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FLASH® BAINITE: ROOM TEMPERATURE WELDABLE ULTRA HARD 600, HIGH HARD 500, AND ADVANCED HIGH STRENGTH STEEL FOR A-CAB

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ABSTRACT

Flash® Bainite Processing employs rapid thermal cycling (<10s) to strengthen commercial off the shelf (COTS) steel sheet, plate, and tubing into Ultra Hard 600 Armor, High Hard 500 Armor, and advanced high strength steel (AHSS). In a continuous process, induction technology heats a narrow segment of the steel cross section in just seconds to atypically high temperature (1000-1300°C). Quenching substantially immediately follows.

*A report by Benet Labs and Picatinny Arsenal, investigating a less mature flash technology in 2011, surmised that the novel flash bainite process for steels has the potential to reduce cost and weight while also enhancing mechanical performance [1]. Receiving five financial grants, the US Dept of Energy has greatly matured flash technology in the last few years and its metallurgical understanding in collaboration with Oak Ridge National Lab and others. DOE has named Flash Bainite as the "**SBIR Small Business of the Year"** in May 2018 and awarded a Phase 3 SBIR to construct a 10 ton coil-to-coil flash processing line to meet the requests of the auto industry.*

CURRENT TRENDS

Many methodologies have been investigated to achieve an advanced high strength steel (AHSS) and grades of high performance armor with an ultimate strength of 225ksi or higher. While armor grades achieve 300ksi presently, they still seek to improve bendability, weldability, and blast resistance. The commercial auto industry desires to form automotive components at room temperature in a stamping press. While numerous paths have been researched, most methods have several elements in common. Typically, these concepts all involve costly intensive alloying 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 plate versus automotive sheet. While both desire lightweight while maintaining safety, automotive uses range from 0.5-3mm thick while defense uses are generally 4-12.5mm thick.

The basic steelmaking rolling processes can be challenged by these alloying strategies to simply produce the coils of steel. Mini-mills that use recycled steel as feedstock can also have contamination from tramp residual elements. Ramadan et al found that "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."[2] 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 remelting 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 when vehicles are shredded at the scrap yard. Higher manganese concentrations in long products, rebar, or lower manganese HSLA in which retained austenite could be created on cooling may be considered undesirable. Manganese in armor can lead to retained austenite which could affect welding consistency and strength/hardness due to localized inhomogeneity.

A COMPARISON OF METHODS

For millennia, steel has been heated and quenched to modify the mechanical performance. When steel alloys are heated to 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 converts into a matrix of various microstructures. Depending on the time and cooling rate used to cool the steel, ferrite, pearlite, bainite, martensite, and other microstructures 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 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 microstructures and chemistry. This is accomplished in sheet and plate products with lengthy exposure times of several minutes or hours to elevated temperatures in the range of 850 to 950°C followed by a variety of time-consuming cooling and temper methodologies.

Contrary to current steel processing technologies, the SFP Works, LLC and its flash bainite research staff, with assistance from Ohio State Univ, Univ of Tennessee-Knoxville, Oak Ridge National Lab, Edison Welding Institute, the US Army's RDECOM, and others, has discovered that the mechanical properties of steel can be improved by maintaining a varied and random distribution of microstructures and carbon concentrations at the intragranular scale. With flash processing, oxy-propane heating, and more recently, standard induction heating technology, has been used to rapidly increase the temperature of steel plate, sheet, and tubing to over 1000°C to form austenite and then quenched substantially 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 process is performed in less than 10 seconds.

Flash processing rapid thermal cycles preserve heterogeneous microstructures because kinetically sluggish processes do not have time to homogenize the chemistry of the austenitic microstructure. The result is a heterogeneous, complex metal matrix composite of chemistries that each provides a different advantage. The low carbon regions are readily weldable and ductile while the high carbon regions are strong and hard. In particular, flash processing of commercial available chrome-moly (AISI41XX series) steels produces especially strong complex microstructures exceeding 300ksi while plain carbon (AISI10XX series) steels produce highly form-able steel up to 260ksi. Stainless grades such as 13Cr have led to 260ksi ultimate strength after flash processing.

