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Transverse-Weld Tensile Properties of a New Al-4Cu-2Si Alloy as Filler Metal

K. Sampath

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AA2195, an Al-Cu-Li alloy in the T8P4 age-hardened condition, is a candidate aluminum armor for future combat vehicles, as this material offers higher static strength and ballistic protection than current aluminum armor alloys. However, certification of AA2195 alloy for armor applications requires initial qualification based on the ballistic performance of welded panels in the as-welded condition. Currently, combat vehicle manufacturers primarily use gas metal arc welding (GMAW) process to meet their fabrication needs. Unfortunately, a matching GMAW consumable electrode is currently not commercially available to allow effective joining of AA2195 alloy. This initial effort focused on an innovative, low-cost, low-risk approach to identify an alloy composition suitable for effective joining of AA2195 alloy, and evaluated transverse-weld tensile properties of groove butt joints produced using the identified alloy. Selected commercial off-the-shelf (COTS) aluminum alloy filler wires were twisted to form candidate twisted filler rods. Representative test weldments were produced using AA2195 alloy, candidate twisted filler rods and gas tungsten arc welding (GTAW) process. Selected GTA weldments produced using Al-4wt.%Cu-2wt.%Si alloy as filler metal consistently provided transverse-weld tensile properties in excess of 275 MPa (40 ksi) UTS and 8% El (over 25 mm gage length), thereby showing potential for acceptable ballistic performance of as-welded panels. Further developmental work is required to evaluate in detail GMAW consumable wire electrodes based on the Al-Cu-Si system containing 4.2-5.0 wt.% Cu and 1.6-2.0 wt.% Si.

Keywords Al-Cu-Li alloy, Al-Cu-Si alloy, aluminum armor, ballistic performance, consumable development, transverse-weld tensile properties, weldalite aluminum alloy, welded panels

1. Introduction

Aluminum armor is used extensively in combat vehicles primarily to minimize weight for a given level of force protection, thus enhancing vehicle mobility, serviceability while allowing life cycle cost savings. Current aluminum armor alloys include Al-Mg alloy AA5083-H115, and Al-Zn-Mg alloys such as AA7017-T651, AA7018-T7651, AA7020-T651 and AA7039-T651. Of these aluminum alloys, Al-Mg armor is non-heat treatable, while Al-Zn-Mg armor responds to natural aging. Both major and minor alloy elements in aluminum armor alloys substitute for aluminum, and provide solid solution strengthening and/or precipitation strengthening.

Combat vehicle manufacturers prefer the above armor alloys as no post-weld heat treating is required, thus allowing significant manufacturing cost savings. In fact, Al-Zn-Mg alloys are particularly attractive as they show only a minimal tendency to overage during or following welding. Other candidate aluminum armor alloys (Ref 1-6) include AA2219-T851 (Al-5.8 to 6.8 wt.% Cu-0.2 to 0.4 wt.% Mn) and AA2519-T87 (Al-5.5 to 6.4 wt.% Cu-0.05 to 0.04 wt.% Mg-0.10 to 0.5 wt.% Mn) that have about 6 wt.% alloy content. These aluminum alloys, based on the Al-Cu system, offer higher static strength in the age-hardened condition.

Weldalite[1] series aluminum alloys (Ref 7-11) were developed at Martin Marietta Laboratories (now Lockheed Martin Corporation). These alloys belong to the heat-treatable Al-Cu-Li alloy family, with minor but significant additions of Ag and Mg to stimulate metallurgical precipitation. One of these alloys, AA2195 (Al-4.0wt.%Cu-1.0wt.%Li-0.3wt.%Ag-0.3wt.%Mg-0.14wt.%Zr, nominal) has a total alloy content of about 6 wt.%. This chemical composition offers attractive short-transverse properties (Ref 11) in the T8P4 age hardened condition. A typical T8P4 treatment schedule consists of solutionizing at about 500 °C (945 °F) for 1 h, followed by quenching to ambient, 2.75-4.5% cold stretching, and artificial aging at about 150 °C (300 °F) for 36 h. Following heat treatment, both Al_2CuLi (T_1) and Al_2Cu (Θ') precipitates form and provide precipitation strengthening.

Alloy AA2195 sheet (typically under 12 mm thick) and plate (typically over 12 mm thick) processed to a T8P4 condition are commonly offered with the following nominal tensile properties (Ref 12): 590 MPa (85 ksi) ultimate tensile strength (UTS), 550 MPa (80 ksi) 0.2% yield strength (YS) and 8-10 percent elongation (%El).

