gaps at the interface plays a significant role in enhancing heat generation during the resistance spot welding process. Air gaps exhibit high resistance to welding current, potentially causing an increased softening rate at the contact areas on the peaks of the coating, ultimately leading to successful bonding and load-bearing capability during the monotonic test.

Upon examining the fracture surfaces of the monotonic lap-shear test samples, it was evident that no Al/Mg intermetallic compounds were present. This observation confirmed that the coating interlayers introduced through the cold spray process effectively prevented the formation of undesirable intermetallic compounds. As a result, the samples exhibited high ultimate loads. However, the cause of failure in these samples was attributed to the presence of voids and porosity in the coated welded areas. The porosity,

which contained a notable percentage of Mg, facilitated crack initiation and propagation within the welded coating layer. To comprehend the failure mechanism, SEM examination was conducted on the samples that had experienced failure. SEM images illustrated how these cracks propagated along porous regions containing traces of Mg. The examination revealed the presence of Mg on the fracture surface, but it was insufficient for intermetallic compound formation. Nevertheless, this limited presence of Mg contributed to crack propagation and failure. The majority of sample failures occurred on the Mg side, specifically at the interface of Mg and the welded coating layer.

Chapter 7: Performance of Cold Spray-Assisted

Dissimilar RSW

7.1. Introduction

Monotonic test and fatigue test are significant requirements for many applications that provide valuable insights into joint durability, offering an estimate of the expected service life of the joint. Fatigue tests are commonly applied to evaluate dissimilar resistance spot welds of Al and Mg for several key purposes:

- Lifespan estimation: Fatigue tests enable the prediction of how long such joints will remain in service before experiencing fatigue-related failures, ensuring the safety and reliability of the components.
- Condition assessment: These tests help determine the specific conditions and types of loading under which dissimilar Al/Mg welds can perform reliably, ensuring their suitability for diverse real-world applications.
- Quality assurance: By simulating real-world conditions, fatigue tests serve as a vital tool for quality assurance, enabling manufacturers and engineers to ensure compliance with safety and performance standards, reducing the risk of unexpected failures.
- Design optimization: Through fatigue testing, potential failure points, crack initiation, and propagation data are identified, facilitating the optimization of weld design, materials, and welding processes, thereby enhancing durability and reliability.
- Research and development: In research and development, fatigue tests offer essential data for the advancement of welding techniques, the development of new materials,

and the refinement of joining methods. These tests contribute to ongoing improvements in dissimilar Al/Mg welds.

- Obtaining the fatigue properties: in such case as current study which is new welding method for dissimilar Al/Mg welding, fatigue test can play essential role for comparing the fatigue properties of the new welding with other method of RSW welding.

In summary, fatigue testing is an indispensable tool for evaluating the durability and performance of Ni-coating or Ti-coating dissimilar resistance spot welding joint Al/Mg. It aids in estimating service life, understanding behavior under cyclic loading, and ensuring compliance with the stringent requirements of various applications.

7.2. Monotonic test of Ni-coating Al/Mg samples

In all of the quasi-static tests performed on the Ni-coating samples, the welding parameters were consistent, with each sample welded at 27 kA and using 15 cycles with 2 pulses, separated by a 5-cycle delay. The average peak load, observed across these samples, was 4,208 N, and the standard deviation was relatively low at 112 N, see Table 7:1.

It is noteworthy that all the samples displayed similar behavior during the tests. They exhibited minimal plastic deformation after reaching the peak load, as demonstrated in Figure 7:1. This consistency in behavior suggests that the welding process and parameters used resulted in predictable and repeatable outcomes across the tested samples.

Table 7:1: Peak loads measured during repeated tensile test results for condition or welding parameters of test 2 from Table 5:3 which are 27kA and 15 cycles 2 pulses.

Sample #	1	2	3	4	5
Max load (N)	4273	4069	4104	4309	4283

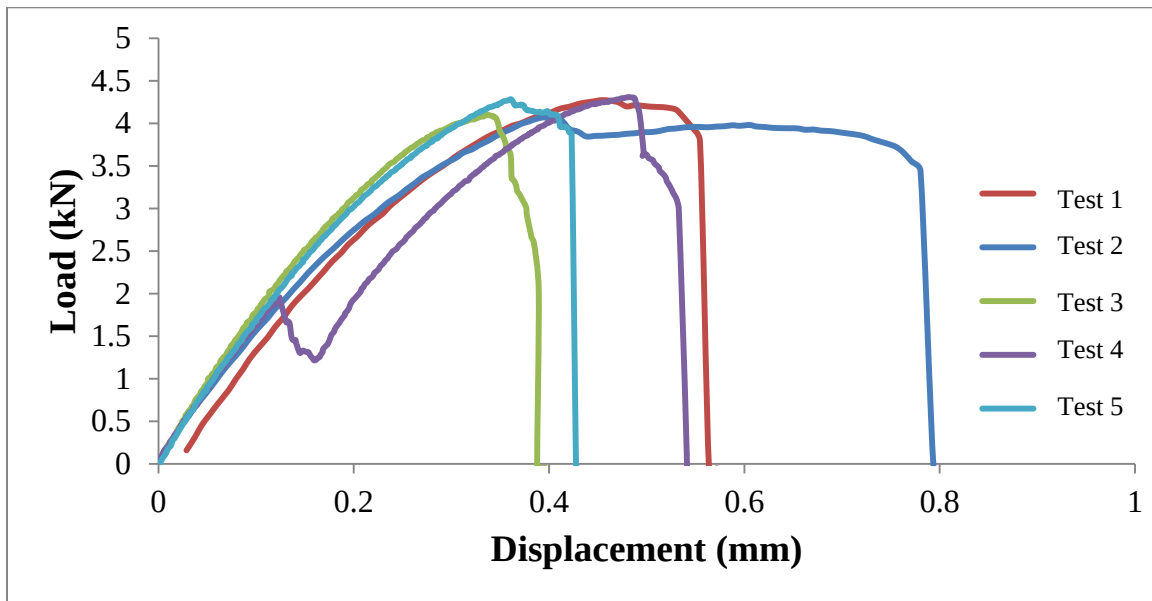


Figure 7:1: Load displacement curves Ni-coating samples (1-5) obtained from lap-shear specimens produced using welded parameters: 27 kA and 15 cycles 2 pulses with 5 cycles delaying time.

7.3. Monotonic test of Ti-coating Al/Mg samples

The Ti-coating group of samples underwent the same testing methodology as the Ni-coating group. During the quasi-static tests, consistent welding parameters were applied, with each sample welded at 20 kA using 15 cycles and 2 pulses, separated by a 5-cycle delay. The average peak load observed across these Ti-coating samples was 3,852 N, and the standard deviation remained relatively low, measuring 216 N, see Table 7:2.

Similar to Ni-coated welds, all the Ti-coating samples exhibited consistent behavior during the tests. They displayed minimal plastic deformation after reaching the peak load, as illustrated in Figure 7:2. This uniformity in behavior underscores that the welding process and parameters used were effective in producing predictable and consistent outcomes across the tested samples.

Table 7:2: Peak loads were recorded during repeated tensile tests for welds made using 20 kA current, 15 cycles, and two pulses with a 5-cycle delay between them.

Sample #	1	2	3	4	5
Max load (N)	4114	4060	3666	3710	3709

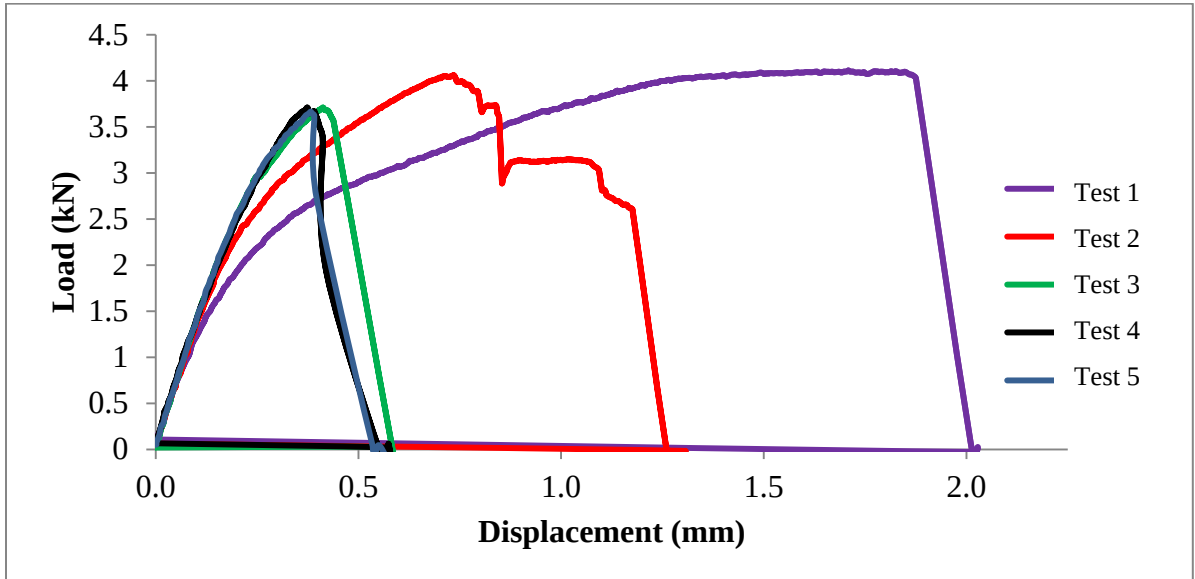


Figure 7:2: Load displacement curves of Ti-coated samples (1-5) obtained from lap-shear specimens produced using welded parameters: 20 kA and 15 cycles 2 pulses with 5 cycles delaying time.

