ARMY RESEARCH LABORATORY

Development and Ballistic Testing of a New Class of Auto-Tempered High-Hard Steels Under Military Specification MIL-DTL-46100E

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) was directed to investigate various ways to expand current steel armor plate production as the large military demand for armor plate exceeded the current production capacity at U.S. steel facilities for quench and tempered high-hard armor (HHA) steel plate. The solution was to expand the availability of HHA steels under the current HHA military specification (MIL-DTL-46100) to include a new class of air-quenched, auto-tempered steels that do not use existing water quench and temper facilities. Allegheny Technologies Incorporated (ATI) developed an auto-tempered steel alloy, ATI 500-MIL (trademark of ATI Properties, Inc.), that has physical and mechanical properties that meet the current HHA specification. ARL procured sufficient amounts of ATI 500-MIL plate to allow acceptance testing and subsequent certification of ATI 500-MIL plate as complying with the First Article requirements of the newly revised MIL-DTL-46100E specification. This report documents the development of ATI 500-MIL plate and subsequent ballistic testing and inclusion into the specification as Class-2 auto-tempered HHA steel.

15. SUBJECT TERMS
high-hard steel, auto-tempered, armor, ballistic testing

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1. Introduction

The U.S. armor community is currently engaged in accelerated efforts to deliver lightweight armor technologies that can defeat armor-piercing (AP) projectiles at reduced areal weights that are available across a large industrial base. While many of these programs involve the application of lower-density metals such as aluminum and titanium, the selection of steel alloys is still competitive for many ballistic and structural applications; the ability to fabricate armor components in both commercial and military operational areas with available equipment and personnel is a major advantage of steel solutions. To meet these requirements, the U.S. armor community has increased the availability of quenched and tempered armor steels by updating current steel military specifications, the most important of which has been the updated/revised MIL-DTL-46100E, *Armor Plate, Steel, Wrought, High-Hardness*.[1] This improved specification was necessary to supply the large steel demands for combat operations in Iraq and Afghanistan. This high-hard armor (HHA) specification allows modern, continuous processing technologies to be used efficiently as well as introducing a new class of auto-tempered high-hard steels.

The U.S. Army Research Laboratory (ARL) was directed to investigate various ways to expand current steel armor plate production as the large military demand for armor plate exceeded the current production capacity at U.S. steel facilities for quench and tempered HHA steel armor plate. The solution was to expand the availability of HHA steels under the current military specification to include a new class of air-quenched, auto-tempered steels that do not use existing water quench and temper facilities. Allegheny Technologies Incorporated (ATI) developed an auto-tempered ATI 500-MIL[*] steel alloy that has physical and mechanical properties that meet the current HHA specification. ARL procured sufficient amounts of ATI 500-MIL plate to allow acceptance testing and subsequent certification of ATI 500-MIL plate as complying with the First Article requirements of the newly revised MIL-DTL-46100E specification.

Currently, the highest-performing U.S.-made steel alloys for AP bullet protection are manufactured to MIL-DTL-46100E HHA with a hardness range of 477-534 Brinell hardness number (BHN) and to MIL-A-46099C Dual Hardness Armor (DHA) that is produced by roll-bonding a 601-712 BHN front plate to a 461-534 BHN back plate.[2] The roll-bonded DHA steels are complex to produce and have known production limitations. In the near-term, the U.S. Army will be releasing a new ultra high-hard steel specification for plate hardness over 534 BHN that will further expand the hardness range for ballistic applications. The improved ballistic resistance of steel as a function of increasing hardness is well established in the ballistic

[1]MIL-DTL-46100E. *Armor Plate, Steel, Wrought, High-Hardness* **2008**.

[*]ATI 500-MIL is a trademark of ATI Properties, Inc.

[2]MIL-A-46099C. *Armor Plate, Steel, Roll-Bonded, Dual Hardness (0.187 Inches to 0.700 Inches Inclusive)* **1987**.

community, particularly by Rapacki et al. in the 15th International Symposium on Ballistics.[3] HHA steel increases AP bullet defeat, reduces armor weight, and is less difficult to manufacture than the DHA. This report documents the development of ATI 500-MIL plate and subsequent ballistic testing and inclusion into the specification as Class-2 auto-tempered HHA steel.

