Underwater Robotic Welding of Lap Joints with Sandwiched Reactive Multilayers: Thermal, Mechanical and Material Analysis

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ABSTRACT

Underwater welding using reactive materials pre-deposited at the junction surfaces as a self-contained, in-situ ignitable heat source mitigates external power and gas supply requirements. Consequently, lending itself to robotic implementation eliminating the cost along with health and safety hazards of human welder-divers. This project reports on lap joining of aluminum sheets with sandwiched commercial reactive Ni-Al multilayers that are perforated to allow for melt fusion under compression upon ignition, in saline and deionized water as well as air for comparison. Finite-element thermal simulations are employed to study the resulting welding temperature field and melt conditions. Infrared pyrometry and thermocouple measurements during welding were used to validate the computational simulations. The lap joints are subjected to standard shear testing, and comparable compliance, strength and toughness values of the welds are assessed for underwater and dry joints. Scanning electron (SEM) of the weld sections reveal rapidly melting and solidifying microstructures of the parent metal, with minimal melt flow and perfusion of nickel aluminide aggregates from the reacted multilayers, and no signs of cavitation.

**Figure Captions**

**Figure S1.** Igniting nanofoil in saline water (a) unreacted nanofoil (b) formation of bubbles around the multi wire cable and the change of nanofoil appearance to bronze (c) formation of black material on the surface of the nanofoil (d) ignition of the nanofoil.

**Table Captions**

**Table S1.** Toughness and maximum force results of 0.1 mm thick AA-1100 lap-joints. The lap-joints were created using 0.12 mm thick (2x60 μm) nanofoils with 4 mm hole while being compressed by a 45 kN force in ambient air.

**Table S2.** Toughness and maximum force results of 0.1 mm thick AA-1100 lap-joints. The lap-joints were created using 0.12 mm thick (2x60 μm) nanofoils with 4 mm hole while being compressed by a 12.5 kN force underwater.

**Table S3.** Toughness and maximum force results of 0.1 mm thick AA-1100 lap-joints. The lap-joints were created using 0.12 mm thick (3x40 μm) nanofoils with 2 mm hole while being compressed by 8 kN force in ambient air.

**Table S4.** Toughness and maximum force results of 0.2 mm thick AA-1100 lap-joints. The lap-joints were created using various combinations nanofoils with 2 mm hole while being compressed by 8 kN force in ambient air.

**Table S5.** Toughness and maximum force results of 0.2 mm thick AA-1100 lap-joints. The lap-joints were created using (2x60 μm) nanofoils with 4 mm hole while being compressed by 12.5 kN force in ambient air.



**Figure S1.** Igniting nanofoil in saline water (a) unreacted nanofoil (b) formation of bubbles around the multi wire cable and the change of nanofoil appearance to bronze (c) formation of black material on the surface of the nanofoil (d) ignition of the nanofoil.