Flash processing of steel plate such as readily available AISI4140 (300ksi ultra hard), AISI4130 (260ksi high hard), AISI1020 (225ksi structural sheet), and 13Cr (260ksi stainless high hard) has shown excellent weldability at room temperature for use as A-cab and B-kit. Flash ultra hard was certified to MIL DTL 32332 in Nov2017 while flash high hard was certified to MIL DTL 46100 earlier. While still under development, flash stainless armor has demonstrated that ability to pass the ballistic requirements to MIL DTL 46100 high hard in internal research and development (IRAD) testing. Flash processed tubing and sheet for automotive stampings has been demonstrated by automotive OEMs to reduce mass, reduce cost, and simultaneously improve performance. At Aberdeen Test Center, flash processed AISI4130 high hard was found, on a per mass basis, to outperform titanium, typical high hard armor, and aluminum armors against 0.30-cal M2AP at 0d obliquity and 20mm FSP. While it is acknowledged that high hard, per MIL DTL 46100 is to be tested at 30d obliquity, the 0d obliquity comparison is offered as demonstration to a more difficult angle of attack that other metals are tested to, similar to the DARPA Armor Challenge. The DARPA Armor Challenge was an annual contest to find new methods, metallic, composite, or hybrid, that can reduce armor's areal density while providing leading protection. By standardizing the threats and vector approach, it leveled the playing field to compare various armor solutions.

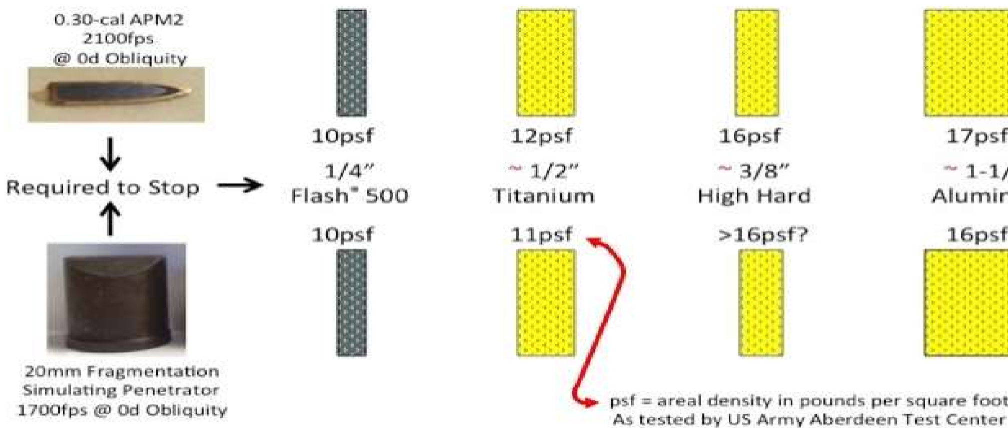


Fig1: Comparison of flash high hard 500 to other metals

US Dept of Energy support led to commercial scale flash processing equipment, shown below in Figure 2. The flash coil-to-coil line is anticipated operational Q3-2018. The equipment will is designed for 48" wide steel at thicknesses ranging from 0.5mm to 1.8mm thick and strength ranging from 160ksi to 235ksi (1100 to 1600MPa).

