2021 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
SURVIVABILITY TECHNICAL SESSION
AUGUST 10-12, 2021 - NOVI, MICHIGAN

FLASH® 600 ULTRA HIGH HARD: ROOM-TEMP ER120S-1 WELDABILITY TEKKEN, H-PLATE, BALLISTIC, & FSP DATA FOR IMPROVED SURVIVABILITY

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ABSTRACT

Survivability of a welded vehicle hull is directly tied to the performance of the grade of steel armor used. Selecting the highest performing grade of armor that can be welded into a specific location on a vehicle will improve survivability. While rolled homogeneous armor is the simplest to weld, challenges in welding high hard, and especially ultra high hard, are well known. Preventative measures to avoid weld cracking in vehicle structures can lead to increased costs during fabrication. Cracking of welds, both seen and unseen, in deployed vehicles directly impacts the survivability of the vehicle. Weld cracking during deployment further magnifies repair costs and leads to non-mission capable status.

This analysis examines the weldability, ballistic/blast performance, and underlying metallurgy of Flash® Processed steels that have been tested by Army, Academia, and Industry.

Citation: G. Cola, "Flash® 600 Ultra High Hard: Room-Temp ER120S-1 Weldability Tekken, H-Plate, Ballistic, & FSP Data For Improved Survivability", In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 10-12, 2021.

INTRODUCTION

While the steel vehicle fleet relies heavily on high hard armor (HH) as the best overall solution, according to the 1992 LAV Armor Plate Study "*MIL-A-46100 was originally developed as an applique armor and was never intended to be used in a welded structural application"* [1]. PEO CS&CSS cites this report and states HH "*has led to excessive cracking, which leads to non-mission capable status and costly inspection and repair activities"*. Further, *"the development of a revised specification or grades as a subset to the existing specification has the potential to save millions in the life cycle sustainment costs"* [2].

Ultra high hard armor (UHA) offers improved ballistic survivability over HH yet is recognized to have more stringent requirements for welding. MIL-STD-3040A (DRAFT 17Sep20) states in Section 5.1.2.1 that "*Ultra-high-hardness armor steel is considered unweldable by standard techniques due to the elevated carbon equivalence."* UHA welding *"shall be specifically approved by the procuring activity prior to use"*. Preheating to 200°F minimum yet a maximum of 300°F is encouraged with *"controlled or slow cooling after welding is completed"*.

Further, "*In impact scenarios, fracture toughness decreases as temperature decreases, grain size decreases, and strain rate increases. Basically the* *processes and effects that increase the strength of the material, make it more brittle, also result with the decrease in fracture toughness"* [3]. The metallurgy scenario of elevated carbon and high alloy content, lengthy thermal cycles, and costly equipment challenges the steel industry to achieve readily weldable, formable, low cost armor and advanced high strength steel. Further, the thermal cycles, especially the cooling aspects, must be precisely controlled to avoid undesirable phases upon solidification [4].

Room temperature weldable UHA could increase survivability over both HH and UHA used today for ballistic, blast, and structural performance of a welded vehicle hull.

TRENDS TODAY & WELDING DIFFICULTY

The metallurgical science of high alloy content is interesting and more than 60 alloy composition methodologies have been looked into over the last few decades to achieve an advanced high strength steel (AHSS) which has 150-320 ksi ultimate strength, recognizing the need for formability for use in vehicle impact and structural applications [4]. Grades of high performance armor are also being looked at which focus primarily on ballistic and blast resistance achieved by a retained austenite and/or bainitic phase [4][5][6][7][8][9]. While HH and UHA armor grades achieve 230 ksi to 300 ksi presently, there remains a well-known need to improve weldability and bendability for structural fabrication. Reports on weldability are hard to find since weld cooling of these heavily alloyed steels cannot match the precisely controlled cooling cycles of heat treating furnaces, thus leading to undesirable phases upon solidification. Weldability is often considered years after ballistic testing as evidenced by the current Broad Agency Announcement of PEO CS&CSS [2].

Numerous paths have been researched and most methods have several elements in common. Typically, these concepts all involve costly intensive alloying, often with significant amounts of manganese, and high capital expenditures for time-consuming thermo-mechanical processing routes. The basic difference between current methods is the alloying intensity which varies from 4 to 40% by weight and the thickness of the armor.[4] Armor plate specifications start at 0.098" in MIL DTLs such as 12560K-1, 46100E-3, and 32332A. Although Abrams uses very thick armor plates, lighter vehicles up to MRAP primarily use armor thicknesses ranging from 3/16" to 1/2" for parts such as side panels, roof panels, floor, V-hull, rear wall, and rear ramp.[10]

The basic steelmaking rolling processes can also be challenged by these enriched manganese, aluminum, and silicon alloying strategies to simply produce the coils of steel. Known as TWIP (twinning induced plasticity) and FeMnAl (iron-manganese-aluminum) steels, the strength and elongation are desirable but other problems arise in their use. Mini-mills that use recycled steel as feedstock can have contamination from tramp residual elements. Ramadan *et al.* found "*Tramp elements affect steel properties in two different ways: influencing steel mechanical properties or influencing processing quality of steel especially in the continuous caster and during deformation processes.*"[11] These heavily alloyed steels will be problematic to recycle. Contaminating future heats of steel or simply losing the alloy content without financial recapture are genuine concerns. The most common alloying element, manganese, is considered a "persistent contaminant" because it remains after the re-melting process to produce new steel. Manganese inclusion of 5 to 15% will be troublesome when recycled into future heats of steel as it will be impractical to sort by the chemistry of the recycled feedstock when vehicles are shredded at the scrap yard. Manganese in concentrations exceeding 5% in steel, which are focused on creating retained austenite phases, can lead to significant difficulty when welding due the uncontrolled cooling rates upon weld solidification [12]. A 4 year Dept of Energy funded $10M project was led by General Motors teaming with Ford, Fiat Chrysler America, AK Steel, Arcelor Mittal, Nucor Steel, EDAG, Livermore Software Technologies, Brown Univ, Clemson Univ, Colorado School of Mines, Pacific