**Table S1.** Toughness and maximum force results of 0.1 mm thick AA-1100 lap-joints. The lap-joints were created using 0.12 mm thick (2x60 μm) nanofoils with 4 mm hole while being compressed by a 45 kN force in ambient air.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Test No.** | **Maximum force (N)** | **Accepted/ Rejected Specimens** | **Fracture point** | **Toughness (MPa)** | **Toughness (KPa)** |
| 1 | 102.02 | Accepted | At joint/ at weld | 0.0167 | 16.70 |
| 2 | 65.86 | Rejected | At joint/ at weld | 0.0084 | 8.40 |
| 3 | 124.25 | Accepted | Along the ignited lip | 0.0387 | 38.70 |
| 4 | 97.49 | Accepted | Along the ignited lip | 0.0122 | 12.20 |
| 5 | 136.77 | Accepted | Along the ignited lip | 0.0145 | 14.50 |
| 6 | 130.42 | Accepted | Along the ignited lip | 0.0290 | 29.00 |
| 7 | 132.32 | Accepted | Along the ignited lip | 0.0183 | 18.30 |
| 8 | 143.95 | Accepted | Along the ignited lip | 0.0197 | 19.70 |
| 9 | 135.43 | Accepted | Along the ignited lip | 0.0170 | 17.00 |
| 10 | 142.62 | Accepted | Along the ignited lip | 0.0201 | 20.10 |
| 11 | 150.57 | Accepted | Along the ignited lip | 0.0284 | 28.40 |
| 12 | 132.32 | Accepted | Along the ignited lip | 0.0261 | 26.10 |
| 13 | 118.51 | Accepted | Along the ignited lip | 0.0183 | 18.30 |
| 14 | 98.46 | Accepted | Along the ignited lip | 0.0244 | 24.40 |
| 15 | 64.04 | Rejected | Along the ignited lip | 0.0068 | 6.80 |
| 16 | 88.08 | Rejected | At joint/ at weld | 0.0289 | 28.90 |
| 17 | 11.77 | Rejected | At joint/ at weld | 0.0006 | 0.56 |
| 18 | 131.72 | Accepted | Along the ignited lip | 0.0300 | 30.00 |
| 19 | 123.37 | Accepted | Along the ignited lip | 0.0276 | 27.60 |
| **Average Value** | 126.68 |  |  | **Average Value** | 22.73 |
| **Maximum** | 150.57 |  |  | **Maximum** | 38.70 |
| **Minimum** | 97.49 |  |  | **Minimum** | 12.20 |
| **Standard deviation** | 15.80 |  |  | **Standard deviation** | 6.93 |

**Table S2.** Toughness and maximum force results of 0.1 mm thick AA-1100 lap-joints. The lap-joints were created using 0.12 mm thick (2x60 μm) nanofoils with 4 mm hole while being compressed by a 12.5 kN force underwater.

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| --- | --- | --- | --- | --- | --- |
| **Test No.** | **Maximum force (N)** | **Accepted/ Rejected Specimens** | **Fracture point** | **Toughness (MPa)** | **Toughness (kPa)** |
| 1 | 132.73 | Accepted | Along the ignited lip | 0.0224 | 22.40 |
| 2 | 75.52 | Rejected | Along the ignited lip | 0.0263 | 26.30 |
| 3 | 146.62 | Accepted | Along the ignited lip | 0.0205 | 20.50 |
| 4 | 146.62 | Accepted | Along the ignited lip | 0.0201 | 20.10 |
| 5 | 128.37 | Accepted | Along the ignited lip | 0.0189 | 18.90 |
| 6 | 38.18 | Rejected | At the weld (Pull out) | 0.0027 | 2.70 |
| 7 | 65.19 | Rejected | At the weld (Pull out) | 0.0317 | 31.70 |
| 8 | 87.29 | Rejected | At the weld (Pull out) | 0.0261 | 26.10 |
| 9 | 71.49 | Rejected | Along the ignited lip | 0.0100 | 10.00 |
| 10 | 58.33 | Rejected | Along the ignited lip | 0.0120 | 12.00 |
| 11 | 2.74 | Rejected | Along the ignited lip | 0.0003 | 0.29 |
| 12 | 31.95 | Rejected | Along the ignited lip | 0.0008 | 0.84 |
| 13 | 29.10 | Rejected | Along the ignited lip | 0.0013 | 1.30 |
| 14 | 138.57 | Accepted | Along the ignited lip | 0.0473 | 47.30 |
| 15 | 139.05 | Accepted | Along the ignited lip | 0.0264 | 26.40 |
| 16 | 6.27 | Rejected | At the weld (Pull out) | 0.0005 | 0.50 |
| 17 | 49.40 | Rejected | At the weld (Pull out) | 0.0187 | 18.70 |
| 18 | 60.46 | Rejected | At the weld (Pull out) | 0.0033 | 3.30 |
| **Average Value** | 138.66 |  |  | **Average Value** | 25.93 |
| **Maximum** | 146.62 |  |  | **Maximum** | 47.30 |
| **Minimum** | 128.37 |  |  | **Minimum** | 18.90 |
| **Standard deviation** | 6.68 |  |  | **Standard deviation** | 9.85 |