2. Allegheny Technologies ATI 500-MIL Plate

In June 2008, ATI announced the successful launch of a new class of HHA specialty steel. This next-generation armor steel, designated ATI 500-MIL, was developed in response to limited American HHA production and limited performance features of materials in this class. ATI 500-MIL alloy is melted, rolled, and finished in America on fully integrated assets owned and operated by ATI. This new material is designed to offer additional features that were not previously available in traditional quench and temper high-hard armor steels. Product design is also geared to obtain improvements in ballistic and blast resistance when compared with other HHA materials. ATI 500-MIL steel plate is designed to meet the requirements in MIL-DTL-46100E while also offering features that address several common challenges frequently encountered with conventional HHA plates.

The composition of ATI 500-MIL alloy includes appreciable amounts of Ni-Cr-Mo, which results in relatively high hardenability and increased toughness compared to other HHA alloys (tables 1 and 2).[4] As a result, the balanced combination of unique properties and consistent quality allows this alloy to meet the specifications outlined in the MIL-DTL-46100E, which was recently revised to account for these improvements.

ATI 500-MIL armor addresses secondary processing difficulties associated with various operations. Specifically, operations such as forming (cold and hot), cutting or sectioning, and postoperation heat treatments for restorations of ballistic properties were successfully alleviated.

These postprocess improvements are partly due to the fact that the alloy is auto-tempered upon air cooling, thereby eliminating the traditional liquid-quenching and temper treatment. The slower air cooling combined with ATI's proprietary processing results in significantly higher dimensional armor stability.

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[3]Rapacki, E.; Frank, K.; Leavy, B.; Keele, M.; Prifi, J. Armor Steel Hardness Influence on Kinetic Energy Penetration. *Proceedings of the 15th International Symposium on Ballistics*, Jerusalem, Israel, May 1995.

[4]ATI Defense. ATI 500-MIL High Hard Specialty Steel Armor, version 3; ATI Defense Data Sheet, Washington, PA, 3 September 2008.

Table 1. Chemical composition of ATI 500-MIL plate.

Alloy	% C (max)	% Si	% Mn (max)	% P (max)	% S (max)	% Cr (max)	% Ni (max)	% Mo (max)
ATI 500-MIL	0.22–0.32	0.25–0.45	0.80–1.20	0.020	0.005	1.60–2.00	3.50–4.00	0.22–0.37

Table 2. Mechanical properties of ATI 500-MIL plate.

Alloy	Hardness BHN	Charpy-V –40 °C ft/lb (J)	Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)	Elongation (%)
ATI 500-MIL	477–534	20 (27)	150 (1034)	260 (1792)	13

Residual stresses in ATI 500-MIL products are also reduced compared to traditional liquid-quenched and tempered products. These improvements result in flatter armor products that exhibit minimal distortion during fabrication operations, such as hot or cold cutting. Since the product is auto-tempered, the alloy does not require any special postwelding operations involving liquid quenching and temper to restore ballistic properties.

3. Experimental Procedure

The ballistic performance of ATI 500-MIL steel plates was determined by obtaining the V_{50} ballistic limit for each thickness of plate against the corresponding specified test projectile. The test methodology is described in detail in the MIL-STD-662F.[5] The V_{50} ballistic limit is the velocity at which an equal number of fair-impact complete penetration (target is defeated) and partial penetration (target is not defeated) velocities are attained using the up-and-down firing method. Fair impact is defined as occurring when a projectile with an acceptable yaw strikes the target at a distance of at least two projectile diameters from a previously damaged impact area or edge of plate. A complete penetration is determined by placing a 0.5-mm (0.020-in) 2024 T3 aluminum witness plate 152.6 mm (6 in) behind and parallel to the target. If any penetrator or target fragment strikes this witness plate with sufficient energy to create a hole through which light passes, the result is considered a complete penetration. A partial penetration is any impact that is not a complete penetration. For the MIL-DTL-46100E specification, the V_{50} ballistic limit is defined as the average of six fair impact velocities comprising the three lowest velocities resulting in complete penetration and the three highest velocities resulting in partial penetration. A maximum spread of 45.7 m/s (150 ft/s) shall be permitted between the lowest and highest velocities employed in determining ballistic limits. The data for the ATI 500-MIL steels are compared to the baseline ballistic acceptance data of MIL-DTL-46100E.

[5]MIL-STD-662F. *Department of Defense Test Standard* **1997**.