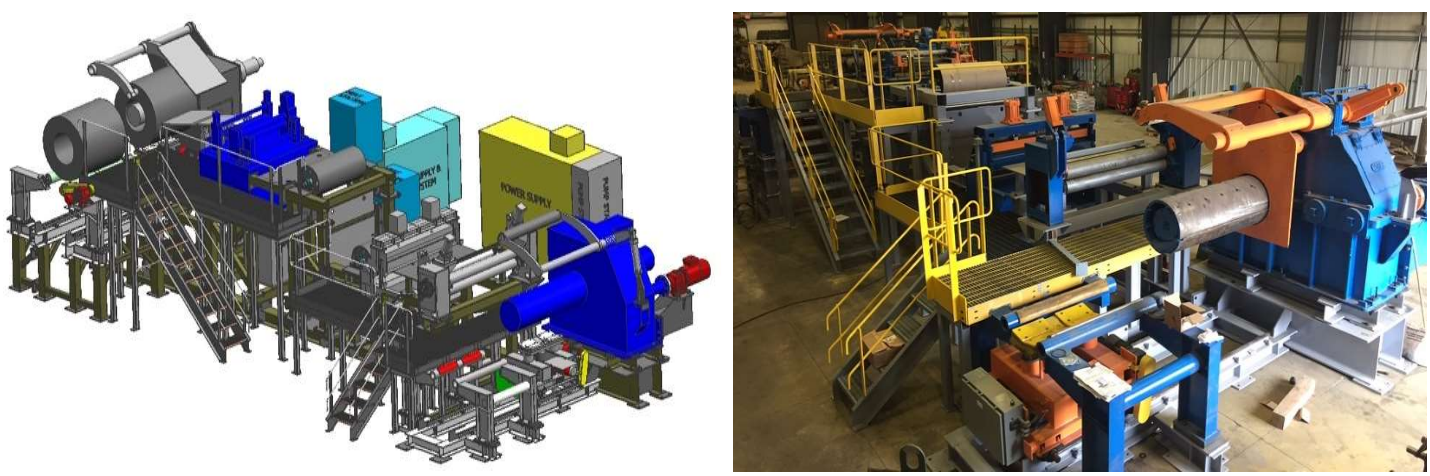


Fig 2: Flash 10 ton Coil Processing (left) and equipment build (right)

While DOE sponsored research was ongoing, IRAD studies led to the validation of flash ultra hard 600 made from common AISI4140 steel. With minimal alloying elements, flash processing can be controlled to produce a matrix of up to 20-25% bainite with remainder primarily martensite. Since the 1980s Academia has known this 20/80 or 25/75 ratio will yield what is considered "maximum strength™" steel for a given iron alloy [3] leading to 7-10% increased strength over other heat treating methods. However, until flash technology, a process to consistently produce this 7-10% stronger complex microstructural mixture from lean alloy steel remained elusive. Flash processing is the first known process capable of producing cost effective steels that combine maximum strength, form-ability, lean recyclability, and leading weldability. While martensite does constitute a majority of the result, bainite is the unexpected aspect for which the flash bainite process is named. Similar to other heat treating methodologies, the chemistry of the steel will control the resulting morphology to increase or negate the bainite volume fraction which can tailor the resulting mechanical properties.

A COUNTERINTUITIVE GRAIN REFINEMENT MECHANISM FOR STRENGTHENING

Long held notions exist that significant cold working to a "full hard" condition is the preferential method to initiate grain refinement in AHSS. Coils of steel are systematically reduced in thickness while elongating grains in the rolling direction. The steel strip is then processed with precise temperature control in a continuous annealing line (CAL) or batch furnace requiring many minutes to hours at elevated temperatures. The goal of the 3-4 micron prior austenite grain size (PAGS) refinement is achieved thus strengthening the strip due to the smaller grains as shown in Figure 3 (left).

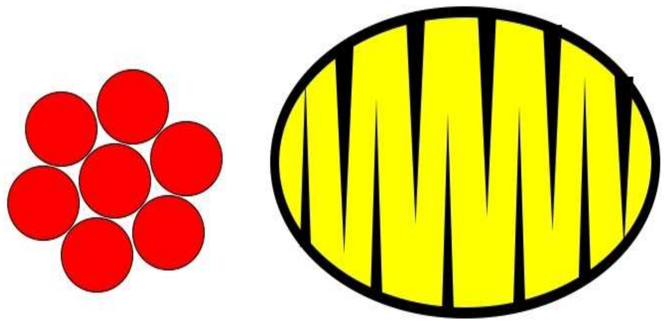


Fig 3: 3-4 micron grain refinement (left) versus grain growth initiated refinement (right)