Northwest National Lab, Ohio State Univ, Univ of Illinois at Urbana-Champaign, Auto/Steel Partnership, and US Automotive Materials Partnership [13]. Citing this effort, GM's material technical fellow Curt Horvath wrote [12]:

> *"It is becoming increasingly clear that a re-evaluation of general chemistry/processing strategies is needed for current and future retained austenite bearing steel designs. … due to the demonstrated compromises in manufacturability, performance predictability, and increased material costs necessary to achieve these combinations."*

> *"The remaining challenges to implementation of both Q&P and TBF-type retained austenite bearing steels must be overcome. Although numerous, most challenges are currently considered as manageable with the exception of the presence of liquid metal embrittlement of resistance spot weld(s)."*

Concurring with Horvath, Zeytin, *et al.* wrote that "*the acceptable welding parameter area is very narrow for resistance spot-welded TWIP steels, because of cracks and cavities in the weld nugget, surface cracks in the [heat affected zone (HAZ)]*" [14]. If the cooling of manganese enriched sheet steels leads to weld embrittlement failure due to the uncontrolled cooling cycle, it could be anticipated that similar effects will be present in other manganese enriched steel shapes and thicker sections.

In a recent paper on FeMnAl armor plate, Evans *et al.* wrote "*To date, little research has been conducted on the weldability, and cracking response of this material during fabrication.*" Evans further wrote "*Solidification cracking was observed in several cast pins, this was confirmed by observing the fracture surfaces of failed pins*" [5]. Acknowledging Evans' work is investigational and not intended to be an exhaustive report on many grades of high manganese steel, if solidification cracking is present in the simple casting of pins, it stands to reason that during the uncontrolled cooling that occurs during welding that solidification cracking is also possible to occur.

A PATH TO MORE WELDABLE STEEL

For millennia, steel has been heated and quenched to modify the mechanical performance. When steel alloys are heated and held at temperatures generally above 800°C, a crystalline structure known as austenite is formed. This crystalline structure can contain a more homogenized carbon distribution than the morphologies present at lower temperatures. As the iron alloy cools, carbon diffuses and austenite, known as the parent phase, converts into a matrix of various microstructures called daughter phases. Depending on the time and cooling rate used to cool the steel, microstructures known as the austenite daughter phases of martensite, ferrite, pearlite, bainite, and other morphologies are formed. Ferrite and pearlite are relatively weak but ductile. Bainite is a strong yet relatively ductile microstructure, while martensite is a harder, stronger, less ductile microstructure. The thermal cycle and alloy content of the steel determine the relative proportions of the daughter phase microstructures, which in turn determine the mechanical properties such as hardness, tensile strength, ductility, toughness, and formability of the processed steel. Traditional steel heat treating is designed to produce a uniform, homogeneous distribution of carbon, chemistry, and microstructures. This is accomplished in sheet and plate products with lengthy exposure times of several minutes or hours to elevated temperatures in the range of 800 to 950°C followed by a variety of time-consuming cooling and temper methodologies.

Contrary to current steel processing technologies, Flash Steelworks and its flash bainite research staff, with assistance/guidance from The Ohio State University, University of Tennessee-Knoxville, Oak Ridge National Lab, Edison Welding Institute, the US Army, Cambridge University-UK, Ghent University, and others, has demonstrated that the mechanical properties of steel and subsequent weld heat affected zones can be improved by maintaining a varied and random distribution of microstructures and carbon concentrations at the intragranular scale leading to a partially bainitic microstructure [15][16][17] [18][19][20].

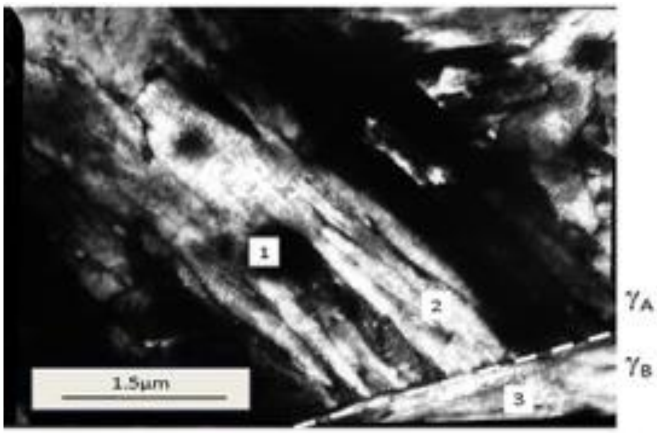

Figure 1: TEM showing bainitic sheaves, noted as 1, 2, and 3 in Flash microstructure. Dashed line is the grain boundary.

Young *et al.* wrote that a mixture of 20-25% bainite in a martensite matrix will lead to 7-10% higher strength for a given alloy of steel [19]. Flash Processing has been shown in some alloys to create such a 20-25% bainite phase fraction shown in Figure 1. Since 2008, Flash processing has leveraged decades-old standard induction heating technology to rapidly increase the temperature of steel plate, sheet, and tubing to over 1000°C to form austenite and then quenched immediately to limit carbide dissolution and control carbon migration. Rapidly reducing the temperature controls the formation of martensite, bainite, and other morphologies from the chemically heterogeneous austenite. The entire Flash transformation process is performed in <10 seconds.

Steel, upon slow cooled solidification from the melt ladle, segregates to low carbon, high carbon, and carbide regions. Developing material characteristics which are instrumental to making highly weldable armor plate and AHSS, Flash processing's rapid thermal cycle leverages steel's inherent carbon segregation. By doing so, Flash processing preserves heterogeneous microstructures because kinetically sluggish processes do not have time to homogenize the austenite chemistry. Resulting is a heterogeneous complex metal matrix composite of microstructures in which each provides a different advantage. Low carbon regions within the Flash morphology are readily weldable and ductile while high carbon regions are strong and hard.