4. Test Projectiles

The eight ATI 500-MIL plates tested for First Article certification ranged in thickness (nominal) from 0.1875 in (4.8 mm) up to 1 in (25.4 mm). The corresponding test projectiles and plate obliquities required for each thickness under MIL-DTL-46100E are listed in table 3. The weights and sizes of the projectiles are shown in table 4. These projectiles are shown in figures 1 and 2, with the 14.5-mm BS41 being a tungsten carbide core and the rest hardened steel. In some cases, additional testing was conducted outside this range to allow the data to be graphed. This is noted for the nominal 8-mm (0.315-in) thickness.

Table 3. Thickness ranges and corresponding test projectiles for First Article testing.

Nominal Thickness Range in (mm)	Obliquity (°)	Test Projectile
0.118 (3.0) to 0.300 (7.62) incl.	30	cal. 0.30 APM2
0.301(7.62) to 0.590 (15.0) incl.	30	cal. 0.50 APM2
0.591 (15.0) to 0.765 (19.4) incl.	30	14.5-mm B32
0.766 (19.4) to 1.130 (28.7) incl.	30	14.5-mm BS41

Table 4. Geometries and weights of projectiles utilized in ATI 500-MIL plate testing.

Projectile Type	Projectile			Core		
	Length in (mm)	Diameter in (mm)	Weight gr (g)	Length in (mm)	Diameter in (mm)	Weight gr (g)
0.30-cal. APM2	1.39 (35.3)	0.31 (7.85)	166 (10.8)	1.08 (27.4)	0.24 (6.2)	81 (5.3)
0.50-cal. APM2	2.31 (58.7)	0.51 (12.98)	708 (45.9)	1.87 (47.5)	0.43 (10.9)	400 (25.9)
14.5-mm B32	2.61 (66.3)	0.59 (14.86)	990 (64.1)	2.09 (53.1)	0.49 (12.4)	633 (41.0)
14.5-mm BS41	2.07 (52.6)	0.59 (14.94)	975 (63.2)	1.27 (32.3)	0.43 (10.9)	585 (37.9)

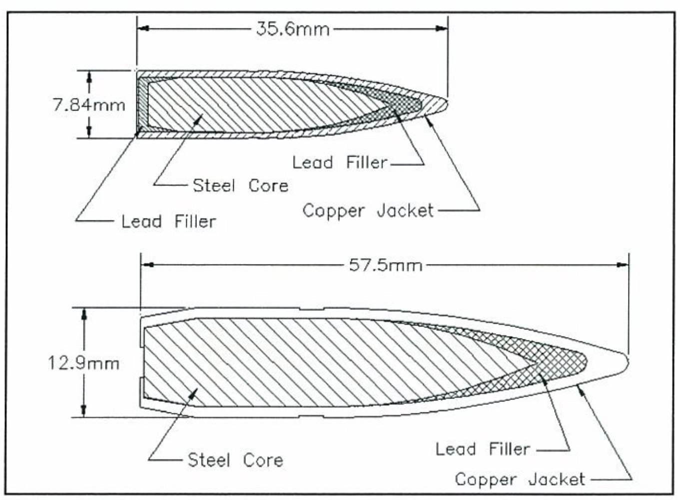

Figure 1. The 0.30-cal. APM2 and 0.50-cal. APM2 test projectiles.

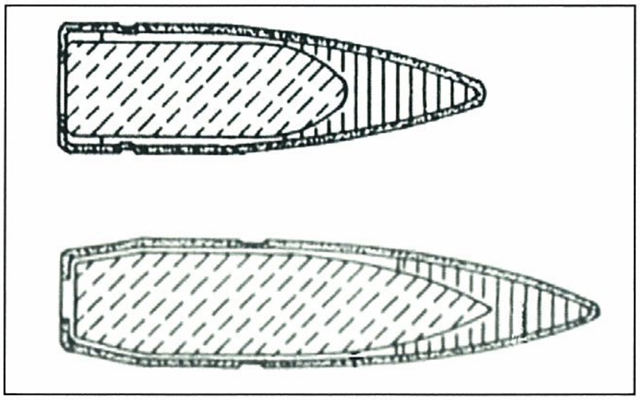

Figure 2. The 14.5-mm BS41 (top) and B32 test projectiles (bottom).