Counterintuitively, it has been found that during flash processing, grain refinement can actually occur by rapidly expanding the prior austenite grain size to 20-25 microns. Rapidly heating to peak temperatures above 1000°C encourages such grain growth. The intragranular heterogeneity that exists during flash processing creates not only a complex microstructure but a novel form of grain refinement achieved through a heating induced grain expansion mechanism. As the heterogeneous chemistry ferrite/pearlite steel strip is heated in the austenitic range, typically above 1000°C, carbon migrates from enriched prior pearlitic regions to depleted prior ferritic regions. While carbon migration is initiating, it is abruptly halted by the quenching of the steel strip. The lower carbon regions transform to austenite daughter phases first. It is these initial high temperature transformation phases that enact a subdivision of the PAG. As shown in Figure 3 (right), an enlarged grain first forms acicular phases shown as triangles, such as bainite, at temperatures cool often between 650°C and 550°C, in just 80 milliseconds during quenching. During further cooling, the remaining intermediate regions can be cooled by a water quench approximately 100 milliseconds later. These intermediate regions have exhibited nano-scale refinement of the intragranular, segregated austenite such that when martensite forms, it is highly refined and thus very strong. The complex flash microstructure that is formed has exhibited 7-10% more strength than sheets from the same heat of steel conventionally processed in a CAL or batch furnace. For example, flash processed AISI1020 steel (at 0.20%wt C) has an ultimate strength of 225ksi while quench and tempered AISI1020, as tested by a major domestic steel mill, only achieves 200ksi.

Figure 4 shows a proposed automotive "crush can" application for Flash 1500 that is part of an ongoing research project. Tubing of 63mm diameter and 1.2mm wall thickness has been formed into two different configurations. The first was a 50mm x 60mm rectangle at a length of 140mm. The second rectangular shape of 40mm x 70mm collapsed straighter in initial testing. The photo at right is of the crush can Wire EDM-ed in half to reveal the 0T to 1T bend radii made during the crushing of the tube from 140mm in length down to 50mm. It should be noted that typical auto crush cans are made of either DP780 steel (780MPa or 115ksi) or aluminum tubing and hydroformed into shape. Further investigation is underway to confirm energy absorbing properties. Given the need for energy absorbing structural metals, there is significant potential for flash processed steels as both armor and structural grades and their ability to bend with limited cracking.

Figure 4 shows a research project for an automotive "crush can" made of Flash® 1500 (225ksi).

To improve automotive crashworthiness in side impact events, boron tubing has been used by many Auto OEMs. Hyundai Motor Group, in its quest to ever increase automotive performance, has sought out higher performing steels as well. Hyundai researchers had interest in testing flash bainite at 1800 MPa against the performance of boron steels as car door impact beams [4]. To fully compare other OEMs work, Hyundai disassembled door beams from five other highly rated current production cars.

A testing regimen was developed using the US Side NCAP pole test. Maximum displacement was limited to 200mm. This could represent 75mm of door thickness reaching to the door inner decorative panel and then 125mm of further intrusion into the passenger compartment. The OEM door beams were tested in the sizes that other OEMs had selected to use as shown in Figure 5 (left). Resisting force is plotted against the displacement as the tubing is deformed during impact. Various diameters of flash bainite tubing were selected between 25 and 32mm. Tubing wall thickness was varied from 1.6mm to 3.0mm. Figure 5 (right) shows the flash tubing performance at various diameters and wall thickness compared to OEM #1's 32mm diameter at 2.2mm wall.

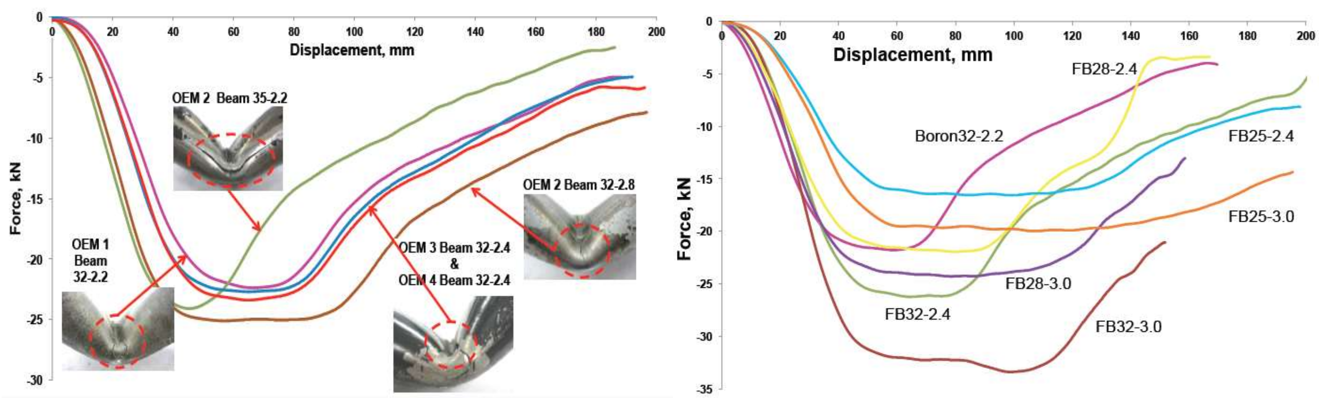


Fig 5: OEM boron tubing compared to flash bainite resisting force vs displacement during US Side NCAP test