7.4. Fatigue test of Ni coated Al to Mg spot welds

The load-life curve in a fatigue test of Ni-coating samples, typically represented as load amplitude (kN) versus the number of cycles to pull out failure, is a graphical representation that illustrates how the Ni-coating Al/Mg samples respond to cyclic loading over time. The failure was mostly in interfacial mode with some samples that failed through welded sheets. Numbers of cycles associated with that failure are mentioned in Table 7:3. The load-life curve is a fundamental tool in fatigue testing, used to evaluate the endurance limit and fatigue strength of materials and components, which it is a critical aspect in assessing the durability and reliability of Ni-coating Al/Mg resistance spot welding joints. The fatigue tests that were performed in this study were load-control tests which give the load-life curve that is represented in Figure 7:3. Each

point on the load-life curve eventually reaches a failure point or represents the failure point of each individual test with respect to the load level and the number of cycles until the failure, where the Ni-coating Al/Mg samples can no longer withstand the applied load. This is a critical parameter for determining the Ni-coating sample's limiting life. The horizontal axis of the curve in Figure 7:3 represents the number of cycles applied to the Ni-coated samples before failure, while the vertical axis represents the load amplitude (kN), which indicates the amplitude of the cyclic load experienced by the coated Al/Mg joint during each cycle of loading. The information obtained from the analysis of the fatigue test results follows:

Load-Life Relationship

Generally, the trend of the curve has an inversely relationship which means increasing the load on the Ni-coating or Ti-coating samples decreases the fatigue life decreased. At the beginning of the fatigue test of the Ni-coating, the maximum load set up to 40% of the ultimate load (4kN) that is obtained by the monotonic test. Since the R-ratio that is selected for the fatigue test is equal to 0.2, the load amplitude at this level of the load was 0.64 kN. The fatigue lives that were obtained at load amplitude 0.64 kN ranged between $(96 - 149) \times 10^3$ cycles as shown in Table 7:3. Then according to the first set of samples, the load was managed to have a different level of fatigue live aimed to find the endurance limit and the strength of the Ni-coating Al/Mg RSW joints. The samples tested in a range of maximum loads from 1.28 to 2.72 kN and the load amplitude range accordingly is 0.512 to 1.088 kN. The higher load level of the fatigue test results in a range of fatigue lives from (261 to 7909) cycles. However, the lower load level of the fatigue tests gives a high cycle fatigue life that mostly reached 2×10^6 cycles or more.

Fatigue Strength:

Fatigue strength: The concept of fatigue strength is important for assessing the durability and reliability of the Ni-coating Al/Mg resistance spot welding joints. The fatigue strength, which is the load level below which the Ni-coating samples can withstand a defined number of cycles without failing, is a critical parameter. In this study, it is indicated that the fatigue strength at 2M cycle is 0.512 kN of load amplitude where 2M cycle was set as test run-out.

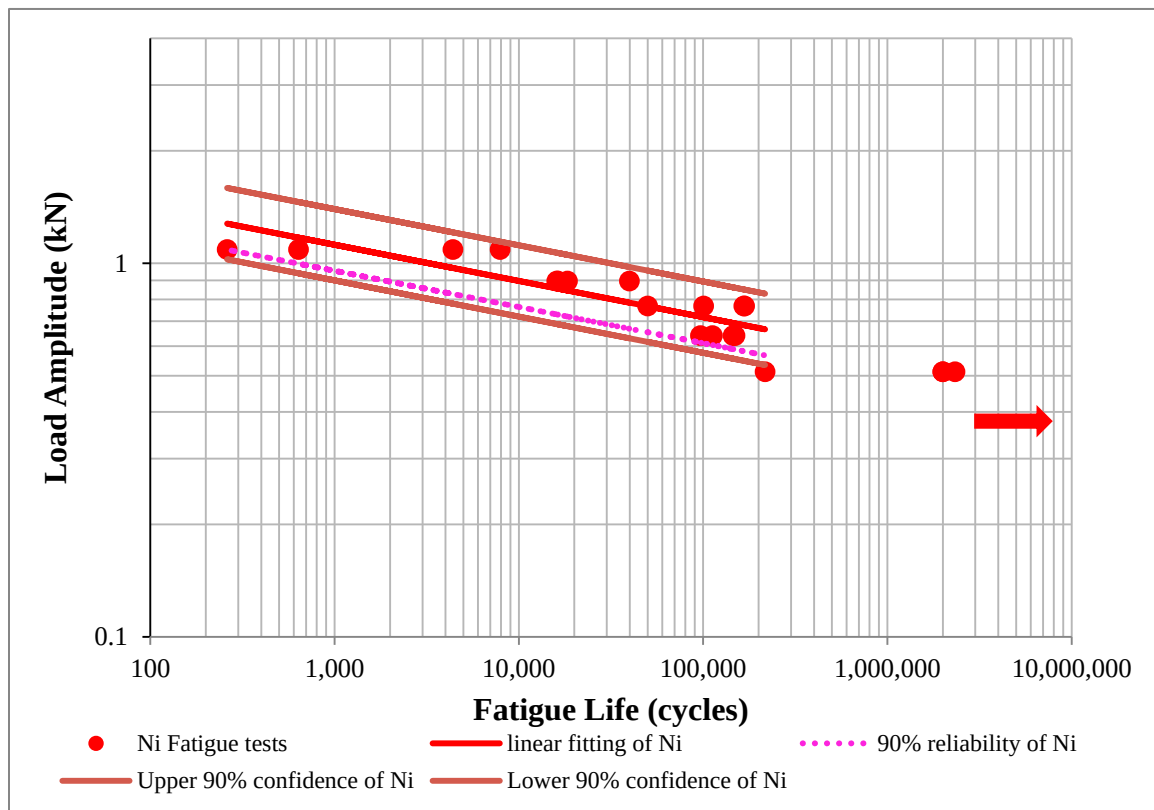


Figure 7:3: Load-life curve of Ni-coated Al/Mg RSW joints for R = 0.2. The curve fitting slope = (-0.0968) and Intercept = 0.34. Linear fitting, 90% confidence and 90% reliability have been calculated.

Table 7:3: Fatigue test data for Ni-coated Al/Mg resistance spot welds

Sample #	Max Load (kN)	R-ratio	Amplitude (kN)	Frequency (cycle/s)	Total Life (cycle)	Failure mode
15	2.72	0.2	1.088	1	637	interfacial failure
16	2.72	0.2	1.088	1	4,387	interfacial failure + crack at the Mg sheet
17	2.72	0.2	1.088	1	261	interfacial failure
18	2.72	0.2	1.088	1	7,904	interfacial failure + crack at the Mg sheet + break the welded coat
19	2.24	0.2	0.896	1	18,346	interfacial failure + crack at the Mg sheet
20	2.24	0.2	0.896	1	16,070	interfacial failure + break the welded coat
21	2.24	0.2	0.896	1	16,291	interfacial failure + crack at the Mg sheet
22	2.24	0.2	0.896	1	39753	failure at the Mg sheet
5	1.92	0.2	0.768	3	100,694	interfacial failure + crack at the Mg sheet and Al sheets
6	1.92	0.2	0.768	3	49,967	interfacial failure + crack at the Mg sheet
7	1.92	0.2	0.768	4	167,821	interfacial failure + crack at the Mg sheet and Al sheets + break the welded coat
8	1.92	0.2	0.768	4	166,061	interfacial failure + crack at the Mg sheet and Al sheets
1	1.6	0.2	0.640	3	145,289	interfacial failure + crack at the Mg sheet and Al sheets
2	1.6	0.2	0.640	3	148,881	interfacial failure + crack at the Mg sheet
3	1.6	0.2	0.640	3	112,213	failure at the Mg sheet
4	1.6	0.2	0.640	3	96,591	interfacial failure + crack at the Mg sheet
9	1.28	0.2	0.512	5	216,854	interfacial failure + crack at the Mg sheet + break the welded coat
10	1.28	0.2	0.512	5	2,327,739	no failure
11	1.28	0.2	0.512	5	2000000	no failure
12	1.28	0.2	0.512	5	2000000	no failure

7.5. Fatigue test Ti coated Al to Mg spot welds

Load-Life Relationship

The fatigue tests conducted on the Ti-coating Al/Mg samples in this study involved load-control tests, resulting in the load-life curve depicted in Figure 7:4. In the Ti-coating fatigue test, the maximum load reached 40% of the 4 kN obtained in the monotonic test. With an R-value (stress amplitude to the maximum stress) of 0.2, the load amplitude at this level was 0.64 kN, and the corresponding fatigue lives ranged from 67,000 to 125,000 cycles, as detailed in Table 7:4. Subsequently, additional samples were tested

across a range of maximum loads from approximately 1 kN to 2.72 kN, with corresponding load amplitudes spanning around 0.4 kN to 1.088 kN. The higher load levels in the fatigue test yielded fatigue lives ranging from 1,726 to 3,611 cycles, while lower load levels resulted in significantly longer high-cycle fatigue lives, which reached 2 million cycles.