Table 1 compares the nominal tensile properties of AA2195 with five current and two other candidate aluminum armor

Gas tungsten arc weld produced using AA2195 as base metal and a new Al-4Cu-2Si alloy as filler metal provides acceptable transverse-weld tensile properties in the as-welded condition showing potential for exceeding the minimum ballistic performance requirements for welded aluminum armor.

K. Sampath, Marietta, GA 30062. Contact e-mail: rs127@yahoo.com.

[1]Weldalite® is a Registered Trademark of Lockheed Martin Corporation.

Table 1 Nominal tensile properties of current and candidate aluminum armor alloys

No.	Alloy type and temper	UTS, MPa (ksi)	0.2% YS, MPa (ksi)	El, %
1	AA5083-Hl15	360 (52)	290 (42)	9
2	AA7017-T651	485 (70)	430 (62)	12
3	AA7018-T765 l	360 (52)	300 (44)	13
4	AA7020-T6S1	400 (58)	360 (52)	12
5	AA7039-T65 l	462 (67)	400 (58)	12
6	AA2219-T851	460 (66)	350 (51)	10
7	AA2519-T87	500 (72)	460 (67)	12
8	AA2195-T8P4	585 (85)	550 (80)	10

alloys. As shown in Table 1, in the T8P4 condition, AA2195 alloy offers higher static strength at room temperature compared to current and other candidate aluminum armor alloys. Thus, AA2195 alloy is expected to offer superior ballistic protection. Currently both AA2195 and AA2519 alloys are candidate armor for future combat vehicles such as the expeditionary fighting vehicle (EFV), formerly advanced amphibious assault vehicle (AAAV) of U.S. Marine Corps.

Combat vehicle manufacturers primarily use gas metal arc welding (GMAW) process to fabricate aluminum armor. In the future, friction stir welding process is expected to replace GMAW process in the domestic manufacturing of light combat vehicles. To certify materials for armor applications, combat vehicle manufacturers require initial qualification based on the ballistic performance of welded panels in their as-welded condition. The ballistic shock test involves firing an aluminum 1100-O slug (75 mm diameter by 150 mm long) into the welded panel at a prescribed velocity, targeting primarily the weld and the adjacent heat affected zone (HAZ), thus subjecting them to a high-energy impact and a high strain rate. Acceptance and certification allow up to 300 mm of total accumulated cracking on the front and back sides of the welded panel (Ref 13). The ballistic shock test is quite expensive to perform, and commonly requires logistical support of the military establishment to carry out the test. To obviate a frequent need for ballistic shock testing, technologists often try to (cor)relate ballistic performance with some other properties that can be evaluated using one or more routine tests, and require the weld to exceed certain threshold values.

As a rule of thumb, ballistic performance of a welded panel is related to the transverse-weld tensile properties (Ref 5), particularly UTS and tensile ductility. In terms of required toughness, a minimum of 50% joint efficiency[2] and 4% tensile elongation over 50 mm gage length (or 8% El over 25 mm gage length) are considered threshold values for achieving adequate ballistic performance of welded panels. The above values are based on transverse-weld tensile properties of GMA weldments in current aluminum armor alloys, and friction stir weldments in AA2519-T87 (Ref 5). These weldments have shown acceptable performance in subsequent ballistic shock testing.

It is well known that GMAW process uses a wire electrode that is consumed during welding to form the weld puddle that subsequently solidifies to form the as-deposited weld metal. In general, the chemical composition of the consumable wire electrode more or less matches the chemical composition of the base metal. The total alloy content of the consumable electrode often marginally exceeds the total alloy content of the base metal. All the same, the chemical composition of individual elements stays within the chemical composition range for respective individual elements specified for the base metal.

Commonly, the "matching welding consumable" for a given aluminum alloy provides a minimal sensitivity to weld cracking, good resistance to weld corrosion, color match after anodizing when anodizing is appropriate, and an ability to offer acceptable weld strength (that either "undermatches" or "overmatches" the base metal) preferably in the as-welded condition, naturally aged condition, or occasionally following an age-hardening treatment. As one would expect, because manufacturing operations connected with post-weld heat treatment of large structures add significantly to overall cost of fabrication, manufacturers of large structures such as combat vehicles often require welding consumables that consistently meet or exceed transverse-weld mechanical property requirements in the as-welded condition, or in the naturally aged condition.

AWS A5.10 Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods (Ref 14) recommends that, for general purpose welding, alloy AA5083 is welded with consumables belonging to the Al-Mg system such as ER5183, ER5356 or ER5556 that contain about 4.3-5.5 wt.% Mg. For joining alloy AA7039, AWS A5.10 recommends using ER5356, or consumables belonging to the Al-Si system such as ER4043 containing 4.5-6.0 wt.% Si. As a general purpose specification, AWS A5.10 does not offer specific recommendations on bare aluminum and aluminum-alloy welding electrodes and rods suitable for joining AA7017, AA7018 or AA7020 armor.