FLASH® 600 VS 0.30-CAL M2AP & M80

Like other investigations, the Flash research team first focused on ballistic performance and mechanical properties prior to investigating weldability[6][7][8][9][19]. Flash® 600 UHA at 290 ksi to 300 ksi was certified to MIL DTL 32332 in Nov. 2017. Tested at Army Research Lab, the average V_{50} of 4 tests of 0.260" thick plates was 151 feet per second (fps) over current MIL DTL 32332A requirements [21]. V_{50}'s were 102, 153, 173, and 175 fps over 32332A velocities.

While it is acknowledged that UHA, per MIL DTL 32332A is to be tested at 30° obliquity, a 0° obliquity comparison was performed in July 2021. NTS Chesapeake determined V_{50}'s at both 30° and 0° in a single 0.260" x 12" x 36" plate. The 30° V_{50} had a passing margin of 174 fps demonstrating consistent performance with the testing in 2017 from a different steel heat. The 0.260" Flash® 600 V_{50} against 0.30-cal M2AP at 0° obliquity was found to be 2215 fps. Partial penetrations (PP) were recorded at 2124, 2166, 2181, and 2206 fps. After 8 rounds of 0.30-cal M2AP at 30° obliquity and 7 more at 0° obliquity, the same plate had 9 rounds of M80 ball fired to a V_{50} of 3049 fps, about 300 fps over muzzle velocity. The M80 round was used as a blunt force impact to intentionally try to crack the plate. Instead of cracking, the plate's highest velocity partial penetrations (PP) dimpled up to 0.150" in the 0.260" thick plate, shown Figure 2. Dimpling demonstrates very high quasi-static energy absorption.

Figure 2: M80 ball dimples of 0.150" deep in 0.260" plate

After 24 total shots, including 11 CPs, no hole-to-hole nor hole-to-edge cracking was observed, shown in Figure 3.

Figure 3: 15 shots of 0.30-cal M2AP and 9 shots of M80 ball, no cracking beyond CP perimeter

To verify that Flash® 600 was not experiencing an upper V_{50} while adiabatic shear plugging occurred, a second 0.260" x 12" x 36" plate had 32 shots ranging from 1475 fps to 2116 fps fired at it, shown in Figure 4. Considering both plates, all 36 PP rounds had their cores shattered verifying that there was no shatter gap phenomena brought on by adiabatic shear [22].

Figure 4: (32) PP shots of 0.30-cal M2AP at 0d, all AP cores were shattered

FLASH® 600 VERSUS FSP

It has been long believed that UHA will perform poorly against fragment simulating projectiles (FSP) because 600 Brinell plate is too brittle. Chatted notes from the discussion panel at the 2020 DOD Steel Summit stated "*thicker plates tend to have brittle failure upon impact. The energy absorption is very high and therefore we see catastrophic failure of the plate after one or two round(s). With thinner plates, we typically see sheer plugging*" [23]. Testing was performed against various thicknesses of Flash® 600 in monolithic, double-plate, and tri-plate scenarios. FSPs of diameter 0.30-cal, 0.50-cal, and 20 mm were fired at plate thicknesses of 6 psf, 21.2 psf, and 31.8 psf, respectively. The results are given in Table 1.

Table 1: FSP Velocities

FSP size	PSF	# Plates	# Shots	V50 fps	High PPs fps
0.30-cal	6.0	1	7	2045	
0.50-cal	21.2	2	17		3736, 3821
20mm	31.8	3	10	3157	

The Flash® 600 plate impacts displayed interesting results. Of the 7 shots fired, the 6 psf monolithic plate tested against 0.30-cal FSP had no hole-to-hole cracking between the 4 CPs nor the plate edge. Similarly, in the 21.2 psf double-plate tested against the 0.50-cal FSP, no cracking was observed in Figure 5. Of the 17 shots fired, all completely penetrated the strike face plate. The back plate was CP-ed by 11 of the 17 rounds. In total, the double-plate combination had 28 holes punched through it by 0.50-cal FSP. Again, no cracking was present hole-to-hole nor hole-to-edge.

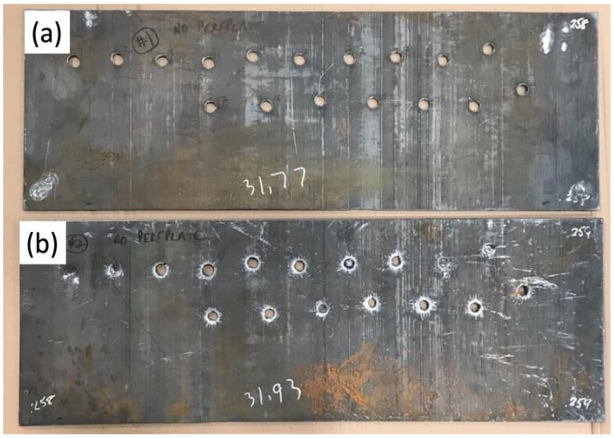

Figure 5: Flash® 600 strike plate (a) with (17) CPs and (11) CPs on the back plate (b)

The back plate of the double plate, upon stopping the 0.50-cal FSP, experienced up to 0.200" deep dimpling from the impact. Shown in Figure 6a are the dimples' back side. Figure 6b shows a two 1/4" diameter carbide shafts supporting a 1/2" diameter shaft. It can be seen the dimple is within 0.050" of touching the horizontal shaft, thus showing 0.200" dimpling of backside deformation in the plate. Demonstrating high quasistatic energy absorption without cracking, adiabatic shear plugging is likely not occuring in the backside plate.

