# Fatigue of Cold Spray-Assisted Resistance Spot Welding of Aluminum to Magnesium

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**Abstract:** Direct fusion welding of Al to Mg creates brittle intermetallics (IMCs) that restrict the application of these joints in structural applications. An interlayer foil can be employed to prevent intermetallic formation allowing successful resistance spot weld joint. However, the presence of a foil increases the part count, and is difficult to place during welding. Cold spray coating is a promising solid-state coating deposition technology used here to provide an enhanced interface to facilitate joining Al to Mg sheets by means of resistance spot welding. The ability of cold spray coating technology to deposit an intermediate layer on a substrate surface using powder material is shown to be beneficial in restricting the formation of the brittle intermetallic between Al and Mg. In this study, Ni powder has been successfully coated onto Al and Mg sheets. The Ni-coated coupons were then welded via resistance spot welding using optimized welding parameters. Successful welds were produced using 27 kA for 15 cycles in 2 pulses with 5 delay cycles between pulses. Metallurgical bonding between the Al, Mg, and Ni coating in the fusion zone were revealed by using scanning electron microscopy. It is shown that the bonding between the three elements prevents the formation of Al-Mg IMCs and restricts formation of deleterious IMCs. Fatigue test was then performed to evaluate the joint performance under cyclic load. The develop weld survived 2M cycles at maximum cyclic load of 1.28 kN at R=0.2. While there are no reports on fatigue of direct weld of Al/Mg, the monotonic tensile strength of lap shear samples of the developed weld is five-fold more than the direct Al/Mg welds, showing significant improvement.

**Keywords**: Dissimilar resistance spot welding; cold spray coating; Ni-coated interface; fatigue characterization.

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## 1. Introduction

Cold spray is a solid-state coating process where metal powders are accelerated to high velocities using compressed gas, enabling bonding without melting. This method avoids problems like oxidation and thermal degradation [1]. The technology has been widely used for coating but not previously applied to facilitate RSW between Al and Mg. The primary issue in Al-Mg direct welding, which led to very low weld strength of 0.83 kN[2], is the formation of brittle IMCs (e.g., $Al_3Mg_2$, $Mg_{17}Al_{12}$. Past attempts using interlayers like Zn and Ni foil had mixed success [2]–[4]. Ni is considered favorable due to its high melting point and tendency to form less brittle IMCs [5][6]. However, there is no data on Ni cold spray as an interlayer for RSW of Al-Mg joints, especially concerning fatigue and fracture behavior [7]. This study aims to fill that gap by obtaining a reliable dissimilar Al/Mg joint by adopting cold spray deposition technology and study the effect of the cyclic load on the welding.

## 2. Materials and methods

Pure Ni powder, produced by centerline under catalogue number SST-N5001, was cold sprayed onto Al 6022-T4 and Mg AZ31B-O substrates. The Ni powder has irregular shape and the average particle size is 5- 45 µm. The Al and Mg sheets were cut into 25×25 mm coupons with respective thicknesses of 1.5 mm and 2 mm to develop optimum weld parameters. Using a Centerline SST Series P system, Ni was deposited at 500 °C and 1.5 MPa with nitrogen as the process gas, and coating parameters shown in Table 1. Figure 1 shows the low pressure cold spray setup used in this study. The average coating thickness was ~110 µm on each side, yielding a 220 µm combined interlayer.

Coated samples were welded using a Medium-Frequency Direct Current (MFDC) welder that shows in Figure 2 (b). The optimized welding parameters were 27 kA current, two 15-cycle pulses, and a 5-cycle delay. Electrode force was 4 kN with asymmetric tip sizes for Al and Mg sides. Using these optimum parameters, lap-shear weld coupon, with dimensions and configuration shown in Figure 2 (a) was manufactured for strength and fatigue studies.

Overlap shear tensile tests were performed first using a 50 kN MTS testing frame that show in Figure 2 (c). Load-displacement behavior was recorded over multiple quasi-static tests.

To perform fatigue test, Instron 8874 machine, shown in Figure (d), has been used. This machine was equipped with an axial force capacity of ±25 kN. All tests were performed in load-control mode with minimum load to maximum load ratio of 0.2 (R=0.2). Test were declared failed at separation points, or stopped if no failure occurred at 2 million cycles, and were declared run-out.