Fatigue Strength:

In assessing the durability and reliability of Ti-coating Al/Mg resistance spot welding joints, the concept of fatigue strength is pivotal. The fatigue strength, representing the load level at which Ti-coating samples can endure an defined number of cycles without failure, is of particular significance. The findings in this study indicate that the fatigue strength at 2M cycle for Ti-coating falls below 0.4 kN of load amplitude. This parameter plays a crucial role in determining the ultimate limits of Ti-coating samples under cyclic loading conditions.

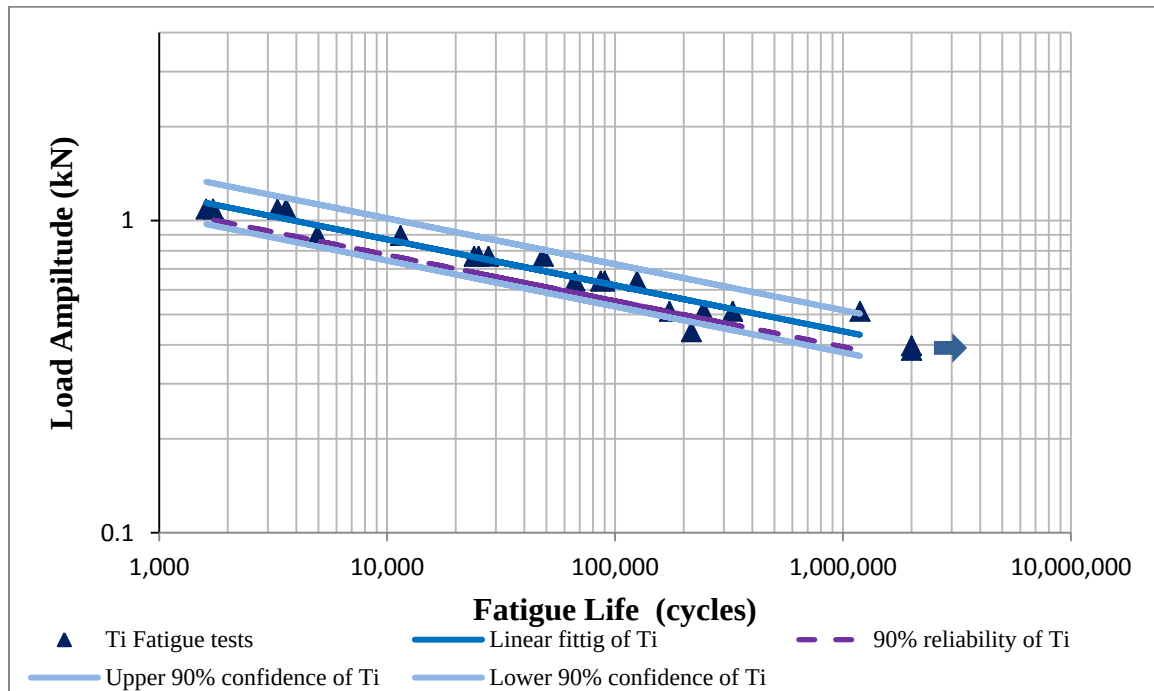


Figure 7:4: Fatigue test of Ti-coating Al/Mg samples. The slope = (-0.147) and Intercept = 0.528. Linear fitting, 90% confidence and 90% reliability have been calculated.

Table 7:4: Fatigue test data of Ti-coated Al/Mg RSW samples

Sample #	Load Max (kN)	R-ratio	Amplitude (kN)	Frequency (cycle/s)	Total Life cycle	Failure mode
15	2.72	0.2	1.088	1	3,308	interfacial failure
16	2.72	0.2	1.088	1	1,608	interfacial failure
17	2.72	0.2	1.088	1	1,726	interfacial failure
18	2.72	0.2	1.088	1	3,611	interfacial failure
22	2.24	0.2	0.896	1	11,455	interfacial failure
23	2.24	0.2	0.896	1	4,946	interfacial failure
5	1.92	0.2	0.768	3	24,098	interfacial failure
6	1.92	0.2	0.768	3	48,497	interfacial failure
7	1.92	0.2	0.768	3	27,864	interfacial failure
8	1.92	0.2	0.768	3	25,237	interfacial failure
1	1.6	0.2	0.640	3	86,502	interfacial failure
2	1.6	0.2	0.640	3	66,729	interfacial failure
3	1.6	0.2	0.640	3	124,852	interfacial failure
4	1.6	0.2	0.640	3	90,157	interfacial failure
9	1.28	0.2	0.512	3	173,362	interfacial failure + crack at Mg sheet
10	1.28	0.2	0.512	3	328,424	interfacial failure + crack at Mg sheet
11	1.28	0.2	0.512	3	244,729	interfacial failure + crack at Mg sheet
12	1.28	0.2	0.512	5	1,188,084	interfacial failure +crack at Mg sheet +crack at the Al sheet
19	1.1	0.2	0.440	7	216,469	interfacial failure + crack at Mg sheet
20	0.96	0.2	0.384	8	2,000,000	No failure
21	0.992	0.2	0.397	10	2,000,000	No failure

The slope of the load-life curve reflects the material's sensitivity to cyclic loading.

In this case, the Ni-coated samples and the Ti-coating samples exhibit a slope that suggests they are less sensitive to fatigue damage, particularly at lower load amplitudes. This means the materials are more resistant to fatigue, and capable of enduring more cycles before failure under the same load conditions.

The data from the load-life curve has practical applications in engineering and materials science. It helps in evaluating the endurance limit and fatigue strength of materials and components. In the specific context of this study, it is essential to understand how the Ni-coated and/or Ti-coated Al/Mg resistance spot welded joints behave under cyclic loading conditions. This information is invaluable for designing

reliable and durable engineering structures and products in case coated Al/Mg joint is employed.

7.6. Fracture and failure mode of the cold spray-assisted welds

7.6.1. Failure mode of Ni coating Al/Mg

Two distinct failure modes were observed in Ni-coating Mg/Al joints under cyclic loading: interfacial failure and sheet failure on the Mg side. The two modes were combining to each other in different load levels which give partial sheet failure beside the interfacial failure. These modes have applied with all level of fatigue life except in low cycle fatigue life the interfacial mode occurred without sheet mode as mentioned in Table 7:3 above.

Interfacial Failure

Interfacial failure was the major failure mode in Ni-coating specimens that subjected to cyclic loads. The interfacial in the Ni coating samples also can be divided to two sub-modes that depend on the location where failure occurred. First sub-mode is at the interface between the Ni coating and the Mg substrate and the second sub-mode throughout the welded coat layer. Figure 7:6 shows samples that failed in these modes: (a) interfacial mode in the interface between the Ni coat and Mg, (b) the interfacial failure through the welded coats.

Sheet Failure Mode:

Sheet failure occurred only on the Mg side. Two samples out of 20 tests have been ruptured by this mode; however, the Mg sheets were cracked during the fatigue test in 15 samples in total out of 20 samples. In other words, even when the final failure was interfacial, crack occurred on the Mg sheets in almost all the fatigue life levels. The sheet

failure mode shows in Figure 7:6 (c). Figure 7:6 (d) demonstrate that even when the fatigue crack propagates though the entire Mg sheet width, the final rupture occurred with interfacial mode.