5. Results and Discussion

The V_{50} ballistic limits and standard deviation, σ, for each plate thickness were determined experimentally for the ATI 500-MIL plates; the data is shown in table 5 for each test projectile. Figures 3–6 plot the V_{50} velocities vs. the ATI 500-MIL plate thickness as well as the acceptance velocity specification curve for HHA steel (MIL-DTL-46100E). The ballistic advantage of increased alloying can be seen in figures 3–6 where all the plates exceeded the minimum velocity acceptance velocities of the specification. The differences were significant for the thinner plates and approached the acceptance line as the thickness increased. The solid lines of the acceptance curves for MIL-DTL-46100E incorporate approximately two standard deviations reduction below typical performance, which provides an acceptable variance to allow the high-hard plate to meet the specification.

Table 5. V_{50} plate acceptance results.

Nominal Thickness in (mm)	Projectile	Actual Thickness in (mm)	Obliquity Angle (°)	V_{50} ft/s (m/s)	Standard Deviation ft/s (m/s)
0.1875 (4.8)	0.30-cal. APM2	0.202 (5.1)	30	2174 (663)	43 (13)
0.250 (6.35)	0.30-cal. APM2	0.272 (6.9)	30	2688 (819)	36 (11)
0.3125 (7.94)	0.30-cal. APM2	0.305 (7.7)	30	2672 (814)	40 (12)
0.3125 (7.94)	0.50-cal. APM2	0.305 (7.7)	30	2058 (627)	47 (14)
0.375 (9.53)	0.50-cal. APM2	0.381 (9.7)	30	2373 (723)	43 (13)
0.500 (12.70)	0.50-cal. APM2	0.517 (3.1)	30	2582 (787)	56 (17)
0.625 (15.88)	14.5-mm B32	0.614 (15.6)	30	2396 (730)	43 (13)
0.625 (15.88)[a]	14.5-mm B32	0.607 (15.4)	30	2424 (739)	32 (9)
0.750 (19.05)	14.5-mm B32	0.742 (18.8)	30	2760 (841)	43 (13)
1.000 (25.40)	14.5-mm BS41	0.966 (24.5)	30	2851 (869)	56 (17)

[a] Retest.

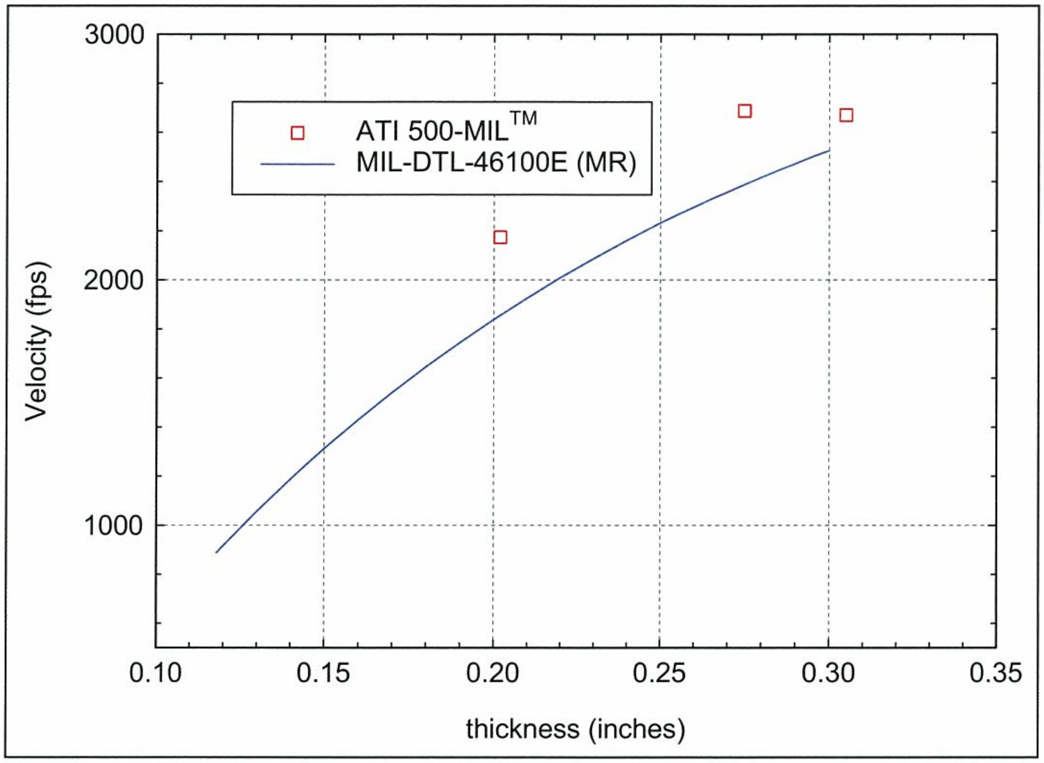

Figure 3. ATI 500-MIL plate thickness vs. V_{50} velocity for the 0.30-cal. APM2 at 30° obliquity.