Table 1: Cold spray coating parameters used for deposition of nickel on both the substrates

| Coating Materials | Ni on Mg | Ni on Al | | Ni on Mg | Ni on Al |
|---|---|---|---|---|---|
| **Flow Gas** | N2 | N2 | **Step Over (mm)** | 2.7 | 3 |
| **Gas Temperature (°C)** | 500 | 500 | **Stand-off Distance (mm)** | 12 | 12 |
| **Gas Pressure (MPa)** | 1.5 | 1.5 | **Nozzle Length (mm)** | 120 | 120 |
| **Powder Feed Rate (gr/min)** | 8 | 8 | **Nozzle Orifice Diameter (mm)** | 2 | 2 |
| **Nozzle Speed (mm/s)** | 25 | 25 | **Nozzle Exit Diameter (mm)** | 6.3 | 6.3 |
| **Type of Nozzle** | a converging–diverging de Laval UltiLife TM | | | | |


Figure 1: (a-b) SST Series P cold spray system with pressure, control, powder feeder, spray booth, and dust collector units, (c) the cold spray gun and nozzle during Ni-coating process of samples.

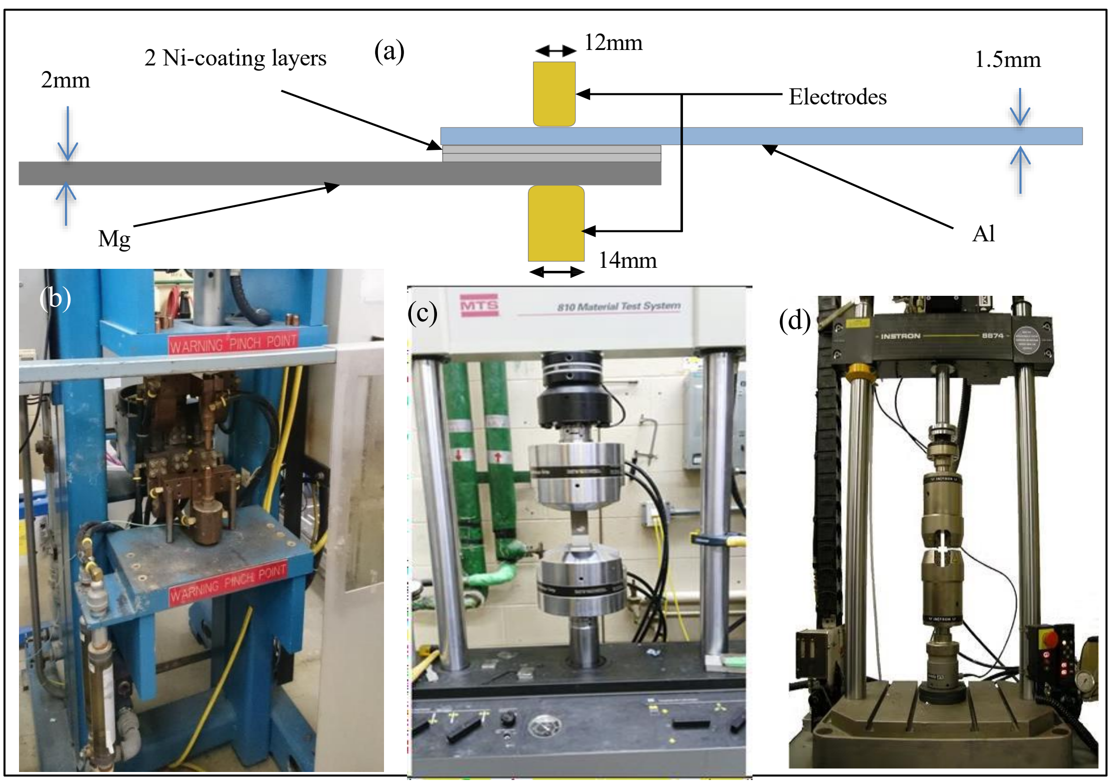


Figure 2: a) Schematic of sheets and welding arrangements. (b) MFDC spot welder with maximum direct current of 60kA and maximum electrode holding force of 25 kN. (c) The MTS 810 fatigue testing machine with ±50 kN. (d) Instron 8874 machine that operated to perform fatigue test.

## 3. Results and Discussion

The Ni coating showed initial micro-porosity and unevenness as depicted in Figure 3 (a), which improved post-welding due to heat-induced diffusion and consolidation, depicted in Figure 3 (b). Elemental analysis confirmed Ni, shown by yellow arrows in Figure (b), penetrated into the Al substrate. Metallography confirmed welded area formation between Ni layers with minimal IMC presence of the Al and Mg. Optimal welding parameters (27 kA, 2 pulses, 15 cycles) yielded the largest fusion zone ~12–15 mm.