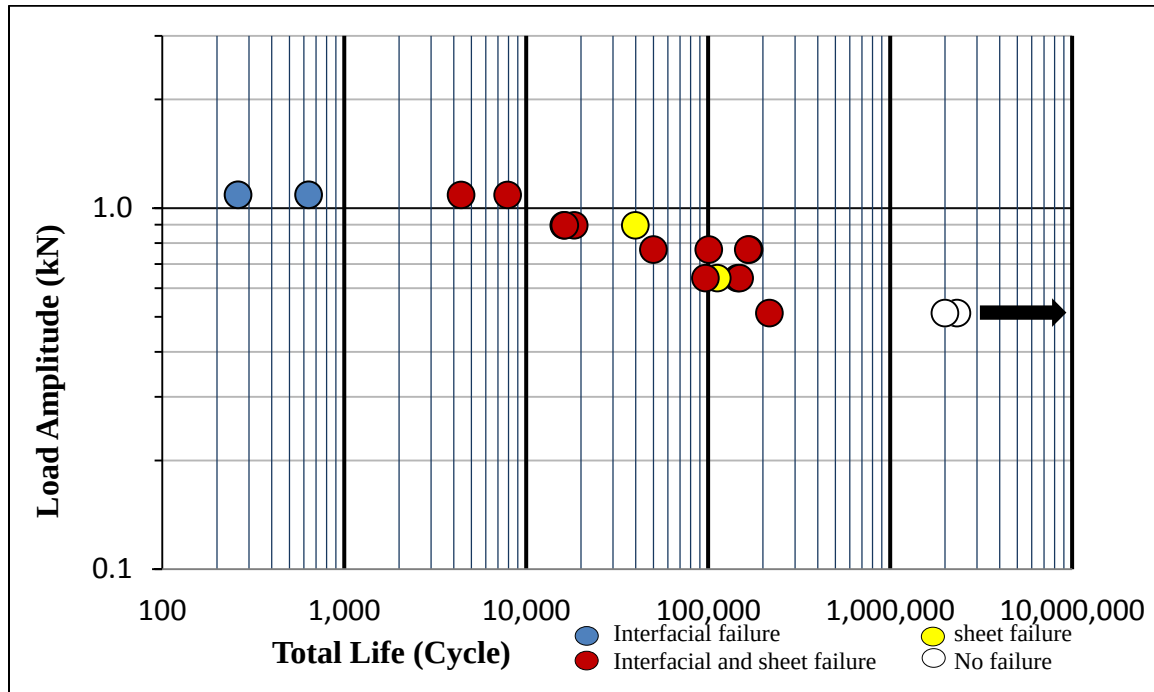


Figure 7:5: failure modes in the fatigue test of Ni-coating Al/Mg RSW samples. The major failure mode was interfacial failure with sheet failure.

The variation in failure modes observed in the fatigue-tested welded Al-Mg samples, despite identical testing conditions, can be attributed to several factors related to material properties, coating inconsistencies, and welding characteristics. One primary factor is the variability in Ni coating thickness. The cold spray deposition process may result in slight differences in coating uniformity, leading to uneven load distribution at the welded interface. This variation can create stress concentrations that influence crack initiation and propagation. Additionally, small amount of intermetallic compounds (IMCs) at the Ni coating Al-Mg welded area should be created in some samples where the inconsistent Mg was observed in SEM due to fluctuations in heat input and diffusion during welding. Since IMCs are brittle, their irregular distribution can contribute to

different failure behaviors. Moreover, minor defects or porosity in the Ni coating or weld region, as observed in SEM images, may act as stress concentrators, influencing whether failure occurs at the interface, weld, or base materials that resulting in different failure modes. These factors collectively explain the inconsistency in failure behavior observed during fatigue testing.

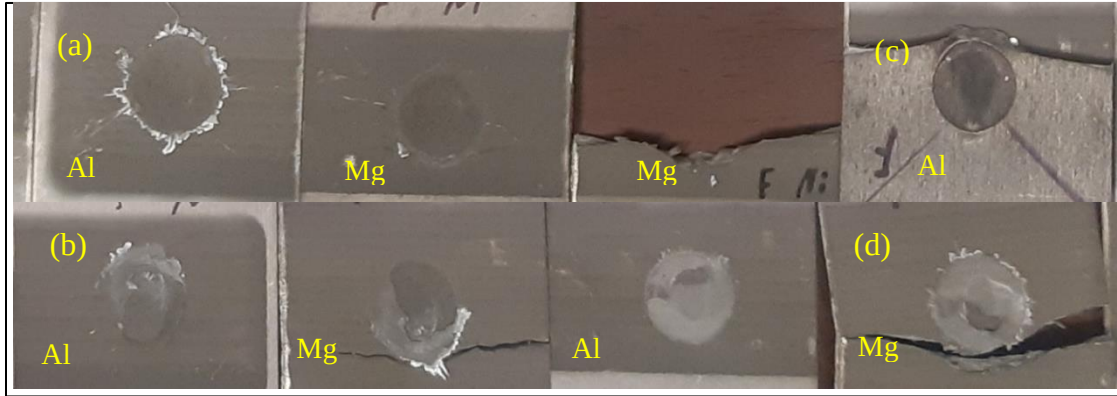


Figure 7:6: (a) shows interfacial mode of failure that occurred between the Ni-coat and the Mg substrate at max load 1.6 kN and fatigue life 148881 cycles, (b) shows interfacial mode of failure that broke the welded Ni-coat at max load 1.6 kN and fatigue life 96591 cycles (c) shows the sheet failure mode max load 1.6 kN and fatigue life 112213 cycles and (d) shows the combing failure mode with interfacial rapture at max load 1.28 kN and fatigue life 216854 cycles.

7.6.2. Failure mode of Ti coating Al/Mg

One failure mode was observed in Ti-coating Mg/Al joints under cyclic loading which is the interfacial failure; however, this mode is sometimes associated with crack that propagate on the Mg sheet and /or Al sheet. The mode has applied with all level of fatigue life as represented in Figure 7:7. The interfacial mode in the Ti coating samples repeatedly occurred at the interface between the Ti coating and the Al substrate. Figure 7:7 (a) shows all the Ti coating samples that subjected and failed in fatigue test. Figure 7:7 (b) shows example of the crack on the Mg sheet, and Figure 7:7 (c) shows the crack on Al sheet in addition to crack on the Mg sheet is associated with interfacial failure mode. Figure 7:7 (d) the welded Ti coat that remained on the Mg side.

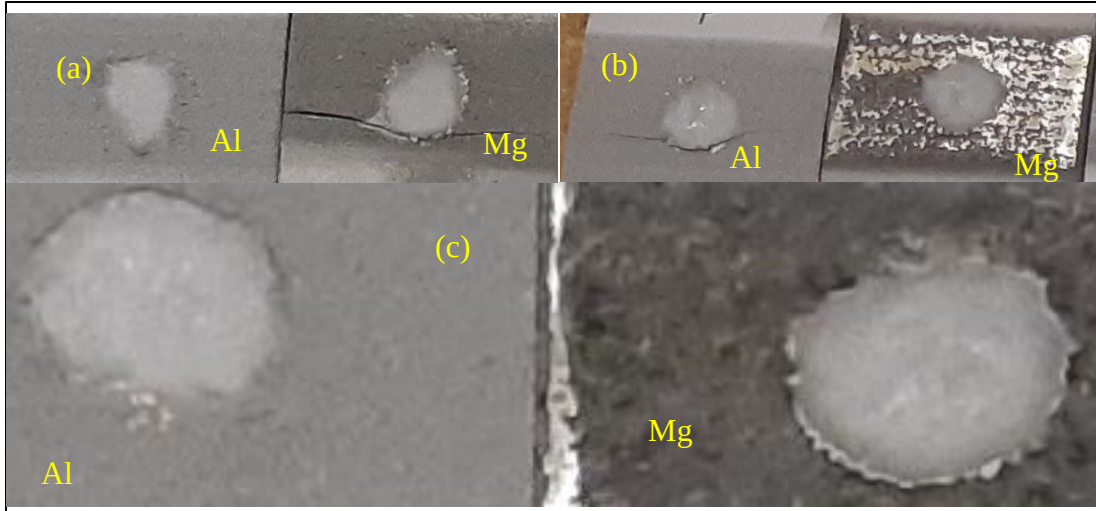


Figure 7:7: (a) shows the crack on Mg sheet that associated interfacial failure and (b) shows both Al and Mg sheets cracked before failure mode with interfacial rupture. (c) is the welded Ti coat that pill out of the Al side to stay with Mg side after final failure.