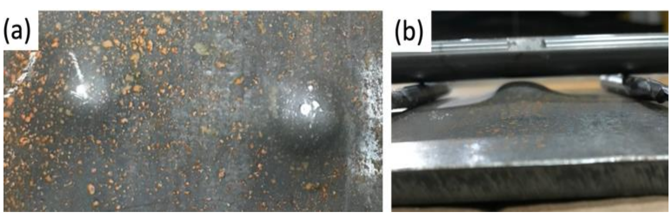

Figure 6: Flash® 600 back plate with 0.200" dimpling

The 31.8 psf tri-plate was tested against 20 mm FSP. Of the 10 shots fired, all completely penetrated the strike face plate and the middle plate. The back plate was CP-ed by 4 of the 10 rounds. In total, the tri-plate combination had 24 holes punched through it by 20 mm FSP rounds.

After 56 PPs, no cracking from hole-to-hole nor hole-to-edge was observed at any thickness of the total 6 plates (single, double, tri-plate) tested against the various FSP sizes. The complete lack of cracking in overmatched Flash® 600 can provide structural robustness that will not compromise the remainder of the armor plate when involved in multi-hit impact scenarios. Comparing V_{50}'s of the Flash® 600, performance is close to that of monolithic RHA against FSP. Further testing against thicker monolithic is planned.

Half scale Charpy testing was performed by Westmoreland Mechanical Testing in both the longitudinal (4.0, 4.0, and 3.0 ft-lbs) and transverse (4.0, 4.0, and 4.0 ft-lbs). Samples were cut and ground from the plate in Figure 3. While the Charpy values are passing to MIL DTL 32332A, they do not appear to be a good litmus test for the quasistatic energy absorbing performance of Flash® 600.

EARLY TESTS - WELDING FLASH ARMOR

By demonstrating desirable mechanical properties, the weldability of Flash® 600 UHA becomes of great interest and the next step toward widespread deployment. Welded armor typically fails where the armor has been reheated during welding in the area known as the HAZ. Different weld settings, filler metal, number of weld passes, and more variables can have a profound impact on the HAZ. For the initial analysis, 1/4" thick commercially acquired Algoma High Hard 500, Flash® 500 made from AISI4130 melted at Nucor Crawfordsville, Indiana, and Flash® 600 made from AISI4140 melted at Nucor Gallatin, Kentucky were Flash Processed. TIG welds for Algoma HH and Flash® 500 HH were performed at Edison Welding Institute, the Navy Joining Center for research. The chemistry for the armor plate and welding consumables used in this investigation are in Table 2.

Table 2: Chemistry of Armor Plate and Weld Rod

Armor	Fe	C	Si	Mn	Ni	Cr	Mo	V	Cu	W	Ti	Co	Al
Algoma	Bal	.30	.43	.90	.90	.55	.55	.005	.10	.010	.030	.005	.050
Flash 500	Bal	.28	.20	.50	.02	.88	.17	.005	.03	.003	.008	.002	.001
Flash 600	Bal	.42	.20	.82	.05	.84	.20	.002	.09		.004		.022

Weld Rod	Fe	C	Si	Mn	Ni	Cr	Mo	V	Cu	W	Ti	Co	Al
E110C-K4	Bal	.05	.66	1.6	.60	2.5	.06						
ER70S	Bal	.04	.54	1.2	.05	.07	.04						

According to Hanhold, in Figure 7, "*from the review of literature on welding of steels and the effect of HAZ softening, low-heat input direct current, electrode positive (DCEP) GMAW was performed on both 1/4" thick Flash 500 and the Algoma High Hard steel with identical parameters with 0.045" E110C-*

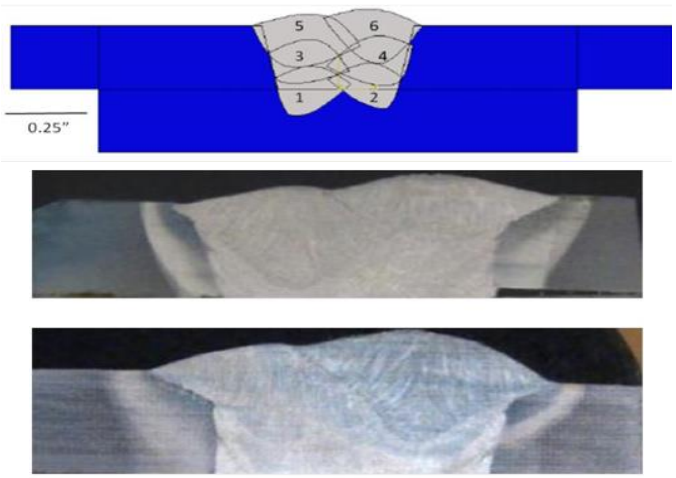

Figure 7: Schematic of welding used in EWI GMAW, Algoma High Hard above, Flash 500 below

22.5° v-groove joint. As usually done with fusion welding processes on armor materials, a matching material backing bar of equal thickness was placed behind the v-groove. The average heat input of 19.4kJ/in is based off the average current of 250 amps, voltage of 31 volts, and 24 inches per minute travel speed" [16].

Figure 8 shows micro-hardness mapping of Algoma high hard, Flash® 500, and Flash® 600 as welded. No preheating nor post-tempering was performed.