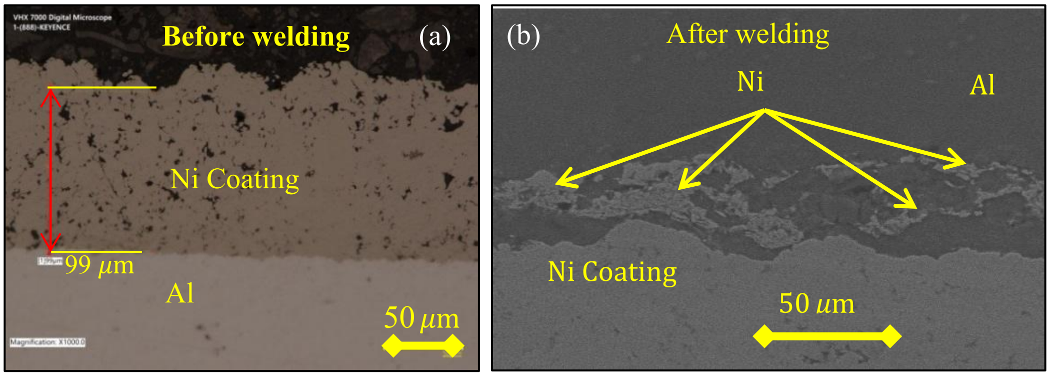


Figure 3: SEM images of the Al coated sheet before (a) and after (b) welding. (a) Shows a clear interface between coating and the substrate, porosity in coating, and uneven thickness of coating. (b) Shows a mixed Al-Ni region between coating and substrate, no porosity in the coating.

The fatigue performance of Ni-coated Al/Mg joints fabricated using cold spray-assisted RSW was evaluated through load-controlled fatigue tests. The results are illustrated in the load-life curve Figure 4, which plots the load amplitude in (kN) against the number of cycles to failure in log-log scale. This curve is critical for determining the fatigue strength of the welded joints.

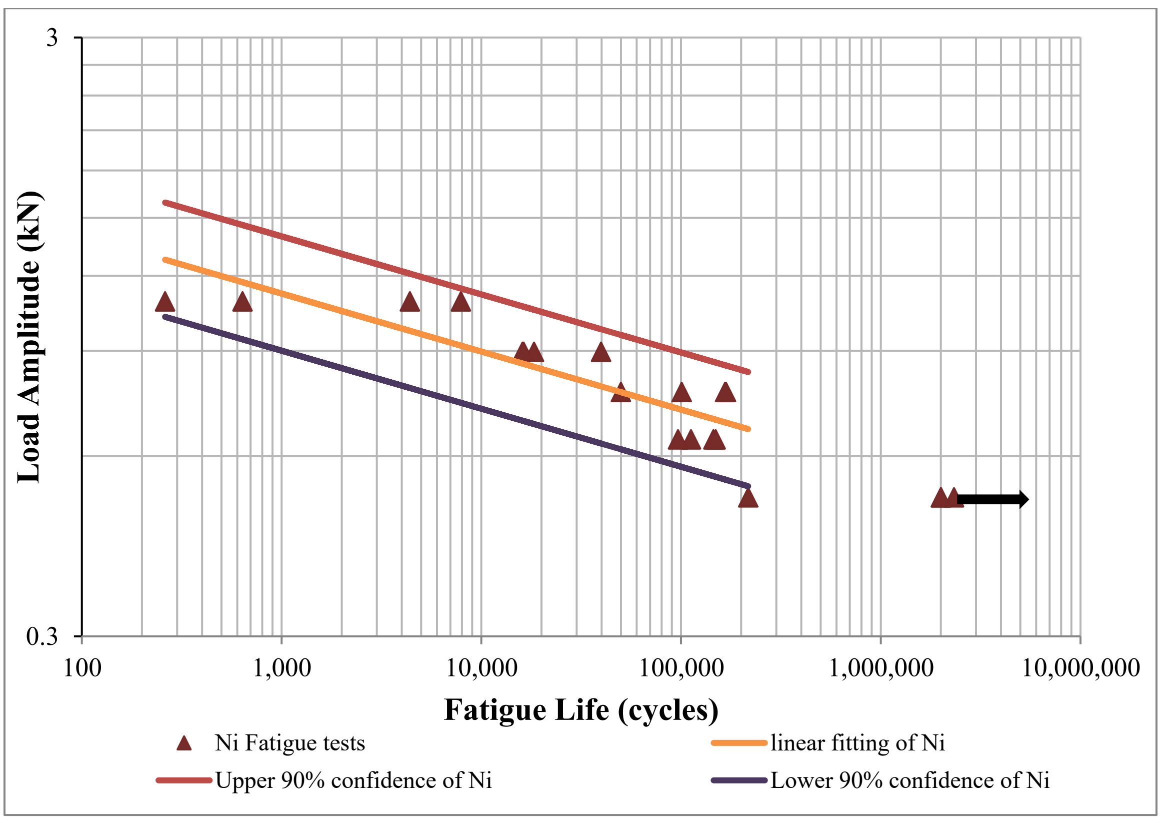


Figure 4: Load-life curve of Ni-coated Al/Mg RSW joints for R=0.2. The curve fitting slope = (-0.0968) and Intercept = 0.34. Linear fitting, 90% confidence and 90% reliability have been calculated.