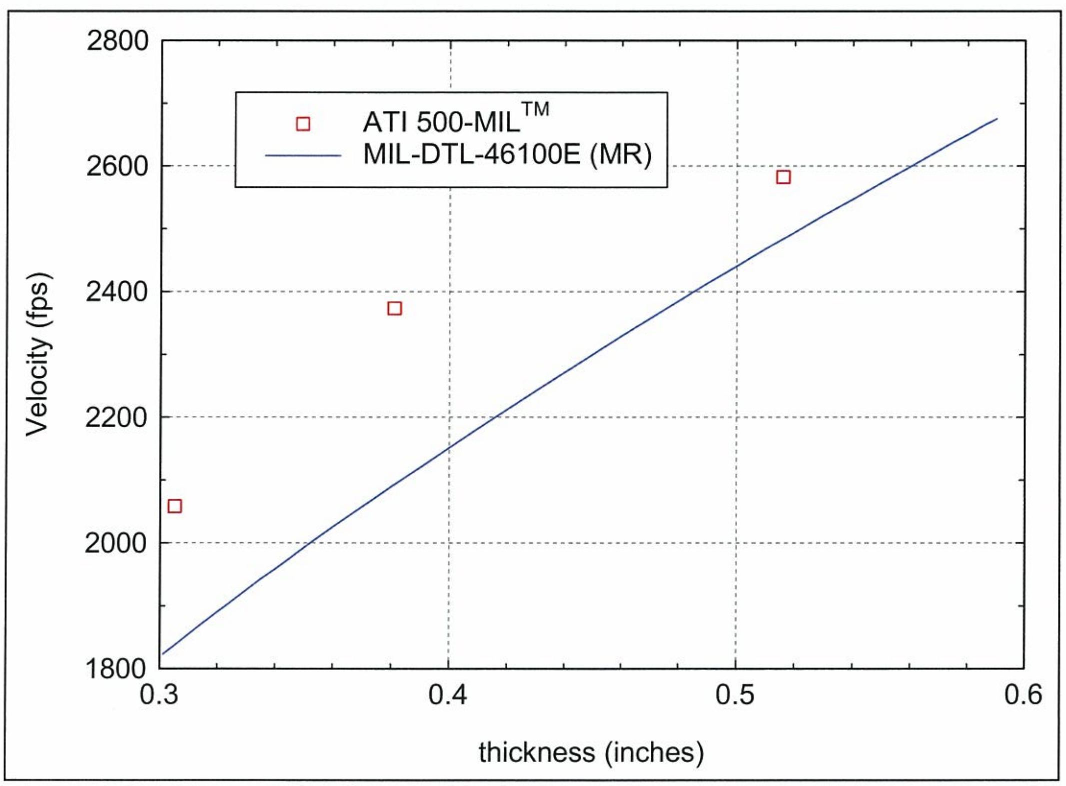

Figure 4. ATI 500-MIL plate thickness vs. V_{50} velocity for the 0.50-cal. APM2 at 30° obliquity.

