



## Focus Hope Industries, Inc.

1400 Oakman Blvd., Detroit, MI 48238

CAGE 6KWK9, DUNS 078270052

**TITLE:** A preliminary report on the strength and metallography of a bimetallic friction stir weld joint between AA6061 and MIL-DTL-46100E High Hardness steel armor.

### **ABSTRACT**

One half inch thick plates of 6061-T6 aluminum alloy and High Hardness steel armor (MIL-STD-46100) were successfully joined by the friction stir welding (FSW) process using a tungsten-rhenium stir tool. Process parameter variation experiments, which included inductive pre-heating, tool design geometry, plunge and traverse rates, tool offset, spindle tilt, and rotation speed, were conducted to develop a parameter set which yielded a defect free joint. Laboratory tensile tests exhibited a maximum yield stress 204 MPa, which exceeds the strength of a comparable all-AA6061 FSW joint. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDAX) analysis also show atomic diffusion at the material interface region.

### **COUPON FABRICATION AND TENSILE TESTS**

Using an existing FSW coupon fixture mounted to a multi-axes friction stir welder (Transformation Technologies, Inc. GG1 Series), ½-inch thick x 1-inch wide x 8-inches long bars of AA6061-T6 aluminum alloy and high hardness steel (HHS, MIL-STD-46100E High Hardness Wrought Armor) material were subjected to a series of process parameter development experiments. Table 1 lists the specific process parameters that were varied during this study.

Table 1 – FSW Process Parameters

Parameter	Range
Inductive heating	
Power - pre-heat, plunge/dwell, traverse (kW)	2.5 - 7.5
Time - pre-heat, plunge/dwell, traverse (min)	0.5 - 3.0
Plunge/Dwell	
Plunge tool rotation speed (RPM)	1000
Plunge rate (mm/min)	6 - 30
Dwell tool rotation speed (RPM)	300 - 600
Dwell duration (min)	2 - 3
Traverse	
Tool rotation speed (RPM)	250 - 500
Traverse rate (mm/min)	8 - 50
FSW tool	
Pin diameter (in)	0.3 - 0.5
Pin pitch (degrees)	10.5 - 12
Spindle tilt axis (degrees)	2 - 3
Rotation direction	CW/CCW
Bimetallic offset (mm)	0 - 2.5

To potentially reduce aggressive tool wear observed during another prior FSW study involving the HHS material, an inductive heating system was initially tried as a method to soften the steel material supplemental to the inherent frictional heating of the FSW process. However because of the small bimetallic tool offsets (and therefore minimal tool-to-steel interference) used in this study and adverse effects of the additional heat on the relatively lower solidus point aluminum material, the pre-heating system was removed from the parameter matrix but may be required during future experiments.



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Initial parameter sets expectedly produced unacceptable weld quality with excessive surface flash and considerable internal defects. After a series of parameter variations, the weld flash was reduced and externally-visible weld voids were eliminated. During a second series of parameter variations, saw-cut joint cross sections were used to determine internal weld quality for each parameter set and further parameters adjustments were made to eliminate weld voids and improve visual weld quality. Finally, a series of welds was made with each weld having a parameter variation of traverse speed or bimetallic tool offset within the process envelop established by the earlier series with all other process parameters common. Several tensile test specimens were extracted from each weld and then tensile tested using an Instron Model 5982 testing machine. Average tests results for each final series parameter set are shown in Table 2.

Table 2 – Tensile Test Results (MPa)

250 rpm				300 rpm			
Traverse Speed (mm/min)	Yield Strength (MPa)			Traverse Speed (mm/min)	Yield Strength (MPa)		
	Tool Offset (mm)				Tool Offset (mm)		
	0.5 mm	1.0 mm	1.5 mm		0.5 mm	1.0 mm	1.5 mm
10		57.31		10	---	122.00	113.57
20	156.83	146.08		20	125.44	138.48	128.25
30		138.78		30	113.20	120.36	134.96
40			204.48	40	118.84	86.06	129.28
50				50			176.02

## METALLURGICAL ANALYSIS

A metallurgical analysis specimen was extracted and prepared from a representative joint sample. Figure 1 shows two levels of magnification of a section of the bimetallic joint using a scanning electron microscope (SEM). These images show the intermetallic diffusion of the aluminum material (dark gray) into the HHS (light gray due to etching solution).

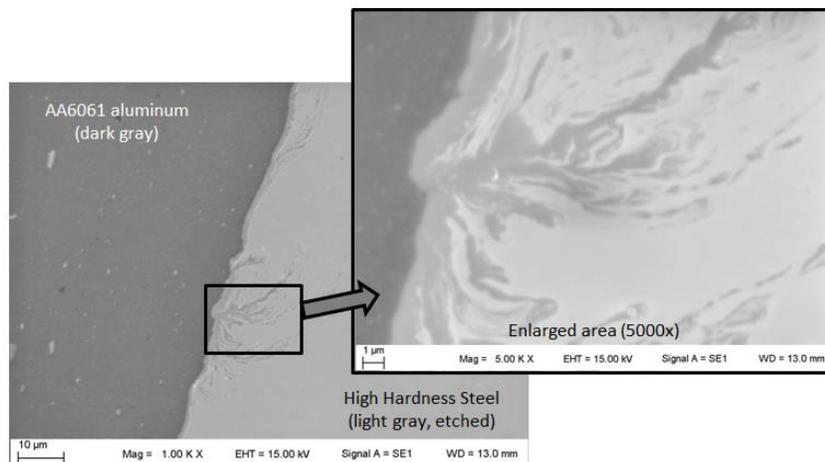


Figure 1 – Scanning Electron Microscope image showing atomic diffusion



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### CONCLUSIONS

Our analysis indicates metallurgical bonding between the aluminum and steel alloys has occurred with an atomic diffusion zone approximately 2-5  $\mu\text{m}$  wide at the bimetallic interface. Relative to the unwelded constituent materials the transverse tensile strength of the bimetallic FSW joint is significantly weaker, approximately half of the weakest unwelded base material AA6061. However relative to the comparative weld joint strengths of all-aluminum weld joints (Table 3), the tensile strength of the bimetallic friction stir weld is 65% stronger than that of a fusion-welded AA6061 joint and 5% stronger than a friction stir-welded AA6061 joint.

Table 3 – Comparing Material and Weld Joint Strength

MATERIAL / WELD TYPE	Yield Strength (MPa)
AA6061-T6511	
base material	345 <sup>a</sup>
arc/fusion welded	124 <sup>b</sup>
FSW	194 <sup>c</sup>
High Hardness Steel (HHS)	
base material	1034 <sup>d</sup>
arc/fusion welded	tbd
AA6061/HHS FSW joint	204 <sup>e</sup>

<sup>a</sup> Kaiser Aluminum Certified Test Report, Lot #Z00222015

<sup>b</sup> AWS Welding Handbook, Vol. 3, Material and Applications, p. 13

<sup>c</sup> at FHI April 2011

<sup>d</sup> ATI Allegheny Ludlum 500-MIL™

<sup>e</sup> at FHI Nov 2012

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