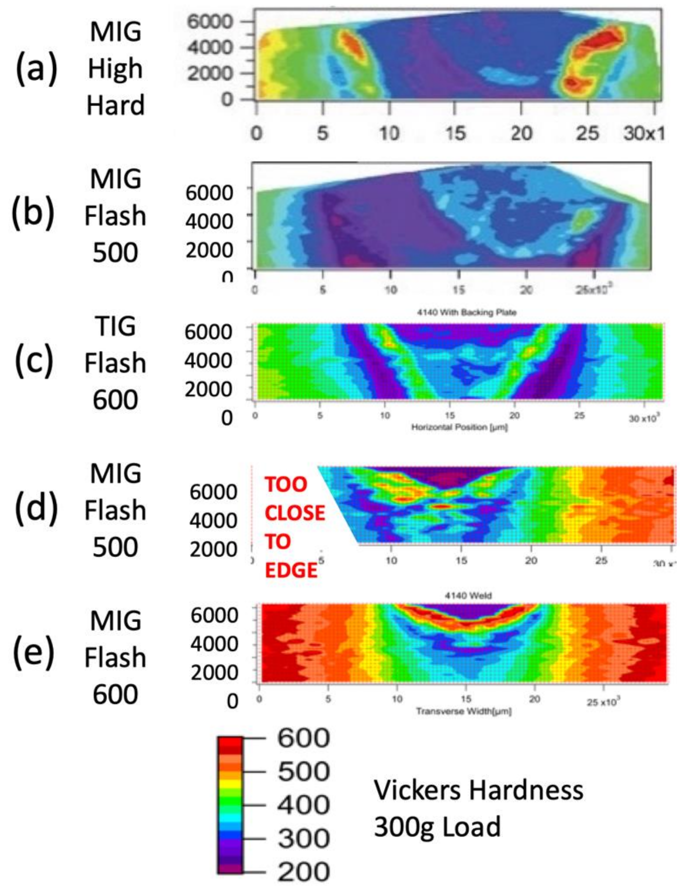

Figure 8: Weld hardness mapping of typical high hard (a), Flash® 500 (b & d), and Flash® 600 (c & e)

In Figure 8a and 8b, MIG High Hard and MIG Flash 500 were welded at EWI as described. While the EWI welding was well controlled to a prescribed regimen, Figure 8c, 8d, and 8e show hardness maps of TIG Flash 600, MIG Flash 500, and MIG Flash 600, respectively, using best shop floor practices and ER70S-6 weld wire. In Flash Steelworks's shop floor experience, over 20 different weld technicians at 10 different locations have MIG, TIG, and/or spot welded Flash Processed steels without difficulty and without instructions as to the settings they should use. For example shown in Figure 8c, in welding Flash® 600, a 1990s Miller TIG welder Syncrowave 351 used the settings of negative electrode, 10% background amps, 0.75 pulses per second, 65% on-time, and post flow of 9 to weld successfully. Note these are the same settings used by shop personnel to weld/fab all mild steel in the shop.

The colors in Figure 8 depict hardness within the weld with red representing the harder areas and violet representing the softer areas. In typical high hard armor like Algoma shown in 8a, the interface between the bulk metal and the weld filler material, known as the fusion line, is very hard as depicted by the deep red color. The fresh hardness at the fusion line exists for two primary reasons. When the armor steel is melted at the steel mill, significant alloying additions are made to the steel to increase hardenability which in turn increases the carbon equivalence value. The Algoma high hard has a CEV of 0.723, Flash® 500 has a lower CEV of 0.634, and interestingly Flash® 600 has a lower CEV of 0.671 than Algoma even though the Flash® 600 is 100 points Brinell higher.

The alloys increase the transformational driving forces to promote the martensitic shear transformation upon quenching. When the armor parent material is welded, the austenitized fusion line transforms to martensite when cooled. While weld cooling of austenite in the HAZ is not a water quench, like in the production of armor, it is well recognized that the parent material outside of the heat affected zone acts to rapidly cool the freshly made austenite in the fusion line by extracting the HAZ's heat through convection into the rest of the armor panel being welded. The convection of the welding heat is why the regions around the weld seam become hot and nearest the weld seam can be tempered to lose some ballistic resistance. Further away from the HAZ centerline, the parent material remains below the austenitic conversion temperature and only loses hardness due to high heat tempering of the steel. Since in production, a majority of armor plate is water quenched and then, importantly, tempered, a problem arises in a weld HAZ because the fresh martensite in the fusion line that was created during the welding process is not tempered as the rest of the armor plate was. In effect, the weld fusion line is armor-plate-chemistry martensite without the benefit of the required tempering that was performed on the armor plate at the steel mill which originally produced it.

The extreme hardness of the fusion line is caused by a homogenous martensitic structure which is very brittle due to lack of tempering and the primary source of weld failure. Such failures in the untempered fresh martensitic regions appear during blast events, fatigue from daily wear, or with 0 miles of use in Buffalo MRAPs [2]. The blue/violet area in the center of the HAZ of the weld (Figure 8) is softer than the bulk material and not the source of embrittlement. This softer region is defined by the chemistry of the welding rod consumable used. In the case of low carbon weld rod such as ER120S-1, a desired strength of 120 ksi is sought. Testing confirmed that ER120S-1 weld consumable led to 129 ksi tensile strength across the weld seam [18]. When even lower carbon weld rod is used, as in ER70S-6, less strength is achieved. In the case of using austenitic stainless welding rod, less strength is achieved due to its austenitic microstructure but susceptibility to cracking is reduced provided the stainless rod is stored properly prior to use to prevent hydrogen induced cracking. While some feel proper storage of weld wire is not required, Heagey writes, "*Moisture is one of the primary sources of hydrogen in weld metal. Hydrogen comes in many forms, both on the plate and in the filler material. Eliminating the source of moisture will minimize the overall cost and prevent premature weld failure*" [24].

The TIG Flash® 600 in Figure 8c is a six pass weld HAZ with the final pass as a weave weld. Flash processed steel has a unique HAZ because it does not develop a fusion line predominantly hardened into brittle martensite upon cooling. As can be seen in the hardness mapping of the weld figure, the Flash® 600 is softest in the center of the HAZ and gradually increases hardness moving outward into the bulk Flash® 600 plate being welded.

Figure 8d showing MIG Flash 500 and 8e of MIG Flash 600 show the local hardness of a single pass MIG weld. Note Flash® 500 has overall lower average hardness measurements than the TIG Algoma high hard weld shown in Figure 8a. Even the Flash® 600 has minimal fresh martensite-based hardness which only penetrates 25% through the thickness. This indicates that the lack of embrittlement should lead to structural robustness since a majority of the thickness of the Flash® 600 plate is only tempered by the welding process's added heat, not recrystallized to austenite and then to form untempered martensite.