**Table S3.** Toughness and maximum force results of 0.1 mm thick AA-1100 lap-joints. The lap-joints were created using 0.12 mm thick (3x40 μm) nanofoils with 2 mm hole while being compressed by 8 kN force in ambient air.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Test No.**  | **Maximum force (N)** | **Accepted/ Rejected Specimens** | **Fracture point**  | **Toughness (MPa)** | **Toughness (KPa)** |
| 1 | 128.26 | Accepted | Along the ignited lip  | 0.0172 | 17.20 |
| 2 | 141.60 | Accepted | Along the ignited lip  | 0.0195 | 19.50 |
| 4 | 136.79 | Accepted | Along the ignited lip  | 0.0326 | 32.60 |
| 5 | 94.18 | Rejected | Along the ignited lip  | 0.0212 | 21.20 |
| 6 | 131.26 | Accepted | Along the ignited lip  | 0.0215 | 21.50 |
| 7 | 123.49 | Accepted | Along the ignited lip  | 0.0233 | 23.30 |
| 8 | 131.89 | Accepted | Along the ignited lip  | 0.0260 | 26.00 |
| 9 | 113.04 | Accepted | Along the ignited lip  | 0.0268 | 26.80 |
| 10 | 134.13 | Accepted | Along the ignited lip  | 0.0183 | 18.30 |
| 11 | 140.85 | Accepted | Along the ignited lip  | 0.0169 | 16.90 |
| 12 | 118.43 | Rejected | Along the ignited lip  | 0.0197 | 19.70 |
| 13 | 128.73 | Accepted | Along the ignited lip  | 0.0243 | 24.30 |
| 14 | 129.87 | Accepted | Along the ignited lip  | 0.0177 | 17.70 |
| 15 | 135.69 | Accepted | Along the ignited lip  | 0.0151 | 15.10 |
| 16 | 122.55 | Accepted | Along the ignited lip  | 0.0197 | 19.70 |
| 17 | 107.77 | Rejected | Along the ignited lip  | 0.0161 | 16.10 |
| 18 | 137.66 | Accepted | Along the ignited lip  | 0.0242 | 24.20 |
| 19 | 116.99 | Rejected | Along the ignited lip  | 0.0191 | 19.10 |
| 20 | 120.05 | Accepted | Along the ignited lip  | 0.0155 | 15.50 |
| **Average**  | 130.39 |  |  | **Average**  | 21.24 |
| **Maximum** | 141.60 |  |  | **Maximum** | 32.60 |
| **Minimum** | 94.18 |  |  | **Minimum** | 15.10 |
| **Standard deviation**  | 7.74 |  |  | **Standard deviation**  | 4.74 |