Furthermore, AWS A5.10 requires electrode manufacturers to qualify aluminum welding consumables based primarily on results of chemical analysis, radiographic test and bead-on-plate test, but does not require transverse-weld tensile or all-weld metal tensile test results. Nevertheless, aluminum welding consumable manufacturers often provide baseline transverse-weld tensile properties data to enable selection of appropriate welding consumables for various general purpose applications involving selected base materials. Welding consumable manufacturers often provide data sheet (Ref 15, 16) that show ER5183, ER5356, ER5556 or ER4043 welding consumables to exhibit transverse-weld tensile properties ranging from 140 to 325 MPa (20-47 ksi) UTS and 4-17% El depending on base metal type, weld joint (edge) preparation, weld energy input, etc.

Commonly, one would observe that at a low weld energy input, the highly alloyed filler metals provide highest strength weld metals, yet undermatched relative to the base metal, that simultaneously offer high weld ductility due to the presence of refined weld metal grains. However, when the weld energy input is progressively increased, the same highly alloyed filler metal would provide progressively lower strength weld metals with reduced weld ductility, because of the presence of relatively coarser weld metal grains and coarser microstructural constituents.

Use of very high weld energy input conditions could lead to excessively undermatched weld metal systems. In defect-free undermatched welds in the as-welded condition, transverse-weld tensile properties primarily depend on weld metal chemical composition (alloy content) and grain size. However,

[2]Joint efficiency is a ratio of the UTS of the weld (as determined from a transverse-weld tensile test or an all-weld metal tensile test) to the UTS of the base metal. A joint efficiency less than 100% indicates an "undermatched" weldment, while a joint efficiency over 100% indicates an "overmatched" weldment. Commonly, most aluminum weldments are undermatched in the as-welded condition.

various associated factors including weld joint preparation, root gap, welding conditions, number of weld passes, base metal dilution, base metal condition, width of the HAZ, etc., may affect the as-welded transverse-weld tensile properties, and lead the tensile fracture away from the fusion zone (FZ), to the FZ/HAZ interface, HAZ and occasionally to the unaffected base metal. Frequently, the interplay of the above numerous factors does not allow a meaningful comparison or statistical analysis of the as-welded transverse-weld tensile properties of different weldments made using either the same filler metal or the same base alloy.

2. Filler Metal Development for Weldalite Alloys

Filler metal development for aluminum alloys is quite complex. In simple terms, it involves the following four steps: (1) identifying prospective chemical compositions; (2) processing of candidate compositions into wire electrodes and/or wire rods; (3) making of test weldments; and (4) evaluating the test weldments (in the as-welded condition or following post-weld heat treatment) for sensitivity to weld cracking, resistance to weld corrosion, color match after anodizing when anodizing is appropriate, and an ability to offer acceptable weld strength and ductility.

The above steps are inherently expensive. Progress of successive steps traditionally relies on the results of trial and error experimentation. To reduce associated risk and expenses in developing low-cost, low-risk solutions, one could consider using innovative efforts that consolidate existing knowledge, and reach beyond existing knowledge.

In taking a lead to facilitate effective joining of Weldalite alloys, ALCOA developed a new welding alloy containing about 4.5-6.5 wt.% Cu, 0.2-1.5 wt.% Mg, 0.8-2.5 wt.% Li, and 0.07-0.20 wt.% Ti (Ref 17). This welding consumable provided GTA weldments characterized by an acceptable resistance to weld cracking, good resistance to weld corrosion, and an ability to develop weld strength in excess of 240 MPa or 35 ksi UTS following natural aging. A minimum of 0.2-0.7 wt.% Mg addition was considered necessary to allow a natural aging response.

Martin Marietta Laboratories developed a "magnesium-free" yet matching Al-3 to 7 wt.% Cu-0.4 to 1.8 wt.% Li-0 to 0.8 wt.% Ag alloy composition (Ref 18) specifically suitable for joining of Weldalite alloys. Depending on GTA welding conditions and post-weld heat treatment, this Al-Cu-Li alloy composition provided transverse-weld tensile properties of about 352 MPa (51 ksi) UTS and 7% El (over 25 mm gage length). As the transverse-weld tensile properties were obtained from specimens removed from weldments produced with a square-butt joint preparation, the latter possibly allowed extensive base metal dilution.