Based on the displacement versus resisting force findings, relationships were plotted showing the different diameters tested for each wall thickness. Figure 6 (left) clearly illustrates that 32mm diameter flash tubing has higher resisting force than the boron tubing for a given wall thickness. Approximately 15% or more resisting force is provided by the flash tubing for the 32mm diameter tubing size at the exact same mass per unit length. As well, 32mm and 28mm flash tubing have higher total energy absorbed for a given wall thickness than 32mm boron tubing as shown in Figure 6 (right). At least 20% or more total energy absorbed is provided by the flash tubing size at the exact same mass per unit length.

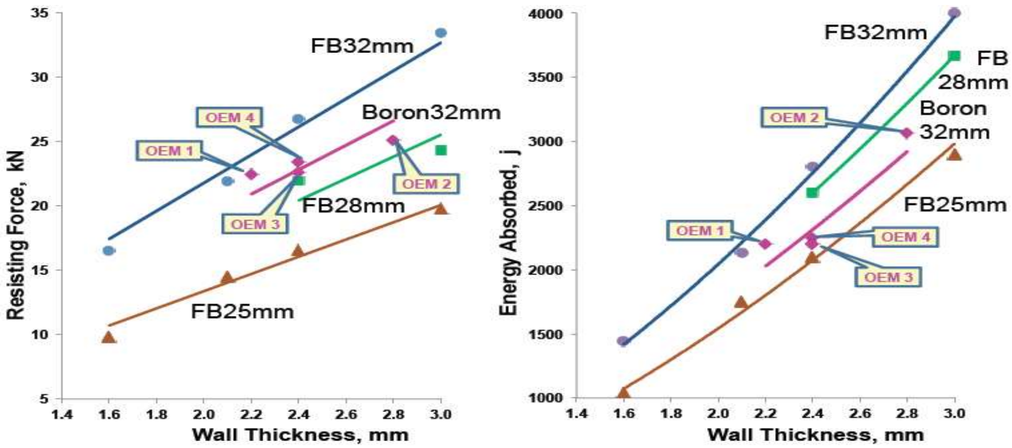


Fig 6: flash and boron tubing resisting force vs wall thickness (left) and total energy absorbed vs wall thickness (right)

Flash bainite tubing has been made in round, square, rectangular, and custom roll formed geometries. Such geometries lend themselves to many transportation related components. In vehicles, bumpers, roll bars, roof members, pillars, frame rails, hitches, and many other parts have been made with tubing and could be made with flash bainite. While the energy absorption capacity of flash bainite tubing is further documented, the formability of flash bainite tubing will lend itself to making tubing components that are considered impossible today. Hydroforming of tubes is currently limited to dual phase steels at a strength of 1000MPa (145ksi) known as DP1000. Flash bainite at 1500MPa (220ksi) has been shown to form the same components in the same tubing geometry as DP1000. This will lead to more robust, lighter structures with a 1/3 mass reduction.

Figure 7 shows an automotive barrier shield stamping and the points measured before and after impact testing[5]. In testing at a major OEM test laboratory, a 3.0mm thick current production barrier shield made of HR550LA steel (hot rolled, low alloy at 550MPa yield strength) was compared to barrier shields made from Flash 1500 at 2.0mm thick, Flash 1500 at 1.6mm thick, and Flash 1600 at 1.27mm thick. Impact testing was performed at 100% of CAE estimated loads for the initial review. Continued testing was performed at 110% and/or 120% of CAE loads for various thicknesses. While the 2.0mm thick Flash 1500 performed statistically similar to the 3.0mm HR550LA parts, even the 1.27mm Flash 1600 part based baseline testing. None of the flash parts exhibited signs of cracking within the part or at location #15 where a support tube was welded per part design. Figure 8 shows the barrier shield on the test fixture before and after impact testing.