**Table S4.** Toughness and maximum force results of 0.2 mm thick AA-1100 lap-joints. The lap-joints were created using various combinations nanofoils with 2 mm hole while being compressed by 8 kN force in ambient air.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Test No.**  | **Maximum force (N)** | **Accepted/ Rejected Specimens** | **Fracture point**  | **Toughness (MPa)** | **Toughness (KPa)** |
| 1 | 339.46 | Accepted | Along the ignited lip  | 0.0583 | 58.30 |
| 2 | 295.58 | Accepted | Along the ignited lip  | 0.0591 | 59.10 |
| 3 | 300.71 | Accepted | Along the ignited lip  | 0.0630 | 63.00 |
| 4 | 148.65 | Rejected | At the weld (Pull out)  | 0.0086 | 8.60 |
| 5 | 287.07 | Accepted | Along the ignited lip  | 0.0455 | 45.50 |
| 6 | 325.4 | Accepted | Along the ignited lip  | 0.0683 | 68.30 |
| 7 | 322.31 | Accepted | Along the ignited lip  | 0.0591 | 59.10 |
| 8 | 257.82 | Rejected | Along the ignited lip  | 0.0459 | 45.90 |
| 9 | 245.79 | Rejected | Along the ignited lip  | 0.0424 | 42.40 |
| 10 | 242.3 | Rejected | At the weld (Pull out)  | 0.0229 | 22.90 |
| 11 | 294.34 | Accepted | Along the ignited lip  | 0.0494 | 49.40 |
| 12 | 285.53 | Accepted | Along the ignited lip  | 0.0511 | 51.10 |
| 13 | 305.31 | Accepted | Along the ignited lip  | 0.0749 | 74.90 |
| 14 | 329.28 | Accepted | Along the ignited lip  | 0.0612 | 61.20 |
| 15 | 301.93 | Accepted | Along the ignited lip  | 0.0524 | 52.40 |
| 16 | 317.55 | Accepted | Along the ignited lip  | 0.0665 | 66.50 |
| 17 | 298.62 | Accepted | Along the ignited lip  | 0.0539 | 53.90 |
| 18 | 336.08 | Accepted | Along the ignited lip  | 0.0750 | 75.00 |
| 19 | 240.2 | Rejected | At the weld (Pull out)  | 0.0623 | 62.30 |
| 20 | 279.89 | Accepted | Along the ignited lip  | 0.0540 | 54.00 |
| 21 | 323.81 | Accepted  | Along the ignited lip  | 0.0612 | 61.20 |
| **Average Value** | 308.93 |  |  | **Average Value** | 59.56 |
| **Maximum** | 339.46 |  |  | **Maximum** | 75.00 |
| **Minimum** | 279.89 |  |  | **Minimum** | 45.50 |
| **Standard deviation**  | 18.24 |  |  | **Standard deviation**  | 8.31 |

**Table S5.** Toughness and maximum force results of 0.2 mm thick AA-1100 lap-joints. The lap-joints were created using (2x60 μm) nanofoils with 4 mm hole while being compressed by 12.5 kN force in ambient air.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Test No.**  | **Maximum force (N)** | **Accepted/ Rejected Specimens**  | **Fracture point**  | **Toughness (MPa)** | **Toughness (KPa)** |
| 1 | 130.93 | Rejected | At the weld (Pull out)  | 0.0063 | 6.30 |
| 2 | 311.42 | Accepted | Along the ignited lip  | 0.0568 | 56.80 |
| 3 | 279.25 | Accepted | Along the ignited lip  | 0.0509 | 50.90 |
| 4 | 301.81 | Accepted | Along the ignited lip  | 0.059 | 59.00 |
| 5 | 35.04 | Rejected | At the weld (Pull out)  | 1.30E-03 | 1.30 |
| 6 | 344.88 | Accepted | Along the ignited lip  | 0.0921 | 92.10 |
| 7 | 292.52 | Accepted | Along the ignited lip  | 0.0559 | 55.90 |
| 8 | 246.46 | Accepted | Along the ignited lip  | 0.0428 | 42.80 |
| 9 | 141.14 | Rejected | Along the ignited lip  | 0.0101 | 10.10 |
| 10 | 161.94 | Rejected | At the weld (Pull out)  | 0.0082 | 8.20 |
| 11 | 290.50 | Accepted | Along the ignited lip  | 0.0535 | 53.50 |
| 12 | 152.90 | Rejected | At the weld (Pull out)  | 0.0921 | 92.10 |
| 13 | 299.38 | Accepted | Along the ignited lip  | 0.067 | 67.00 |
| **Average Value** | 295.78 |  |  | **Average Value** | 59.75 |
| **Maximum** | 344.88 |  |  | **Maximum** | 92.10 |
| **Minimum** | 246.46 |  |  | **Minimum** | 42.80 |
| **Standard deviation**  | 26.10 |  |  | **Standard deviation**  | 13.82 |