Vigilante *et al.* at Army Combat Capabilities Development Command Armaments Center (fka ARDEC) investigated residual stress in Flash® 500 near the ER120S-1 HAZ. Three residual stress locations are shown in Figure 9 while Figure 10 shows measured locations on the backside of the weldment. Residual stress was also measure on the bottom of the plate outside of the HAZ [18].

Figure 9: Location of three residual stress measurements on top of the plate

Figure 10: Locations of two residual stress measurements on bottom of the plate.

When compared to the 1468 MPa (213 [ksi]) tensile yield strength, the magnitude of residual stresses is relatively low: about 220 MPa (32 [ksi]). However, most of the residual stresses measured are tensile, not compressive. Importantly, the tensile residual stresses create susceptibility to embrittling mechanisms, such as stress corrosion. And, the maximum residual stresses were detected in two areas: on the weld and on the bottom of the plate away from weld. The typical residual stress distribution around the weld was not detected perhaps because it does not exist, or it relieved when sectioned, or it was not measured" [18].

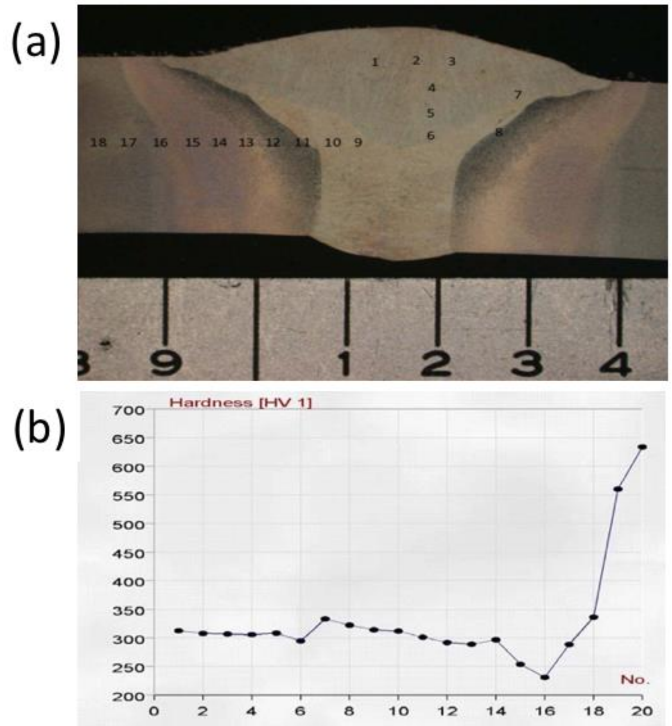

Figure 11: Flash® 500 HAZ showing indent location (a) with microhardness indents graphed (b).

As tested by Vigilante, *et al*., Figure 11a is a low magnification photo of a Flash® 500 HAZ with ER120S-1 filler with microhardness indents labeled. Note that this is a two-pass weld and HAZ. As expected, the ER120S-1 is the softer, weaker link in weld metal and HAZ. Figure 11b charts Vickers hardness. Note that away from the HAZ (indents #19 & 20 not in photo), in a banded area, a microhardness of HV634 was measured in the parent material.

Flash® 500 and 600 armors' weld seams present ductile and bendable weld zones that are less prone to brittle failure under high significant bending of the weld seam. Figure 12 shows bends of welded Flash® 500 and 600 in 1/4" plates welded with ER120S-1 weld filler rod. The report stated "*no weld discontinuities, of any size, were present*" [25]. While typical HH welds can separate and fail, Flash® 500 has been found to have "*ductile shear lips*" in the base metal to resist brittle failure [18].

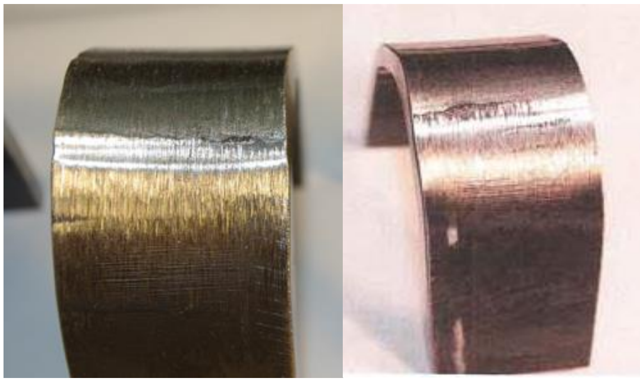

Figure 12: weld bends Flash® 500 (left), Flash® 600 (right)

In further weld testing, a 0.260" Flash® 600 plate had 2.5" and 4.5" circles laser cut from the 12"x24" panel in Figure 13a. The edges were beveled, circles rotated by 90 degrees, and then TIG welded back in the original location with ER70S-6 in Figure 13b.