Unfortunately, neither of the above two welding consumable systems is currently commercially available to allow one to evaluate these filler alloys for effective joining of AA2195 alloy. Instead, for certain components made from AA2195 alloy, such as the External Tank for the Space Shuttle, welding consumable belonging to either ER2319 (Al-Cu system) or ER4043 (Al-Si system) is used (Ref 19). Prior GMAW procedure development work has indicated that individually neither ER2319 nor ER4043 provides weld metals with acceptable ductility in AA2195, in either as-welded or post-weld aged condition (Ref 20).

Thus, none of the above weld filler metal systems has the potential to consistently offer over 275 MPa or 40 ksi UTS and a minimum 8% El (over 25 mm gage length) in the as-welded condition when used for joining AA2195 alloy. Therefore, the current effort focused on an innovative, low-cost, low-risk approach to identify an alloy composition suitable for effective joining of AA2195 alloy, and evaluated as-welded transverse-weld tensile properties of groove butt joints produced using the identified alloy.

3. Objectives

The objectives of this effort were to facilitate ballistic performance of a groove butt joint by demonstrating minimum transverse-weld tensile properties of 275 MPa or 40 ksi UTS—corresponding to about 50% joint efficiency in AA2195—and 4% El (in 50 mm gage length) or 8% El (in 25 mm gage length) in the as-welded condition.

4. Innovative Approach

As is well known, GMAW process uses a consumable wire electrode while gas tungsten arc welding (GTAW) process uses filler rods (straight lengths) for manual welding and filler wires for mechanized or automatic welding. The same welding consumable type is commonly used to produce both GMA and GTA weldments in a given material. GMA welds, particularly pulsed GMA welds, are produced at a relatively lower energy input, steeper temperature gradient, higher melting efficiency and weld cooling rate over corresponding GTA weldments. Therefore, GMA weldments often show increased strength and ductility due to their refined weld metal grains and a minimal HAZ. In other words, in evaluating the properties of a weldment in a base material, one could perform the initial evaluation and qualification of a candidate alloy using GTAW process, and thus substantially reduce the risk of subsequent qualification of the same alloy as a consumable electrode for GMAW process. On this basis, one could use GTAW process to quickly identify an appropriate chemical composition range for a new welding consumable (filler metal) system for joining AA2195 alloy that could be later used for developing and rigorously certifying a GMAW consumable electrode.

Secondly, identifying an appropriate chemical composition range for an alternate aluminum alloy (consumable) system using traditional trial-and-error methods is risky, time consuming and expensive. Risk of failure of a composition is rather significant as a candidate composition has to meet or exceed requirements for strength, cracking resistance, corrosion resistance and color match after anodizing. Instead of the traditional trial-and-error methods, one could consider using innovative, inexpensive, and risk-averse methods to rapidly identify an appropriate chemical composition range.

5. Experimental Work

As an initial effort to evaluate the suitability of a new Al-Cu-Si system, this experimental work used an innovative method: at first, the author selected certain commercial off-the-shelf

(COTS) aluminum alloy filler wires belonging to two different aluminum filler wire systems, and twisted them to form candidate twisted filler rods; produced representative test weldments in AA2195 alloy using the candidate twisted filler rods and GTAW process (Ref 21) and subsequently determined transverse-weld tensile properties. The experimental work also used ER1100, ER2319 and parent metal strips of AA2195, twisted wire rods made from ER1100 and ER2319 as filler metal primarily to draw baseline comparisons, where appropriate.

When the GTA weldment did not show a sensitivity to weld cracking, this approach implicitly assumed, subject to verification, that the chemical composition of the twisted filler rod offered both resistance to weld corrosion, and a color match after anodizing. As-welded transverse-weld tensile properties in excess of threshold values were supposed to indicate that the weldment would allow ballistic performance of welded panels, and thus offered the potential to support the manufacturing technology needs of combat vehicle manufacturers.

Table 2 shows the nominal chemical composition of selected COTS filler wires (ER1100, ER2319, and ER4043). These nominal chemical compositions were obtained from welding consumable manufacturers. In general, both ER1100 and ER4043 provide non-heat treatable weld metal, while ER2319 provides weld metal that responds to an age-hardening heat treatment (Ref 14). Depending on the type of base metal, and the extent of base metal dilution in the weld metal, one could witness the above welding consumables to show a substantially different or minimal age-hardening response.

A mass balance equation that used the size and nominal chemical composition of the individual COTS wire electrodes or filler rods was employed to estimate the chemical composition of the twisted wire rods. Chemical analysis of "buttons" produced from the twisted rods was also used to further ascertain the accuracy of the estimated chemical composition of the twisted wire rods obtained using the mass balance equation. Chemical composition data obtained from "buttons" are not reported here.