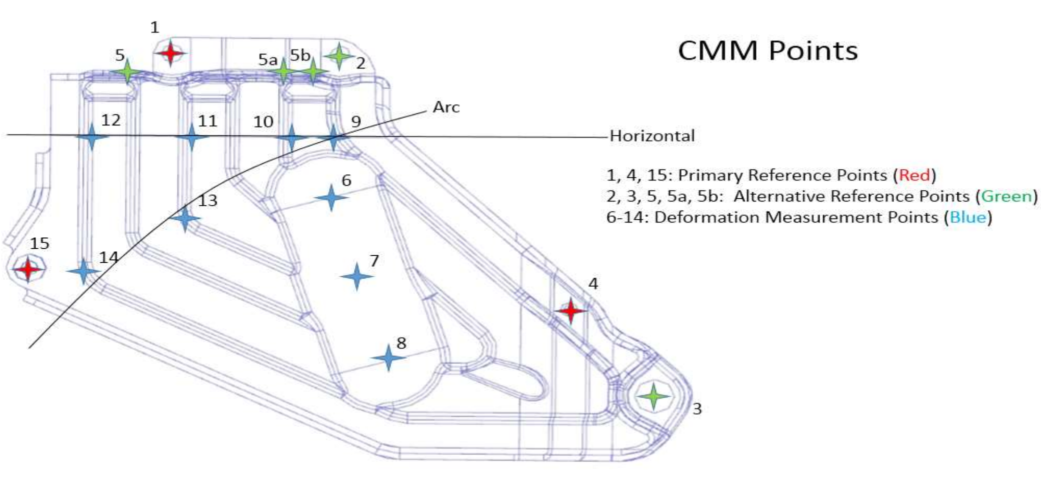
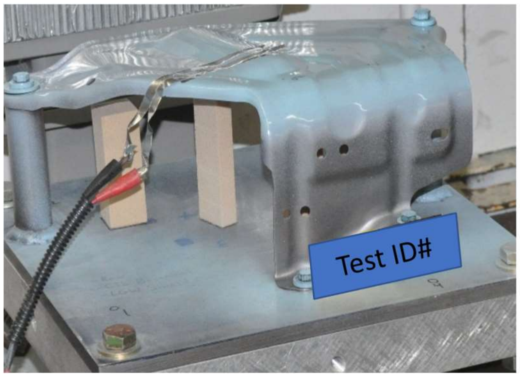


Figure 7 shows the barrier shield points measured by CMM before and after the impact testing.



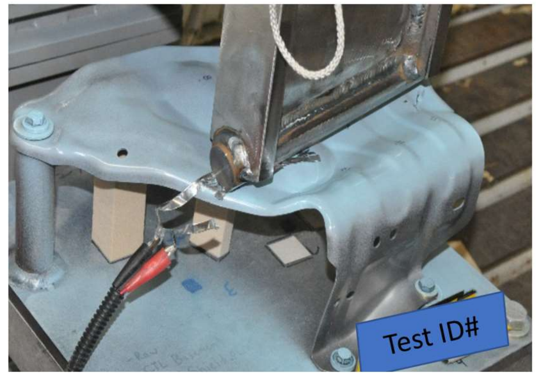


Figure 8 shows the barrier shield before(left) and after(right) the impact testing. Note the test ram (right).

Figure 9 shows an example of a 2mm thick cold stamped Flash 1800MPa (260ksi) component. The chemistry of the Flash 1800 is based on AISI1030 with an elevated manganese of 1.5wt%. This alloy grade is a standard chemistry used for pressure vessels and propane tanks. Throughout the component geometry is a 4mm bend radii leading to a 2(r/t) bend radius. Tensile/elongation testing found a respectable 205ksi yield, 260ksi ultimate, and a 8.4% non-brittle A50 total elongation. At 260ksi, this 2mm thick part stamping is pound per pound as strong as titanium-6Al-4V in its strongest STA Bar condition. This likely makes this complex stamping stronger and harder than 99% of the weldable metallic armor currently in use. Many lightweighting possibilities exist for "armor grade" sheet metal that is readily weldable for the vehicle structure. While difficult to recognize, this part is taken from the geometry of the barrier shield left side as shown in Figure 8.