Failure in most samples occurred through interfacial failure modes, with occasional sheet failure observed primarily on the Mg side. The fatigue test initiated with a maximum load equal to 40% of the monotonic strength of 4.2 kN, corresponding to a load amplitude of 0.64 kN. At this load, fatigue lives ranged between 96,000 and 149,000 cycles. Subsequent tests were performed at varying loads (maximum loads from 1.28 to 2.72 kN), yielding fatigue lives from

261 to 7,909 cycles at higher loads, and up to 2 million cycles at lower amplitudes. The fatigue strength, defined as the load amplitude below which failure does not occur for 2 million cycles, was identified to be around 0.512 kN.

The trend line through data point showing average fatigue life is shown in Figure 4. To account for confidence in the results obtained, the 90% confidence line is also plotted on the same graph as a high fidelity curve.

Two main failure mechanisms were observed which were interfacial and sheet failure mods. Interfacial failure was the predominant mode that further categorized into two modes. First failure at the interface between the Ni coating and the Mg substrate, and the second failure through the welded Ni coating itself. These modes are visually presented in Figure 5 (a, b).

Sheet Failure, occurred only on the Mg side, seen in two out of 20 samples as the final failure mode. However, 15 out of 20 samples showed cracking in the Mg sheet even if the final failure was interfacial. Figure 5 (c, d) illustrates sheet failure.

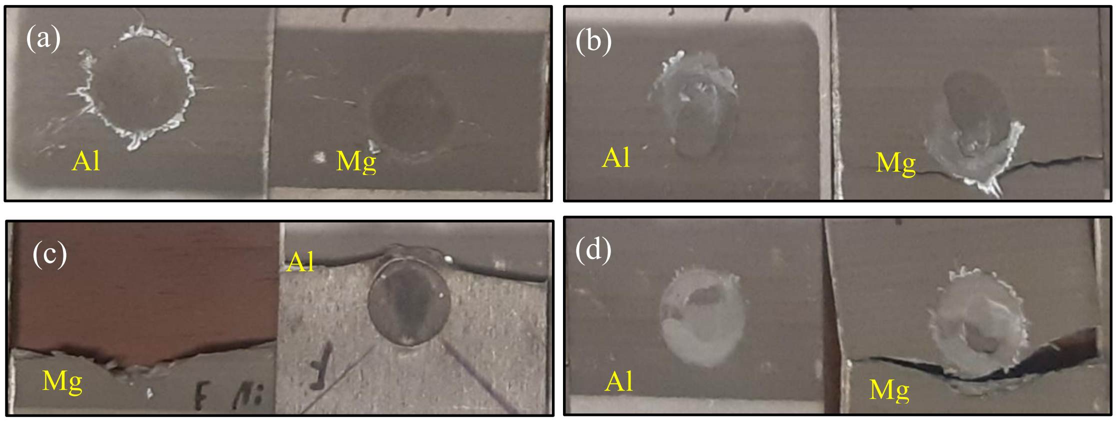


Figure 5: (a) shows interfacial mode of failure that occurred between the Ni-coat and the Mg substrate at max load 1.6 and fatigue life148881 cycles, (b) shows interfacial mode of failure that broke the welded Ni-coat at max load 1.6 and fatigue life 96591 cycles (c) shows the sheet failure mode max load 1.6 and fatigue life112213 cycles and (d) shows the combing failure mode with interfacial rapture at max load 1.28 and fatigue life 216854 cycles.

## 4. Conclusion

Cold spray coating has been employed as a facilitator for welding of Al/Mg dissimilar materials. It is shown that the strength of the weld exceeds the direct Al/Mg weld by five folds. Following conclusions may be drawn from this study on fatigue characteristics of the developed weld:

- Ni-coated Al/Mg RSW joints showed robust fatigue resistance.
- The fatigue strength was established at 0.512 kN load amplitude for 2 million cycles.
- Interfacial bonding strength, minimal IMC formation, and coating uniformity contributed significantly to their improved fatigue life.
- The mixed failure modes suggest strong mechanical performance where joint strength sometimes exceeded the base Mg sheet strength

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