The twisted wire rods were used to produce a set of nine experimental GTA weldments using a variety of weld schedules. For comparative purposes, a set of four GTA weldments were initially produced and evaluated to develop an appropriate baseline for benchmarking. These four weldments were produced using individual COTS filler wires or AA2195 base metal strips.

All 13 weldments were produced in the downhand position, using alternating current (AC). As both aluminum and lithium form adherent surface oxides, use of AC-GTAW conditions was expected to allow automatic break-up and removal of the surface oxides from the joint area during each half cycle when the tungsten electrode remained positive. The weldments typically measured 150-300 mm (8-10 in.) in length and 300-350 mm (10-12 in.) in width.

Prior to welding, the individual plates (or sheets) forming the weldment were cleaned thoroughly using a stainless steel wire brush, held firmly together in a fixture over a copper backing bar. Specific features of the welding fixture allowed one to vary the restraint, depending on sheet or plate thickness. The copper backing bar allowed back-shielding of the weld zone with a copious supply of inert gas at about 1700 L/h (60 cu·ft/h) while aligning the sheets or plates together. A 60% helium-40% argon mixture was used as protective shielding gas.

Table 3 provides typical weld parameters used for producing the test weldments. The individual weld schedules used both sheet (nominally 8 mm thick) and plates (nominally 12 mm or 18.4 mm thick), while varying edge preparations (square-butt for sheet, or single-V with 60° included angle for plate), root gaps, filler wire types (parent metal strips, COTS filler wires, or twisted filler rods), and additional gas shielding. The weld energy input was maintained more or less at a constant value. Two or more weld passes were used to fill the joint from one side.

Tables 4 and 5 show a summary of GTA welding conditions used for producing both baseline test weldments and experimental weldments using selected twisted wire rods, respectively. The number of weld passes increased depending on sheet (or plate) thickness, joint preparation, and wider root-gap. For a given welding condition, (the) higher the number of weld

Table 2 Nominal and estimated chemical compositions of selected COTS filler wires and twisted wires

Electrode/rod type	Nominal chemical composition of COTS wire electrodes, wt.%											
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Be	V	Zr	Al
1.6 mm diameter ER1100			0.08			0.00	0.10					99
2.4 mm diameter ER2319	0.2	0.3	6.3	0.3	0.02	0.00	0.10	0.15	0.0008	0.08	0.18	92
1.6 or 2.4 mm diameter ER4043	5.3	0.8	0.3	0.05	0.05	0.00	0.10	0.20	0.0008			93

No.	Twisted wire rod type	Estimated chemical composition of twisted wire rods, wt.%											
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Be	V	Zr	Al
1	2 of 2.4 mm diameter ER2319 + 1 of 1.6 mm diameter ER1100	0.16	0.25	5.17	0.25	0.02	0.00	0.10	0.12	0.00	0.07	0.15	94
2	2 of 2.4 mm diameter ER2319 + 1 of 2.4 mm diameter ER4043	1.90	0.47	4.30	0.22	0.03	0.00	0.10	0.17	0.00	0.05	0.12	93
3	1 of 2.4 mm diameter ER2319 + 2 of 1.6 mm diameter ER1100	0.11	0.16	3.37	0.16	0.01	0.00	0.10	0.08	0.00	0.04	0.10	96
4	1 of 2.4 mm diameter ER2319 + 1 of 1.6 mm diameter ER1100	0.14	0.21	4.39	0.21	0.01	0.00	0.10	0.10	0.00	0.06	0.12	95
5	1 of 2.4 mm diameter ER2319 + 1 of 1.6 mm diameter ER4043	1.77	0.45	4.45	0.22	0.03	0.00	0.10	0.17	0.00	0.06	0.12	93

passes, (the) lower is the dilution of the base metal in the overall weld metal.

Following welding, the test weldments were inspected by visual examination and liquid penetrant testing. Subsequently, two or more strap transverse-weld tensile specimens were machined from each of the weldments, and the transverse-weld tensile properties of the individual weldments were obtained.