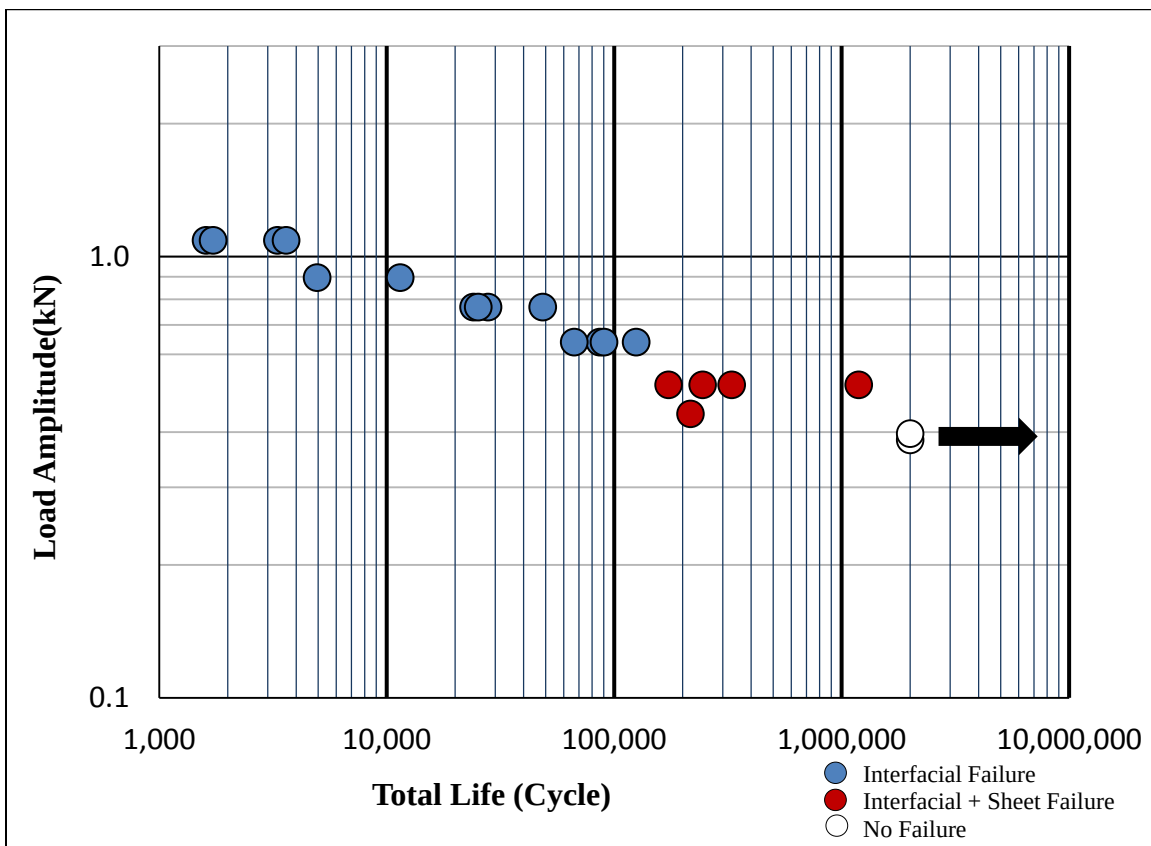


Figure 7:8: failure modes in the fatigue test of Ti-coating Al/Mg RSW samples. The major failure mode was interfacial failure

The differences in failure modes during fatigue testing of Al-Mg welded joints can be linked to variations in material behavior, coating uniformity, and welding conditions. Minor fluctuations in the thickness of the Ti coating applied by cold spray may result in non-uniform stress distribution across the joint, promoting localized stress concentrations and early crack initiation. In some cases, limited intermetallic compounds (IMCs) formation occurred due to uneven Mg diffusion, creating micro-brittle zones within the weld. Additionally, porosity present in the Ti coating near the weld area acted as stress raisers, contributing to the specific locations where failure occurred. However, the final failure modes observed in Ti coating samples revealed the repeatedly interfacial failure between the Ti coating and Al substrate indicating relatively low adhesion between the coat and the substrate, further contributing to failure behavior.

7.6.3. Fracture surface

As discussed in the failure modes section, interfacial failure emerged as the primary failure mode during fatigue testing of Ni-coated and Ti-coated Al/Mg resistance spot weld (RSW) joints. This mode was particularly prominent due to the unique thermal dynamics during the welding process. The heat generated during welding was substantial enough to bond the coating layers effectively but also exceeded the thermal tolerance of the Mg sheet.

As a result, molten Mg was expelled around the welded area, permeating through the coating layers of the Ni and/or Ti coatings. This phenomenon is illustrated in Figure 7:9 (a) and Figure 7:7 (a)-(d) which depict the extent of this material displacement. In essence, the expulsion of molten Mg disrupted the integrity of the coating layers near the welded region, creating localized weaknesses where the coating was breached. These breaches provided a pathway for interfacial cracks to propagate in

the interface between the coat and the substrate, contributing significantly to the observed interfacial failure under cyclic loading conditions.

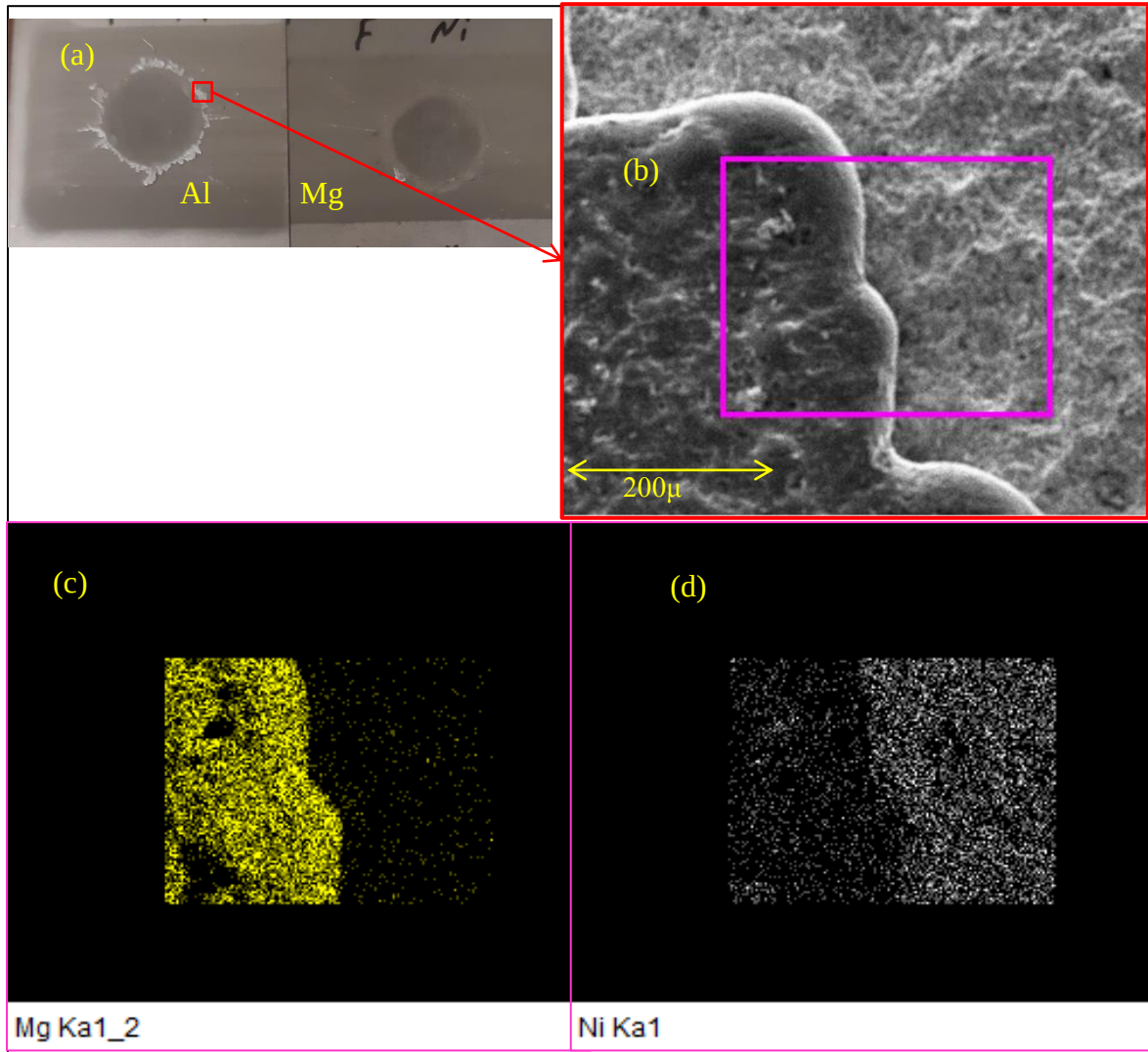


Figure 7:9: (a) shows Mg that was expelled around the welded Ni-coating area and interfacial mode of failure that occurred between the Ni-coat and the Mg substrate, (b) SEM images for the melted Mg that broke the Ni-coat layer (c) Mg distribution (d) Ni distribution.