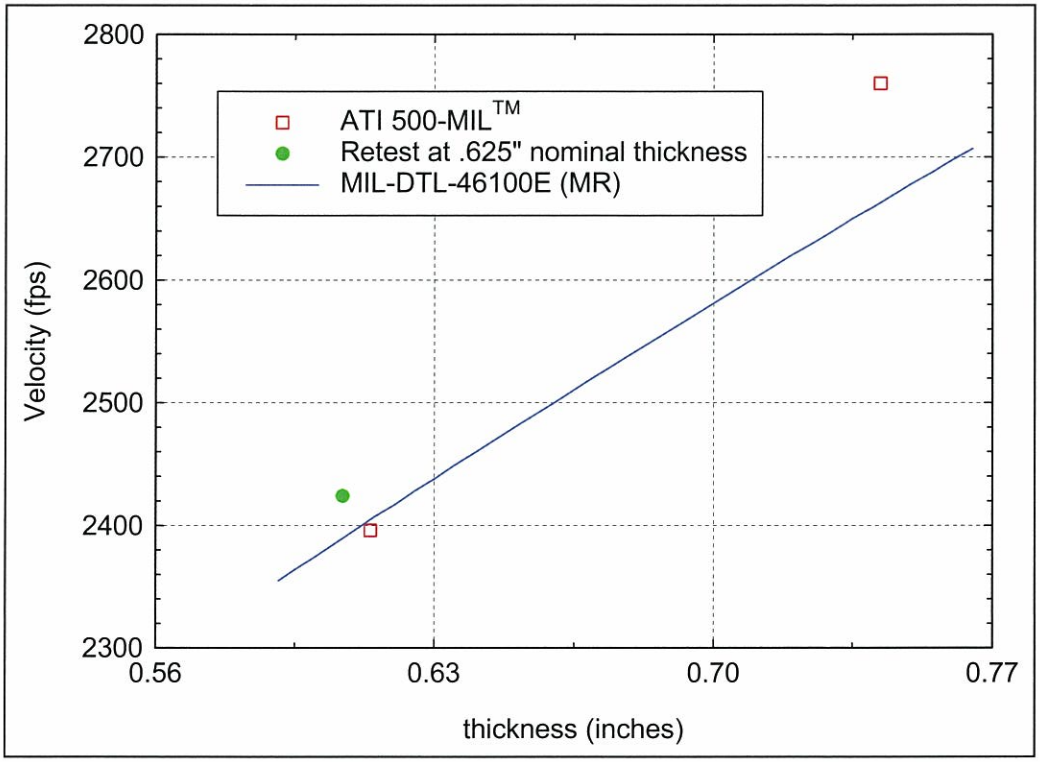

Figure 5. ATI 500-MIL plate thickness vs. V_{50} velocity for the 14.5-mm B32 at 30° obliquity.