Table 3 Summary of typical manual GTA welding conditions

Identification	Experimental weld #T6
Plate type	AA2195-T8P4
Plate chemical composition	Al-4.0wt.%Cu, 1.0 wt.% Li, 0.3 wt.% Mg, 0.3 wt.% Ag, 0.14 wt.% Zr
Plate thickness, mm	18.4
Individual plate size, mm	152 × 152 × 18.4
Plate pre-cleaning	Sanding followed by stainless steel wire brush
Groove geometry	60° single-vee with copper backing
Root-gap, mm	12
Filler metal type	Twisted wire rod, 2-strands of ER2319 with 1 strand of ER4043
Filler metal diameter	2.4 mm Ø ER2319; 2.4 mm Ø ER4043
Estimated chemical composition of filler metal	Al-4.3wt.%Cu-1.90wt.%Si, 0.17 wt.% Ti, 0.12 wt.% Zr
Welding process	GTAW
Polarity	AC
Current, A	300
Voltage, V	27
Travel speed, mm/s	4
Energy input, kJ/mm	2
Preheat/interpass, °C	21/21
Shielding gas	Ar/He (40/60)
Gas flow rate, L/h	1400
Number of weld passes	9

6. Results and Discussion

Table 2 shows the estimated chemical composition of twisted wire rods produced from the COTS wire electrodes or filler rods. A comparison of the data in Table 2 indicated that twisted wire rods #2 and #5 provided nearly identical estimated chemical compositions, and contained about 7 wt.% total alloy additions. Furthermore, based on matching chemical compositions criterion, the new Al-4wt.%Cu-2wt.%Si filler alloy appeared suitable for effective joining of high-strength aluminum armors such as AA2219-T851 and AA2519-T87.

It is interesting to note that AWS A5.10 Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods (Ref 14) does not currently include Al-Cu-Si alloy system with copper as a major alloying addition, and silicon as a minor alloy addition, with a total alloy content in excess of 6 wt.%. This is perhaps due to prior research on binary aluminum alloys that showed increased cracking sensitivity for binary Al-3 to 4 wt.% Cu alloy, and Al-1wt.%Si alloy (Ref 22) (Fig. 1). The increased cracking sensitivity of these binary alloy compositions is commonly attributed to wider freezing range of these compositions, under non-equilibrium weld solidification conditions.

Fusion welds in Al-Li alloys are generally prone to hot cracking, especially in the HAZ (Ref 20). However, liquid penetrant testing did not show any indication for liquation cracking in the HAZ or solidification cracking in the FZ in any of the 13 experimental weldments. Absence of visible hot cracking both in the HAZ and FZ in AA2195 appeared to indicate that liquation due to stresses induced by solidification shrinkage and thermal contraction during welding were not significant (Ref 23), freezing range of the filler alloy composition (Ref 22) was not an issue, and the welding conditions were not extremely rigorous to cause an unacceptably high degree of restraint. This obviated a need to perform macro- and micro-structural characterization to further ascertain the presence and extent of hot cracks in the weld zone.

Table 4 Summary of GTA welding conditions and transverse-weld tensile properties of experimental baseline welds in the as-welded condition

No.	Specimen ID	Sheet/plate thickness, mm	Edge preparation	Filler wire	Number of weld passes	Transverse-weld tensile properties: UTS, MPa (ksi)	0.2% YS, MPa (ksi)	El, %	Fracture location
1	1-1	8	Single-V, 60° included angle	AA2195 base metal strips	2	272 (39.5)	206 (29.8)	1.8	FZ/HAZ
	1-2					261 (37.9)	210 (30.4)	1.3	FZ/HAZ
	1-3					266 (38.6)	198 (28.7)	1.5	FZ/HAZ
2	2-1	8	Square-butt (narrow root gap)	2.4 mm diameter ER2319	2	138 (20.0)	138 (20.0)	0.5	FZ/HAZ
	2-2					258 (37.4)	191 (27.7)	1.6	FZ/HAZ
	2-3					242 (35.1)	203 (29.4)	1.0	FZ/HAZ
3	3-1	8	Single-V, 60° included angle (narrow root gap)	2.4 mm diameter ER2319	2	274 (39.7)	204 (29.6)	1.9	FZ/HAZ
	3-2					263 (38.1)	197 (28.6)	1.3	FZ/HAZ
	3-3					232 (46.8)	208 (30.2)	3.9	FZ/HAZ
4	4-1	8	Single-V, 60° included angle (wider root gap with back shielding)	2.4 mm diameter ER4043	8	270 (39.2)	201 (29.2)	1.6	FZ
	4-2					274 (39.7)	190 (27.6)	1.8	FZ

The 0.2% YS is an estimate provided primarily for comparative purposes. %El reported over 50 mm gage length. FZ/HAZ, fusion zone/heat affected zone interface

Table 4 shows the transverse-weld tensile properties for baseline weldments. As one would expect from prior work (Ref 14, 19), none of the baseline weldments provided adequate ductility. With ER2319, a high base metal dilution appeared to provide a higher transverse-weld tensile strength but at the expense of tensile ductility (Ref 20). Invariably, the tensile fracture occurred along the FZ/HAZ interface. Presence of equiaxed gains along this location (Ref 24, 25) likely contributed to the preferential fracture along this path. However, with a wider root gap and the attendant higher number of weld passes using ER4043, the tensile fracture occurred in the FZ. This undermatched weldment indicated a possible effect of weld metal composition and weld parameters in changing weld solidification conditions along the fusion boundary and in shifting preferential fracture location and path of fracture propagation from the fusion boundary to the FZ.