Fig 9: Flash® 1800 (260ksi) prototype 2mm thick x 125mm x 125mm stamping to 2(r/t) bend radii

As flash bainite is typically made from COTS lean alloyed steel, manufacturing processes such as welding, painting, and laser trimming, remain unchanged, if not less intense. Flash steels up to 0.42wt% carbon, validated as ultra hard 600, have been found to be readily weldable at room temperature, not requiring any preheating or post tempering. Welding bend tests have found no signs of embrittlement after weld bending tests were performed. Welded steels typically fail where the steel has been reheated during welding, an area known as the heat affected zone ("HAZ"). In Figure 10, a typical HAZ in 1/4" armor plate is shown on the right as performed by Edison Welding Institute with gas metal arc welding (GMAW). The left side of the figure below shows the HAZ for a weld between pieces of flash high hard made from AISI4130. The colors depict hardness within the weld with red representing the harder areas and violet representing the softer areas.

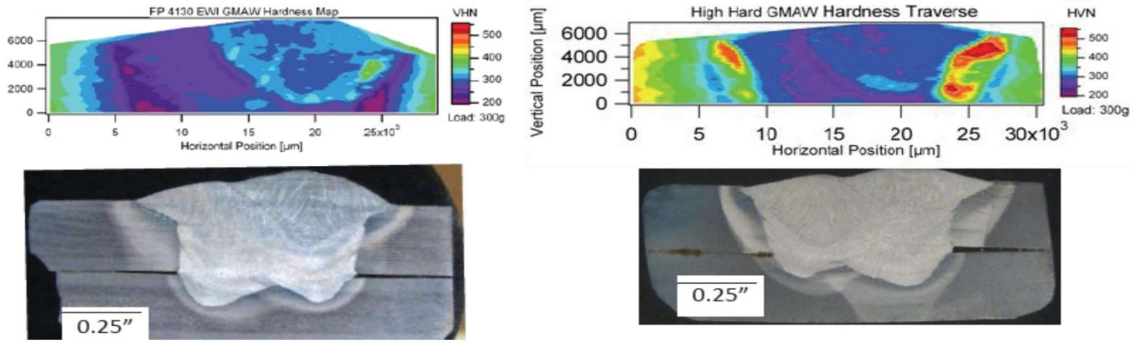


Figure 10 shows the GMA Weld hardness mapping of flash high hard (left) and typical High Hard (right).

In typical high hard armor, the interface between the bulk metal and the weld, known as the “fusion line”, is very hard as depicted by the deep red color. The extreme hardness of the fusion line is caused by a homogenous martensite structure which is very brittle and the primary source of weld failure. Such failures appear during blast events or fatigue from daily wear. The blue/violet area in the center of the HAZ of the AHSS weld is softer than the bulk material and not the source of embrittlement. While conventional high hard welds can separate and fail, flash high hard has been found to have “ductile shear lips” which resist brittle failure.

Flash processed steel has a unique HAZ because it does not develop a fusion line hardened into brittle martensite. As can be seen in the hardness mapping on the left side of the weld figure, the flash processed steel is softest in the center of the HAZ and gradually increases hardness moving outward into the bulk flash steel being welded. This leads to welds on flash processed steel that are more ductile and less prone to brittle failure under high loading conditions when compared to other high hard steels.