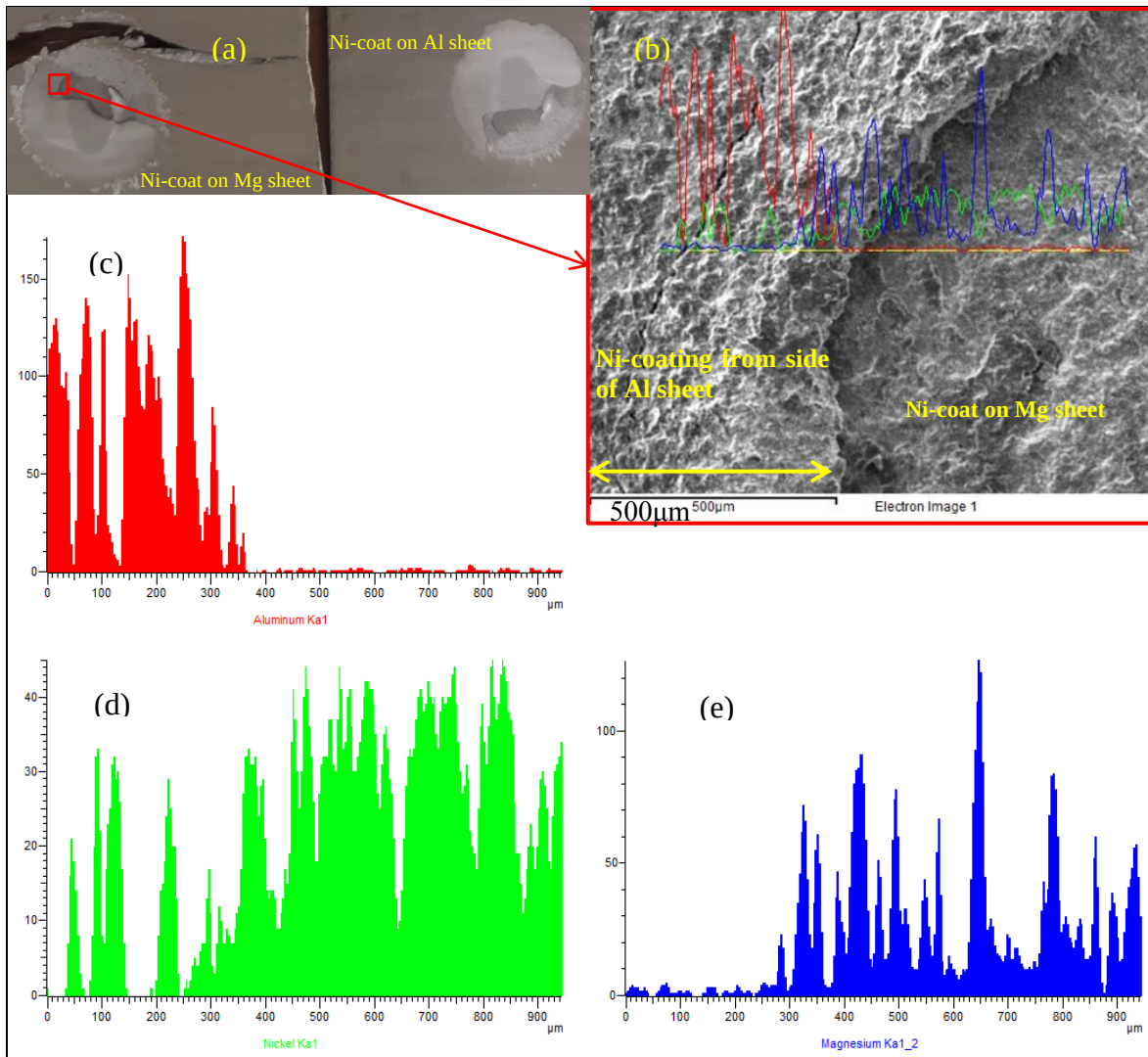


Figure 7:10: (a) represented the fracture welded Ni-coating area (b) the SEM image shows the fracture pathway between the two welded Ni-coating layers (c) the distribution of the Al that left after the fracture on the coat (d) the Ni distribution (e) the Mg distribution that show the penetration of the Mg in between the welded Ni-coating.

Also, as mentioned earlier, the interfacial failure mode observed in the Ni-coated group of samples occasionally extended through the welded coating layer. SEM analysis provided valuable insights into this behavior, revealing that the fracture pathway within the welded Ni coating layer was influenced by the presence of Mg in the fractured region. This observation suggests that Mg played a significant role in altering the structural cohesion of the Ni coating. Figure 7:10 visually demonstrates the fracture caused by the

presence of Mg within the Ni coating, emphasizing the impact of material interactions on the failure mechanism.

In addition to interfacial failure, the sheet failure mode was also observed in some Ni-coated samples. In this mode, fractures typically originated at the edge of the welded area of the Ni coating and propagated across the width of the Mg sheet. This phenomenon offers a noteworthy conclusion: the presence of sheet failure in these instances indicates that the weld exhibited greater strength than the surrounding Mg sheet. This finding highlights the robustness of the welded joint, suggesting its capacity to endure higher stresses compared to the base material. Such insights are essential for understanding the overall performance and reliability of Ni-coated Al/Mg joints under cyclic loading conditions.

7.7. Comparing Ni versus Ti coating influence on fatigue behaviors

Based on the information obtained from the monotonic tests and the fatigue tests of Ni-coating Al/Mg samples and Ti-coating Al/Mg samples, utilizing Figure 7:1 and Figure 7:2 that represent the strength of the both group of samples and Figure 7:11 that represents the load-life curves of both groups of samples, the following comparisons between the two groups can be obtained:

Monotonic strength

- Ni-coating: The average peak load observed across these samples was 4,208 N, and the standard deviation was relatively low at 112 N
- Ti-coating: The average peak load observed across these Ti-coating samples was 3,852 N, and the standard deviation remained relatively low, measuring 216 N

The Ni-coating samples displayed a higher strength under the same test conditions.

Maximum Load and Load Amplitude

- Ni-coating: The maximum load for the Ni-coating samples in the fatigue test ranged from 1.28 kN to 2.72 kN with load amplitudes from 0.512 kN to 1.088 kN.
- Ti-coating: The maximum load for the Ti-coating samples in the fatigue test also ranged from around 1 kN to 2.72 kN, with load amplitudes between approximately 0.4 kN to 1.088 kN.

The maximum load amplitude ranges for both Ni-coating and Ti-coating samples are relatively similar, indicating that similar loading conditions were applied during the fatigue tests.

Fatigue Life

- Ni-coating: The Ni-coating samples exhibited a wide range of fatigue lives, with higher load levels resulting in fatigue lives ranging from 261 to 7,909 cycles, and lower load levels yielding high-cycle fatigue lives typically exceeding 2 million cycles.
- Ti-coating: The Ti-coating samples also showed varying fatigue lives. Higher load levels led to fatigue lives between 1,726 and 3,611 cycles, while lower load levels resulted in high-cycle fatigue lives which exceeding 2 million cycles.

Comparison: Both Ni-coated and Ti-coated samples displayed a broad range of fatigue lives, with high-cycle fatigue lives exceeding 2 million cycles. However, the exact values of fatigue lives are different, with Ti-coating samples generally exhibiting shorter fatigue lives compared to Ni-coating samples under similar load conditions.

Fatigue Strength

- Ni-coating: The fatigue strength at 2M cycles for Ni-coating samples fell at 0.512 kN of load amplitude, indicating that they can withstand millions number of cycles below this load level.
- Ti-coating: The fatigue strength at 2M cycles for Ti-coating samples was at 0.4 kN of load amplitude.

Comparison: The Ti-coating samples displayed a lower fatigue strength at 2M cycle (0.4 kN) compared to the Ni-coating samples (0.512 kN), indicating that Ni-coating have a higher fatigue strength under these test conditions.

The fracture surface and failure modes

- Ni coating: two failure modes were observed during the fatigue test; interfacial failure mode and sheet failure mode. The interfacial mode was at the interface between the Ni-coating and the Mg substrate. Some fracture went through the welded coating area and is classified as interfacial failure mode.
- Ti coating: one failure mode occurred during the fatigue test and it was the interfacial failure mode. The interfacial failure was at the interface between the Ti-coating and the Al substrate. No fracture through the welded coating area has been recorded. The interfacial failure mode was always at interface between the Ti coating and the Al sheet.

Comparison: The sheet failure modes in the Ni-coating group indicate that the Ni-coating has strength capacity higher than the Ti coating group. Some samples in the Ti coating groups cracked that propagated through the width but still the final rapture was by interfacial failure mode. The interfacial failure mode in both groups can be attributed

to the presence of the Mg at the fracture area, which means micro-undesirable IMC might be present.

In summary, both the Ni-coated and Ti-coated samples exhibited a wide range of fatigue lives; with Ni-coating samples tending to have longer fatigue lives than Ti-coating samples. The fatigue strength of Ni-coated sheets at 2M cycles is expected to be 0.1 kN higher than that of Ti-coated sheets, based on the regressions in Figure 7:11. Also, comparing the fatigue life at 0.512 kN load amplitude where the fatigue life of the Ni-coating samples reach 2M cycles, the maximum fatigue life for the Ti-coating was 1.188M cycles. The difference between the performances of the two groups of samples is attributed to the higher rate of interfacial plus sheet failure in the Ni-coated joints (see Figure 7:5 versus Figure 7:8). This appears to be attributed to the slightly thicker coating and resulting higher bending moment on the Ti samples. These results provide insights into the fatigue behavior of these coatings and their potential application in Al/Mg resistance spot welding joints.