Table 5 shows a summary of the transverse-weld tensile test results for the experimental weldments produced using twisted wire rods. Consistent with the results of visual examination and liquid penetrant testing, the fracture surfaces of none of these experimental transverse-weld test specimens showed any identifiable evidence for solidification cracking in the FZ. Weldment #T3 produced using twisted wire rods made from ER1100 and ER2319 showed a limited potential to achieve the target transverse-weld tensile properties. Tensile ductility improved with increasing number of weld passes when base metal dilution was also limited as shown in weldments #T4 and T5. Tensile fracture of these weldments occurred in the FZ.

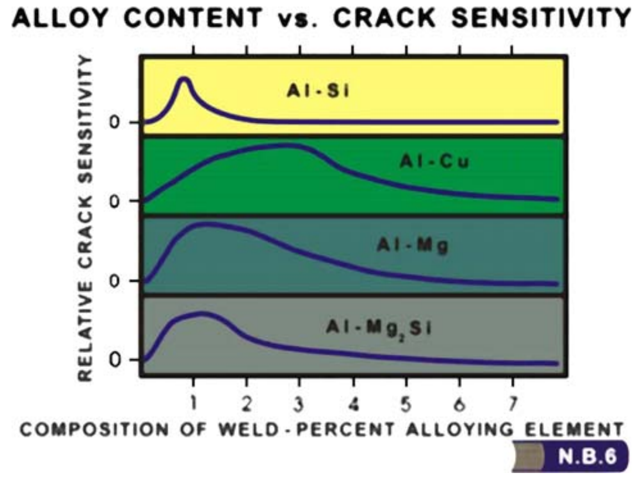

Fig. 1 Weld cracking sensitivity of aluminum alloyed with silicon, copper, magnesium, and magnesium silicide (Ref 22)

Table 5 Summary of GTA welding conditions and as-welded transverse-weld tensile properties of experimental welds produced using twisted wire rods

No.	Specimen ID	Sheet/plate thickness, mm	Edge preparation	Twisted filler rod	Number of weld passes	Transverse-weld tensile properties: UTS, MPa (ksi)	0.2% YS, MPa (ksi)	El, %	Fracture location
T1	T1-1	8	Single-V, 60° included angle (narrow root gap)	#1	2	239 (34.7)	168 (24.4)	2.0	FZ/HAZ
	T1-2					285 (41.3)	172 (25.0)	6.0	FZ/HAZ
	T1-3					271 (39.3)	180 (26.1)	3.8	FZ/HAZ
T2	T2-1	8	Single-V, 60° included angle (narrow root gap)	#1	2	247 (35.8)	183 (26.5)	2.1	FZ/HAZ
	T2-2					259 (37.6)	176 (25.5)	2.6	FZ/HAZ
	T2-3					253 (36.7)	167 (24.2)	2.7	FZ/HAZ
T3	T3-1	8	Single-V, 60° included angle (wider root gap with back shielding)	#1	2	302 (43.8)	192 (27.8)	10.0	FZ
	T3-2					283 (41.0)	217 (31.5)	7.0	FZ
	T3-3					278 (40.3)	195 (28.2)	9.0	FZ
T4	T4-1	12	Single-V, 60° included angle (wider root gap with back shielding)	#1	8	248 (36.0)	115 (16.6)	8.0	FZ
	T4-2					274 (39.7)	128 (18.5)	12.0	FZ
	T4-3					272 (39.4)	116 (16.8)	12.0	FZ
T5	T5-1	18.4	Single-V, 60° included angle (wider root gap with back shielding)	#1	9	268 (38.8)	139 (20.1)	11.0	FZ
	T5-2					269 (39.0)	141 (20.4)	11.0	FZ
	T5-3					268 (38.8)	141 (20.4)	12.0	FZ
T6	T6-1	18.4	Single-V, 60° included angle (wider root gap with back shielding)	#2	9	297 (43.0)	173 (25.1)	12.0	FZ
	T6-2					293 (42.5)	163 (23.7)	11.0	FZ
	T6-3					298 (43.2)	161 (23.4)	10.0	FZ
T7	T7-1	8	Single-V, 60° included angle	#3	2	Specimen broke along FZ/HAZ interface after machining			
	T7-2					Specimen broke along FZ/HAZ interface after machining			
	T7-3					128 (18.6)	128 (18.6)	0.4	FZ/HAZ
T8	T8-1	8	Single-V, 60° included angle	#4	2	223 (32.4)	159 (23.0)	1.6	FZ/HAZ
	T8-2					246 (35.7)	141 (20.4)	4.0	FZ/HAZ
	T8-3					150 (21.8)	141 (20.5)	0.8	FZ/HAZ
T9	T9-1	8	Single-V, 60° included angle	#5	2	300 (43.7)	226 (32.8)	2.1	FZ/HAZ
	T9-2					310 (45.1)	228 (33.0)	2.4	FZ/HAZ
	T9-3					300 (43.4)	219 (31.7)	2.0	FZ/HAZ