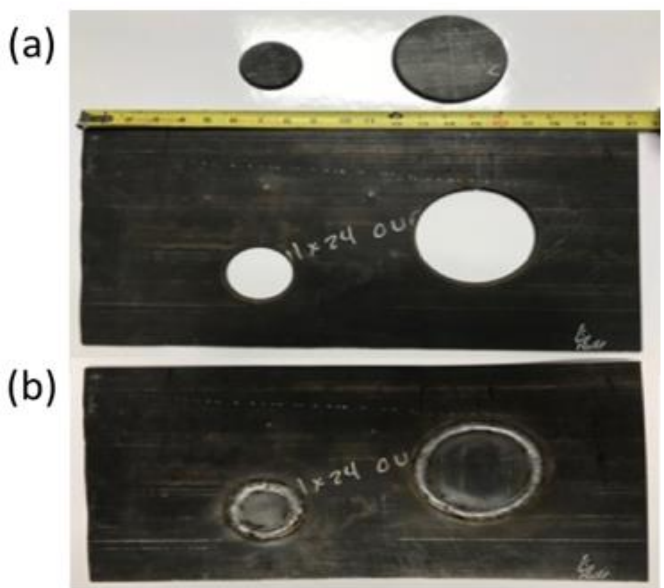

Figure 13: Flash® 600 welded "circles" which have been cut out (a), rotated, welded (b) without cracking

wire. As a welding stress test, this is often done to see if cracking occurs with stresses on the weld seam originating around the circumference [26]. Figure 13b shows the result which exhibited a well penetrated weld with no signs of cracking. Welding was performed with 5 passes from one side of the single grooved plate. The ER70S-6 weld wire used was stored in open atmosphere shop floor conditions in southeast Michigan for over 12 months prior to welding. The welded plate remains uncoated with no signs of cracking after 30 months under shop floor conditions. While not "best practices", this could have induced HIC if Flash® 600 was very susceptible.

In the extreme case meant to simulate in-theatre repair, parking lot stored Flash® 600 UHA was TIG butt-welded together using a coat hanger as weld consumable, shown in Figure 14. The 8" long multi-pass weld seam was free from cracking after 30 months indicating a lack of delayed embrittlement regardless of the low quality weld consumable, lack of preheating, and lack of post weld tempering. Further, the coat hanger was not properly stored as welding wire should be, was exposed to moisture, and thus should represent highly undesirable weld conditions. This is a stark contrast to welding of the standard Mars® 600 UHA which suggests austenitic consumables stored in a temperature and humidity controlled environment and recommended 150°C preheating to prevent weld cracking [27].

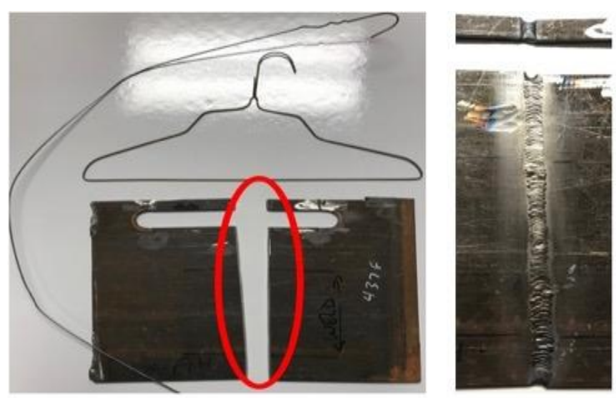

Figure 14: Flash® 600 butt-welded with a coat hanger at room temperature and no tempering

H-PLATE BALLISTIC SHOCK TEST

The weldability of Flash® 600 was tested under (4) different conditions to MIL STD 3040 and the H-plate ballistic shock test (BST). Note that MIL STD

3040 does not have provisions for welding of UHA. In fact, the proposed revision, noted as 3040A, states "*Ultra-high-hardness armor steel is considered unweldable by standard techniques due to the elevated carbon equivalence.*"

A plasma cutter was used to section the 36"x36" panels of 1/4" Flash® 600 plate into 4 parts. Edges were subsequently ground with a 6" abrasive wheel on a hand held grinder to a single or double V-groove. Using a weld process sheet for A-36 steel plate, Absolute Laser Welding Services, LLC in Sterling Heights, Michigan, was tasked with welding the H-plates. The first H-plate was welded with LA-100 wire that ALWS had in-house and used frequently. ER312 and ER120S-1 weld wire were purchased specifically for this project as ALWS does not use either of these consumables on a regular basis. The weld operator, using an A-36 weld process sheet, had 10 years of experience fabricating welded structures but no experience with ER-312 nor ER120S-1 wire and minimal hours of welding armor or AR600 abrasion resistant plate.

Shown in Table 3, parameters such as V-groove, preheat, and weld wire were varied. The proof projectiles PP-M1005 were fired at NTS Chesapeake under the supervision of ARL personnel. Per MIL STD 3040, a passing velocity is 1230 fps ±25 fps with a maximum crack length of 6". Four of four H-plates passed the BST testing criteria as described for HH since there are no provisions for UHA.

Table 3: H-plate Ballistic Shock Test Results

BST Result	V-Groove	Preheat °F	Weld Wire	Crack Length	Velocity in fps
PASS	Single	None	ER120S-1	3.50"	1257
PASS	Single	None	ER312-SS	5.94"	1232
PASS	Double	250-300	LA-100	5.10"	1242
PASS	Double	250-300	ER120S-1	5.40"	1207

Shown in Figure 15, the single V-groove H-plate welded at room temperature with ER120S-1 weld wire had a passing velocity of 1257 fps. The total crack length was 3.5" of the total 6" allowable for a passing result. Of the 4 tests, this was the shortest crack. Figure 16 shows the weld Vickers hardness mapping of the HAZ in which there is minimal fresh embrittlement at the fusion line. The mapping sample was cut from the H-plate after the BST.