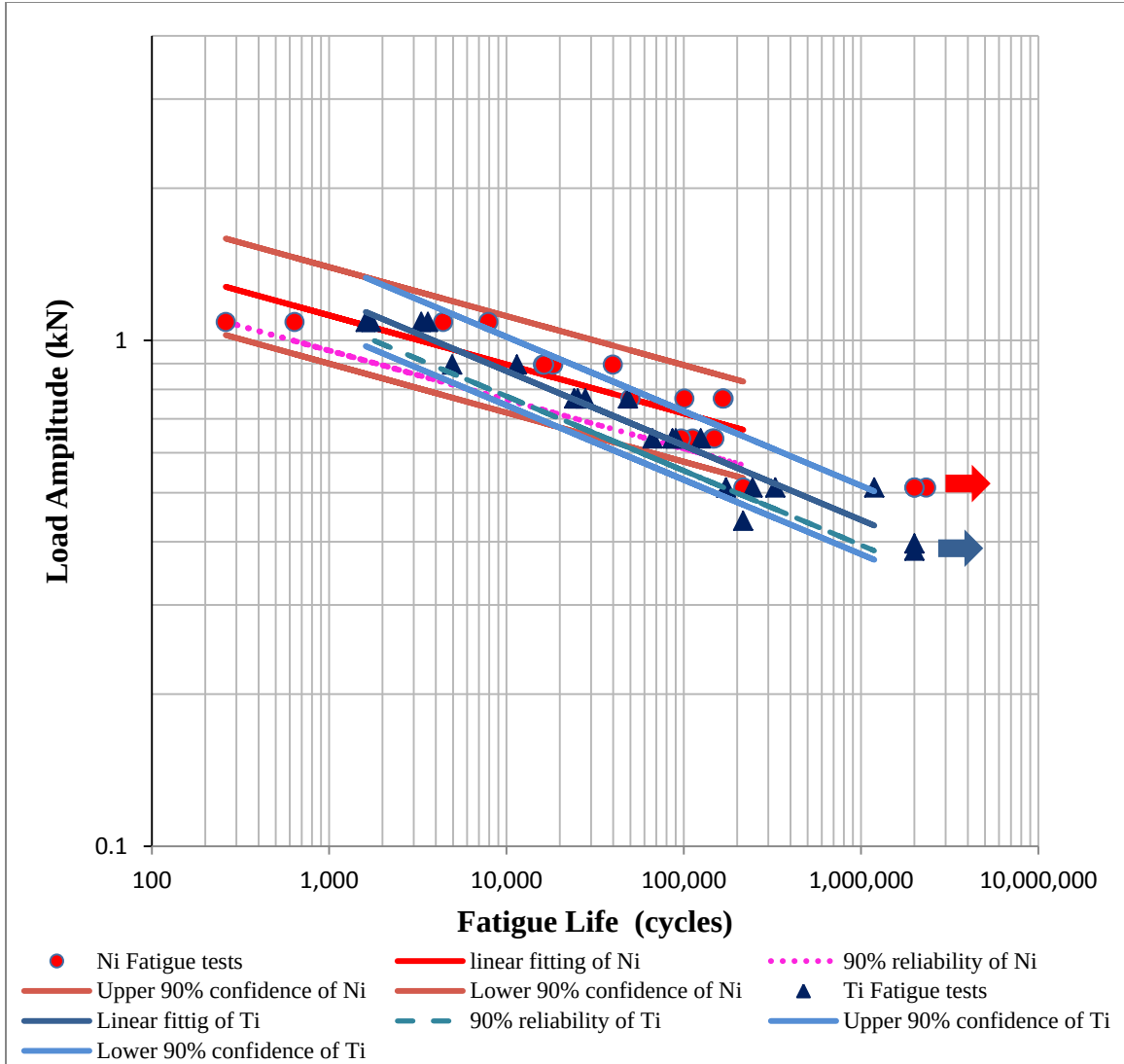


Figure 7:11: Comparison of the fatigue life of Ni-coating Al/Mg and Ti-coating Al/Mg of RSW samples that shows the Ni-coating samples group has higher performance than Mg-coating samples group.

7.8. Discussion

This section analyzes and discusses the mechanical performance of resistance spot welded Al/Mg joints prepared with Ni and Ti cold spray coatings, drawing from both monotonic and fatigue testing results. The monotonic test results showed a higher average strength in the Ni-coated samples of 4.21 kN compared to the Ti-coated ones 3.85 kN. Both coating groups demonstrated low standard deviations, 112 N for Ni and 216 N for Ti, suggesting consistent joint formation. The superior strength of the Ni group

may be attributed to stronger interfacial bonding and more uniform coating distribution during the cold spray process. These insights align with prior studies [5][7][68] that emphasize the importance of interlayer selection and coating quality in mitigating IMCs formation and enhancing joint durability in dissimilar metal welding

Fatigue tests revealed comparable load amplitude ranges between the Ni and Ti groups, with both ranging from approximately 0.4 kN to 1.088 kN. Despite this similarity in loading conditions, fatigue life performance differed. Ni-coated joints endured a broader fatigue life range from 261 to 7,909 cycles at higher loads and exceeding 2 million cycles at lower amplitudes, while Ti-coated joints typically failed earlier, surviving between 1,726 to 3,611 cycles at high loads, and exceeding 2 million cycles only under reduced load amplitudes. In the fatigue strength at 2 million cycles, Ni-coated joints withstood up to 0.512 kN of load amplitude, whereas Ti-coated joints failed beyond 0.4 kN. This approximately 0.1 kN difference underscores the enhanced endurance of the Ni interlayer under cyclic stress. Furthermore, at a 0.512 kN load amplitude where Ni samples sustained up to 2 million cycles Ti samples peaked at approximately 1.188 million cycles.

Fracture-graphic observations support these mechanical findings. Ni-coated joints exhibited both interfacial and sheet failure modes, with some fractures propagating through the nugget zone, suggesting strong interfacial bonding. Ti-coated joints predominantly failed at the interface between the Ti layer and the Al substrate, indicating a comparatively weaker bond. The consistent interfacial failure in Ti samples may be influenced by increased coating thickness, resulting in elevated bending moments that accelerate crack initiation under cyclic loading.

The presence of Mg at fracture zones in both sample sets suggests partial elemental diffusion through the interlayer. However, the reduced fatigue life and singular failure mode in Ti-coated joints could also be linked to higher porosity or microstructural inconsistencies inherent in the cold spray deposition process.

In summary, cold spray-assisted RSW joints with Ni interlayers demonstrated better fatigue resistance and monotonic strength than those with Ti coatings. The findings suggest that Ni offers a more robust barrier to IMC formation while maintaining stronger mechanical bonding across the weld interface. The superior performance of Ni-coated Al/Mg joints over Ti-coated can be attributed to several interrelated factors. First, the Ni interlayer exhibited stronger interfacial bonding, as evidenced by the higher average monotonic strength and the presence of both interfacial and sheet failure modes, suggesting that the joint strength occasionally exceeded that of the base material. In contrast, Ti-coated joints consistently failed at the interface between the Ti layer and the Al substrate, indicating weaker adhesion. Additionally, Ni coatings likely offered more uniform deposition and lower porosity compared to Ti, reducing stress concentrations that can trigger premature crack initiation under cyclic loading. The notable difference in the thickness of the Ni coating and the Ti coating can also influence the difference in performance. The thicker Ti coating introduced higher bending moments during fatigue testing, contributing to early failure. Furthermore, the Ni interlayer may have better restricted elemental diffusion and limited brittle IMC formation at critical interfaces, thereby enhancing fatigue resistance. These combined effects explain the consistently higher fatigue strength and longer fatigue life of the Ni-coated joints under identical test conditions.

Chapter 8: Conclusions and future work

8.1. Summary of contribution

The research conducted in this study has yielded several significant contributions that advance the field of dissimilar welding technology, which are summarized below.

1- Development of Al/Mg Joints using Cold Spray Technology

The present study makes a significant contribution by providing an innovative solution for RSW of dissimilar materials, specifically Al and Mg. It addresses the longstanding challenge of achieving a reliable RSW joint between these two materials while preventing the formation of undesirable intermetallic compounds. The application of cold spray coating techniques in this research besides offering a dependable means of creating these joints also enhances our understanding of dissimilar material welding processes, leading to the development of joints that meet the stringent requirements of various industrial applications.

2- Cold Spray Knowledge Development

A key contribution of this study is the development of optimal cold spray deposition parameters for Ni and Ti coatings on Al and Mg substrates, specifically tailored to enhance dissimilar resistance spot welding (RSW). By systematically optimizing parameters such as carrier gas type, pressure, temperature, powder feed rate, particle size, and standoff distance, the study demonstrates the ability to achieve high-quality coatings with minimal defects. These coatings serve as effective interfacial layers that mitigate the formation of brittle intermetallic compounds (IMCs), such as Al_3Mg_2 and $\text{Mg}_{17}\text{Al}_{12}$, by acting as diffusion barriers. This significantly improves joint strength and durability. Furthermore, the comprehensive micro-characterization of the coatings,

including SEM and mechanical testing, highlights their role in facilitating reliable and efficient welding. This contribution not only addresses the challenges associated with IMCs but also provides a foundation for integrating lightweight materials like Al and Mg in automotive applications, supporting the development of stronger, more durable, and environmentally sustainable solutions.