The 0.2% YS is an estimate provided primarily for comparative purposes. Welds T1-T6, %El reported over 25 mm gage length; welds T7-T9, %El reported over 50 mm gage length. FZ, fusion zone; FZ/HAZ, fusion zone/heat affected zone interface

It is interesting to note that the proportion of ER2319 to ER1100 in twisted wire rod (#1) was high. However, when the proportion of ER2319 to ER1100 was reduced in twisted wire rods (#3 and #4), the resulting weldment fared poorly in transverse-weld tensile testing. In this instance, the tensile fractures invariably occurred along the FZ/HAZ interface. In fact, two of the test specimens from weldment #T7 broke along the fusion boundary immediately after machining, indicating that a minimum amount of silicon and copper may be necessary to ensure adequate metallurgical bonding. Increasing the total alloy content of the FZ appeared necessary to consistently achieve the required metallurgical bonding, and the associated strength levels in the as-welded condition.

In comparison, twisted wire rod #2 obtained from ER2319 and ER4043, also based on Al-4Cu-2Si system, showed adequate potential to achieve the targeted tensile properties. Test results of weldment #T6 corresponding to twisted wire rod #2 showed an ability to consistently exceed the targeted 275 MPa or 40 ksi UTS and 8% El (in 25 mm gage length). Furthermore, this weldment, which was produced using nine weld passes, appeared to show adequate resistance to any hot-cracking tendency both in the FZ and the HAZ despite the imposition of multiple weld thermal cycles.

To a lesser extent, test results of weldment #T9 corresponding to twisted wire rod #5 showed an ability to consistently exceed the targeted 275 MPa or 40 ksi UTS but failed to meet the 4% El (in 50 mm gage length) requirement. As twisted wire rods #2 and #5 showed nearly identical estimated chemical composition, the difference in the behavior of their corresponding weldments is attributed primarily to the limited number of weld passes used and the resultant higher base metal dilution in weldment #T9. Reducing base metal dilution by widening the root gap and increasing the number of weld passes while providing adequate protective gas shielding appeared necessary to improve weld ductility albeit a marginal but acceptable drop in transverse-weld tensile strength.

This limited initial study based on an innovative low-cost, low-risk approach has shown that welding consumable based on the Al-4wt.%Cu-2wt.%Si system has the potential to consistently meet or exceed the targeted transverse-weld tensile properties in the as-welded condition. Commercial consumable electrode manufacturers catering to the needs of combat vehicle manufacturers may benefit from this initial study.

Future work could address manufacturing of experimental consumable wire electrodes for GMA welding, followed by weld evaluations and testing for tensile strength, weldability (cracking resistance), corrosion resistance, and ballistic performance. Such future work could also address the viability of Al-4Cu-2Si alloy system as filler metal for effective joining of other candidate aluminum armors such as AA2219-T851 and AA2519-T87.

7. Conclusions

The above experimental results clearly demonstrated the following:

(1) Use of twisted wire rods offered a simple and yet effective method to quickly identify Al-Cu-Si as an appropriate alloy system for effective joining of AA2195 aluminum alloy.

(2) Transverse-weld tensile properties consistently showed that Al-4Cu-2Si alloy system offered minimal risk in producing GMAW consumable wire electrodes that could be evaluated in more elaborate test schemes for joining AA2195 alloy for armor applications.

(3) Future work could aim at the detailed evaluation of the following welding consumable electrode (filler wire) composition: 4.2-5.0 wt.% Cu, 1.6-2.0 wt.% Si, 0.40-0.60 wt.% Fe, 0.25 wt.% Mn, 0.10 wt.% Zn, 0.15 wt.% Ti, 0.05 wt.% V, 0.15 wt.% Zr, and the balance aluminum with small amounts of other alloy additions that would allow simultaneous improvements to both billet extrusion and wire drawing characteristics.

(4) Al-4Cu-2Si alloy system may also be effective in joining other candidate aluminum armors such as AA2219-T851 and AA2519-T87 that are based on Al-Cu alloy system.

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