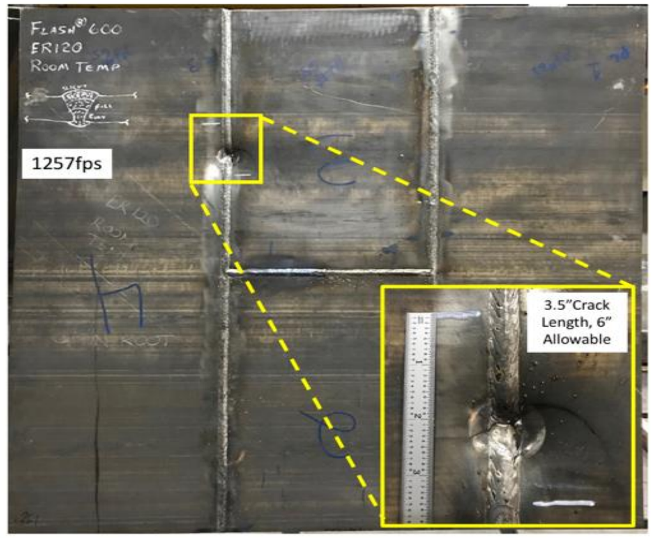

Figure 15: Flash® 600 butt-welded at room temp w/ ER120S-1

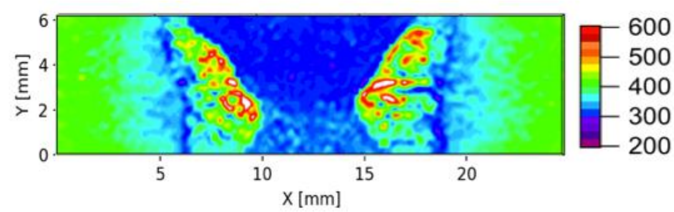

Figure 16: Flash® 600 single groove hardness mapping after being welded at room temp w/ ER120S-1 weld wire

TEKKEN Y-GROOVE

Experimentation has been done to review Tekken y-groove performance with 0.260" thick Flash® 600. Tekken tests are typically not performed at less than 0.394" thickness but it was decided to see what would result. Six Tekken plates were prepared using Wire EDM to put the primary groove in. The final y-shape was completed using an end mill on a Bridgeport milling machine with a sine plate. A few samples were welded to establish proper filler wire feed, advance rate, and other settings required for a good weld. Figure 17 shows the experimental setup.

Results were mixed but encouraging. Using ER70S-6 mild steel weld wire, the welds looked good upon completion. However, cracking was found along the entire length within a few hours. The next welding used LA100 wire, and welds again were crack free after welding. With the LA100, the welds still appeared crack free hours and days later.

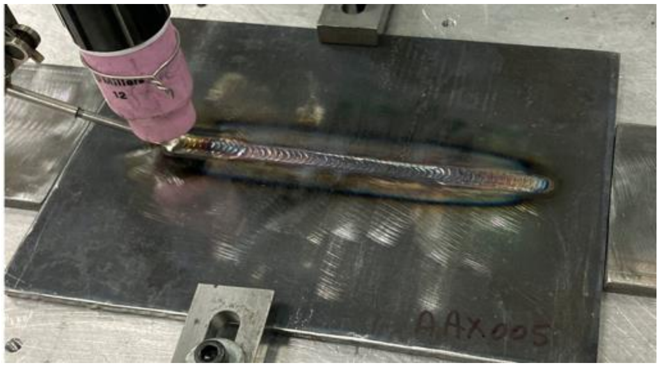

Figure 17: Flash® 600 Tekken y-groove sample after being welded at room temp with ER120S-1 weld wire

Six more Tekken samples were prepared the same as before with Wire EDM and end mill. The next y-groove tests were performed with ER120S-1 weld wire. Like the LA100, the ER120S-1 had better results than ER70S-6. Samples of the y-groove welds were sectioned, polished, and etched with the ER120S-1 shown in Figure 18. The red arrow notes a slight lack of sidewall fusion but no cracking in the HAZ.

It has been decided to proceed with more testing to provide statistical data on the use of LA100 and ER120S-1 weld wire with Flash® 600.

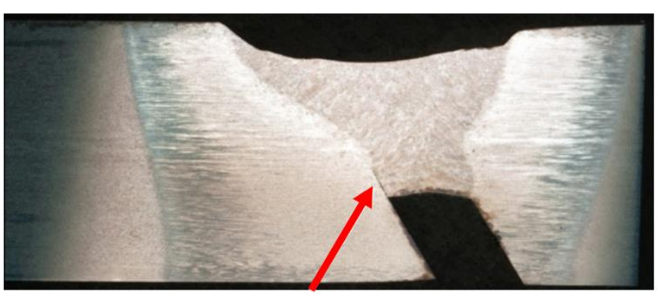

Figure 18: Flash® 600 Tekken y-groove sample. Note the lack of side wall fusion at the red arrow.

BAINITE: THE DIFFERENCE IN WELDING

Contradistinctively to other microstructures, bainite does not recrystallize into austenite upon the rapid application of 3 seconds of heat up to 950C. Flash Processing commercial SSAB bainitic steels like Domex700 to investigate a change in performance, the pre-existing Domex 700 bainite microstructure did not recrystallize into austenite until rapid peak heating temperatures exceeded 950C. Similarly, it should be true that during the rapid welding thermal cycle, bainite will remain locally after welding. SSAB Swedish Steel's Borggren states that bainite's "*ductility (elongation), toughness and temperature resilience is generally superior*" to martensite [28].

CONCLUSIONS

Because steel is widely used in the defense and heavy equipment industries, the use of stronger, tougher, and readily weldable Flash® armor can significantly improve structural robustness, reduce energy consumption, "*cost, and weight while also enhancing mechanical performance"* [18].

The key benefits of the Flash® Steel in industry are:

- Readily weldable at room temperature with less severe heat affected zones as welded by Army, Navy, OEM, and independent research labs.
- Simultaneously combines high strength and resistance to cracking.
- Does not require lengthy thermal mechanical production processes and costly alloying systems
- Process is well defined and readily available for immediate deployment

ACKNOWLEDGEMENTS

The US Dept of Energy supported Flash technology with two small business innovative research (SBIR) Phase I grants, a Phase II grant showing (9) Auto OEM geometries of cold stamped Flash® 1500 (220 ksi) or stronger, a Phase IIB demonstrating tool wear in a progressive stamping die, and a Phase III focusing on research and validation of a fully scaled up Flash Processing 10 ton coil-to-coil operation.

For many years, Dr. Jonathan Montgomery, Prof. Suresh Babu, and, more recently, Dr. John Lawmon have made invaluable recommendations to Flash Technology's progress.

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