3- Identifying the Mechanism of Coating Layer Joining

In terms of welding processes, this research provides crucial insights into the mechanisms governing the joining of coating layers at temperatures lower than the substrate's melting point. The successful use of Ni and Ti coatings, which have higher melting points than Al and Mg substrates, in resistance spot welding RSW demonstrates that a higher melting point of the interfacial layer does not necessarily damage the substrate during the welding process. This revelation makes a profound contribution to our understanding of welding processes. It opens up new avenues for achieving superior joint quality and performance, even in situations where maintaining the integrity of the substrate is of paramount importance.

Moreover, because the welding was performed using a novel method, the underlying welds mechanism and the behavior of Mg throughout the process can be also considered novel mechanism. This contributes new insights into how Mg responds under such conditions, presenting an original joining mechanism not previously observed in conventional welding techniques and highlighting the innovative aspect of this study's approach to dissimilar metal joining.

4- Exploration of Different Powders

Since the mechanism of producing the coating Al/Mg RSW joint by using cold spray is unlike the foil interlayer mechanism that being done in the past, one of contributions of this research is the exploration of different powders that can work with Al and Mg within the cold spray process for dissimilar material joints. By broadening the range of materials compatible with the cold spray technique, this study widens the horizons of potential applications, offering solutions for a diverse array of industrial needs. Researchers can now assess the compatibility and performance of various powders, providing a more versatile approach to dissimilar material welding.

5- Developing knowledge about optimization through Powder Mixing

This research applied the mixing of powders during the cold spray process to optimize its advantages for diverse applications. If the powder does not adhere well to the substrate or if a stronger adhesion is required, a mixed powder approach can be employed by adding a powder of the same material as the substrate. For instance, in the case of Ti and Al powders, Al serves this role in addition to penetrating between the Ti particles and acting as a binder to create a smooth and durable coated layer. The coating process parameters should then be optimized for the powder requiring higher heat and gas pressure, such as Ti in this study. This highlights the importance of mixing powder method that presents opportunities to enhance the benefits of cold spray and adds a new research direction to explore the effects of powder mixing on coating performance and durability. It invites further investigation into how combinations of powders can improve coating characteristics.

6- Crack Initiation Detection Method

An essential research contribution is the development of a method for detecting crack initiation in spot welding joints. The method combined two detection techniques; dye penetration for identifying cracks and digital image correlation (DIC) applied to a modified RSW sample for detecting the crack initiation right when the crack occurred without interrupting the fatigue test. This innovative approach equips researchers with a powerful tool for scrutinizing areas surrounding resistance spot welds, where cracks tend to first appear. The insights garnered through this method not only further our understanding of weld quality and performance but also contribute to advancements in welding technology, enabling the creation of stronger and more reliable joints.

8.2. Conclusions

The present work underscores the viability of employing cold spray coating techniques to apply Ni and Ti layers onto Al and Mg alloy substrates as effective interfacial layers before resistance spot welding, thereby addressing the issue of detrimental intermetallic compounds formation during the welding process. The following key conclusions emerge from the results presented in this study:

1. Finding cold spray coating parameters of the candidate metal powders to coat the Al and Mg sheets using a low-pressure system. This research successfully identified and optimized cold spray parameters for Ni and Ti powders to coat Al and Mg sheets using a low-pressure system. Different interlayer metals Ni and Ti were compared to assess their effectiveness in facilitating welding. Critical cold spray parameters including gas type, pressure, temperature, feed rate, nozzle velocity, and standoff distance, which are tabulated in Table 5:1 for Ni and Table 6:1 for Ti, were optimized

to produce dense, good quality coatings. The selected powders exhibited compatibility with both Al and Mg substrates, minimized detrimental intermetallic compounds formation, and demonstrated suitable mechanical properties for the RSW process. This approach introduced a novel pathway to use cold spray for enhancing dissimilar Mg/Al resistance spot welding.

2. To obtain a reliable dissimilar Al/Mg resistance spot weld using a cold spray coating interlayer. Reliable Al/Mg joints were achieved by applying cold-sprayed Ni and Ti coatings followed by resistance spot welding. Metallographic analysis confirmed that the coatings effectively acted as diffusion barriers, preventing the formation of brittle intermetallic compounds at the welded interface. However, the SEM images confirmed that a notable amount of Mg penetrated into the welded area. This study successfully established the mechanism of Mg penetration into the Ni/Ni or Ti/Ti weld surfaces, shedding light on the factors contributing to this phenomenon during the welding process. Tensile lap-shear tests showed that the cold spray-coated joints achieved peak loads of 4.3 kN for Ni coatings and 4.11 kN for Ti coatings, meeting industry standards and demonstrating excellent mechanical strength. This load capacity aligns with the standards set by AWS for similar sheet joints; please see Table 2:1 where the strength of the dissimilar Al/Mg without interlayer was 0.833kN [68] and the strength reached 5.1kN when Ni foil has been used [7]. These results confirmed that the application of optimized cold-sprayed interlayers successfully enabled strong and reliable dissimilar Al/Mg spot welds.
3. Characterize quasi-static and cyclic behavior of the joints. The quasi-static and fatigue behaviors of the welded joints were systematically characterized. Compared

to conventional Al/Mg welds, joints made with cold-sprayed Ni and Ti interlayers exhibited improved fatigue performance, higher load-bearing capacity. The coated joints showed better resistance to crack propagation due to the suppression of brittle intermetallic phases at the interface, thus enhancing the overall durability and service life of the welded components. The examination of joint fracture mechanisms during mechanical testing highlighted the role of coated Ni or Ti layer roughness, which induced voids and porosity at the weld surface. These areas acted as stress concentration points, coupled with the presence of porosity within the interlayer containing migrated Mg from the base sheets during welding.

4. Optimization through powder mixing: enhancing Ti coating performance. A contribution of this research is the optimization of Ti powder coating via mixing with Al powder to improve coating quality and adhesion. A 3 wt% addition of Al to the Ti powder was identified as optimal, acting as a binder and enhancing deposition efficiency. This adjustment improved the uniformity and durability of the Ti coating while maintaining compatibility with the substrate materials. The optimized powder blend highlighted the importance of trying mixing powder to obtain the desired results for future research into cold spray applications for dissimilar joining.
5. Method for in-situ early crack detection in spot welds under cyclic loads. An initial in-situ methodology was developed for detecting early crack initiation during cyclic loading of spot-welded joints. By monitoring the critical zone for crack formation using DIC on modified specimen. The method provided insights into early-stage crack nucleation and growth without interrupting the fatigue test. This approach lays a foundation for future real-time monitoring techniques, improving the reliability

assessment and lifespan prediction of resistance spot welded joints under dynamic service conditions.

In summary, this research offers valuable insights into the effectiveness of cold spray coating methods to apply a Ni or Ti interlayer to enhance the Al/Mg RSW joint's integrity, while also elucidating the underlying mechanisms responsible for these improvements. These findings have important implications for the welding industry, where preventing intermetallic compounds formation is critical to maintaining the mechanical performance and reliability of welded

8.3. Recommendation and future work

The study's findings offer valuable insights into the application of cold spray coating techniques as interfacial layers in dissimilar material welding processes, specifically focusing on Al/Mg resistance spot welding. These insights provide a solid foundation for proposing future research directions that can further advance the field of materials science and welding technology.

1- Exploring Alternative Powders. To expand the scope of interfacial layer applications, researchers might explore the feasibility of using alternative powders, such as stainless steel 316L, which may require higher cold spray pressures. This approach opens the door to investigating how different materials can be employed as interlayers to mitigate intermetallic formation in dissimilar material welding processes. By comprehensively studying the characteristics of these alternative powders, researchers can provide insights into their suitability and effectiveness for specific applications.

2- High-Pressure CS system for Ti-Coating. Further research could be directed toward optimizing the coating parameters for Ti layers using a high-pressure cold spray system.

Employing smaller particle sizes and increased pressure could yield coatings with enhanced properties, making them even more effective in preventing intermetallic formation during resistance spot welding. Investigating these specific parameters will allow for a more detailed understanding of the potential benefits and limitations associated with different cold spray setups.

3- Mixed Powder Optimization. A promising avenue for future work involves experimenting with mixed powders or adding specific powders during the cold spray coating process. This research could focus on optimizing the coating parameters based on the intended application and objectives. By precisely tailoring the composition and particle size of the mixed powders, researchers can fine-tune the coating's properties, enhancing its performance in various scenarios. This exploration holds the potential to produce coatings with tailored attributes, opening up opportunities in a wide range of industrial applications.

4- Model Calibration for Crack Initiation. An intriguing avenue for future research could involve the calibration of crack initiation models, particularly for steel, utilizing the developed methodology. This entails refining and validating models that predict crack initiation and propagation during resistance spot welding. Through systematic calibration and testing, researchers can fine-tune these models to improve their accuracy and applicability to real-world welding scenarios. The outcome of this research would contribute to more reliable predictions of joint performance and durability, benefiting the welding industry.

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