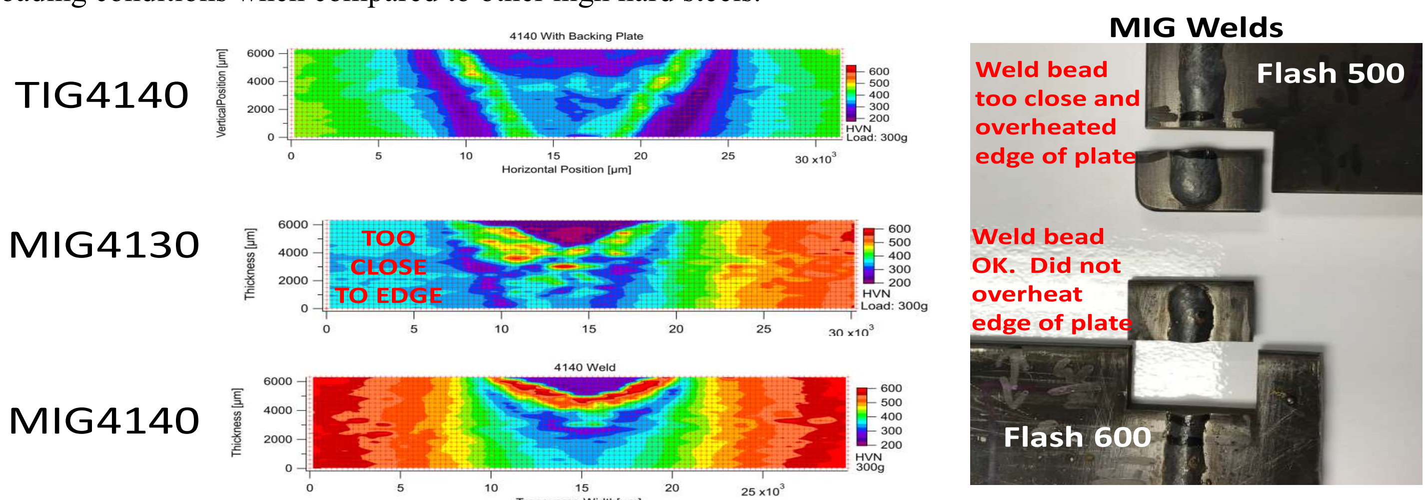


Figure 11 shows the weld hardness mapping from TIG and MIG with flash armor

To complete the comparison to the Edison Welding Institute work (see Figure 10), a TIG weld was performed with flash processed 4140 at 600+ Vickers hardness (Hv) shown in Figure 11. In order to minimize the heat affected zone, five linear passes along the weld seam were performed. The final pass used a weave welding technique to temper and soften the final weld pass. As shown in the TIG 4140 welds of Figure 11, no fresh embrittlement of a hardness above 500Hv was present. It is also noteworthy that both flash processed AISI4130 and flash processed AISI4140 have less embrittlement than the conventional high hard 500Hv plate shown in the right of Figure 10. It is believed that flash processed 4130 high hard, and likely Flash 600 from 4140 plate could achieve less severe HAZ hardening than all other high hard 500 quench/temper plates currently used for applications in heavy equipment, agriculture, mining, armor, the steel industry, and more.

CONCLUSIONS

Because steel is widely used in the defense and automotive industries, the use of formable and readily weldable flash armor and sheet steel can significantly reduce the lifetime energy consumption of millions of vehicles while increasing performance. Flash processing can reduce costs to OEMs, because the small increase in the per pound cost of flash processed steel is more than offset by the fact that less steel is required to produce a component. Flash processing equipment uses induction heating technology made by dozens of manufacturers around the World. flash processing can be performed with compact, low capital cost equipment which will significantly expand the number of entities that can produce 160 to 300ksi armor and sheet steel. Finally, flash processed steel will also benefit other industries, including heavy equipment, shipping, and architectural where low cost high strength steel can reduce material requirements.

In summary, the key benefits of the flash bainite process in steel manufacturing are:

- Simultaneously combines high strength and high form-ability in a cost effective solution
- Enhances welding characteristics with less severe heat affected zones
- Performance benefits can be achieved with a wide range of existing grades of steel
- Can eliminate the need for expensive alloying elements
- Does not require time consuming thermal mechanical production processes
- Simple process reduces complexity of production equipment and capital intensity
- Process is well defined and readily available for immediate deployment

When designing military and automotive structural applications, it is paramount to fully understand the specific structural strength of all potential solutions to design, per mass, the lightest, most robust vehicles. Flash bainite has surfaced as the leader in specific strength surpassing all other readily weldable, cost effective metal solutions. Impact testing to determine crashworthiness has found flash bainite to outperform the best boron steels available to industry today.

ACKNOWLEDGEMENTS

The US Dept of Energy has 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 (220ksi) or stronger, and a Phase III focusing on research and validation of a fully scaled up flash processing 10 ton coil-to-coil operation.

For more details, please contact Gary Cola at (*586) 864-9001 ext. 1 or gary.cola@flashbainite.com.*

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