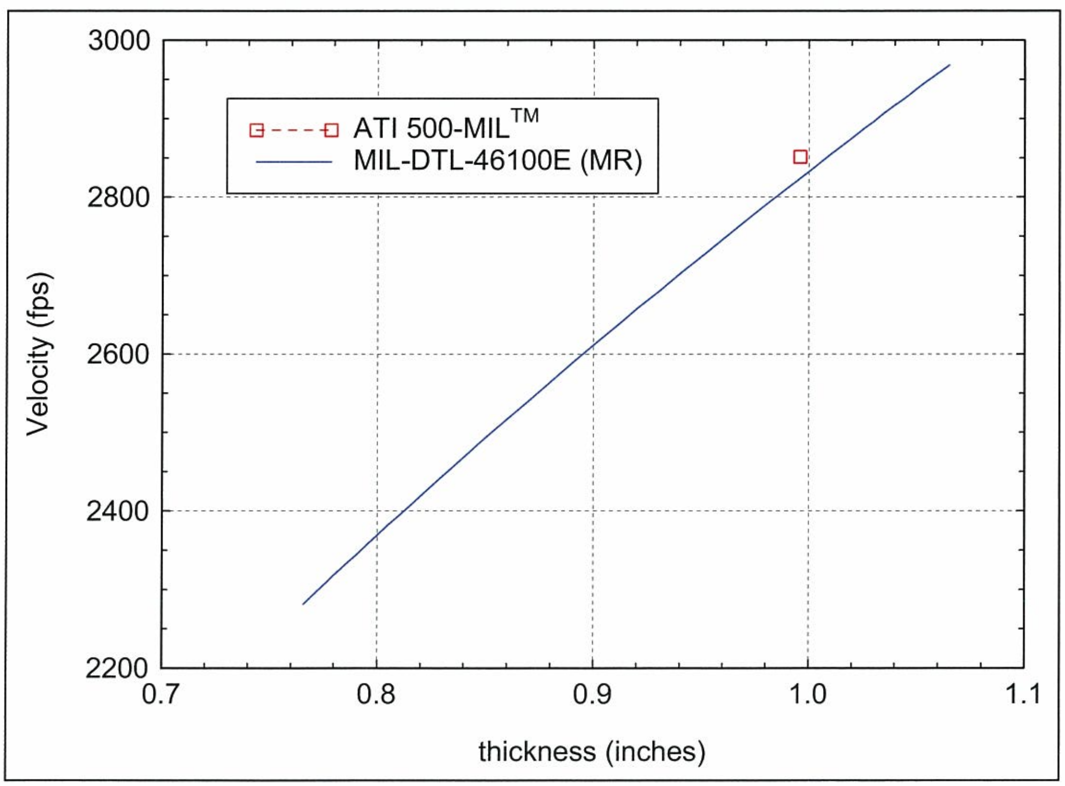

Figure 6. ATI 500-MIL plate thickness vs. V_{50} velocity for the 14.5-mm BS41 at 30° obliquity.

The 0.625-in-thick plate that did not meet the velocity requirement for the first ballistic plate was retested in accordance with the procedures in the specification. The second plate passed by 35 ft/s. The effect of the projectile diameter to the plate thickness may be a contributing factor on possible plug formation for this projectile thickness. At 1-in thickness, the ability to harden the plates by air quenching may be reaching a limit, resulting in the V_{50} velocity approaching the requirement. The armor applications for HHA plates over 0.750 in are limited, and the most important observation is the response of the thinner plates to the ballistic test projectiles. This significant performance is a direct result of the alloying of ATI 500-MIL steel. The first ordered thickness of MIL-DTL-46100E starts at 0.118 in (3 mm); ATI Defense is expected to eventually produce plates between 0.118 and 0.1875 in.

6. Conclusions

This report has documented the ballistic performance of the first Class-2 auto-tempered HHA steel under MIL-DTL-46100E. The increased alloying of ATI 500-MIL steel has resulted in a very tough high hard steel for both blast and ballistic applications. The development and availability of an air-quenched, auto-tempered HHA steel increases the availability of high-hard plate, as traditional water or oil quench and temper facilities are not required. This new class of tough HHA steel plates will increase the metallic armor solutions to armor designers.

Appendix. Shot Data

This appendix appears in its original form, without editorial change.

Plate Type:	ATI 500
Nominal Thickness (mm)	4.8
Nominal Thickness (in)	0.188
Measured Thick. (in)	0.202
BHN	512
Penetrator:	.30 AP M2
Obliquity:	30
Date:	11-Jan-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
6505	1954	596	PP	
6506	1985	605	PP	
6507	2079	634	PP	
6508	2137	652	CP	+
6509	2131	650	PP	-
6510	2129	649	PP	
6511	2160	659	CP	-
6512	2166	660	PP	-
6513	2242	684	CP	+
6514	2209	673	CP	+

Low CP	2137
High PP	2166

	(ft/s)	m/s
V50	2174	663
Std Dev	43	13
Vel Spread	111	34
ZMR	29	9

Plate Type:	ATI 500
Nominal Thickness (mm)	6.4
Nominal Thickness (in)	0.250
Measured Thick. (in)	0.272
BHN	532
Penetrator:	.30 AP M2
Obliquity:	30
Date:	15-Jan-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
6523	2352	717	PP	
6524	2472	754	PP	
6525	2593	791	PP	
6526	2635	803	PP	-
6527	2679	817	PP	-
6528	2790	851	CP	
6529	2731	833	CP	+
6530	2720	829	CP	+
6531	2699	823	CP	+
6532	2663	812	PP	-

Low CP	2699	
High PP	2679	
	(ft/s)	m/s
V50	2688	820
Std Dev	36	11
Vel Spread	96	29
ZMR	0	0

Plate Type:	ATI 500
Nominal Thickness (mm)	7.9
Nominal Thickness (in)	0.313
Measured Thick. (in)	0.305
BHN	532
Penetrator:	.30 AP M2
Obliquity:	30
Date:	14-Jan-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
6515	2613	797	PP	-
6516	2809	856	CP	
6517	2767	844	CP	
6518	2698	823	PP	-
6519	2718	829	CP	+
6520	2690	820	CP	+
6521	2677	816	CP	+
6522	2633	803	PP	-

Low CP	2677
High PP	2698

	(ft/s)	m/s
V50	2672	815
Std Dev	40	12
Vel Spread	105	32
ZMR	21	6

Plate Type:	ATI 500
Nominal Thickness (mm)	7.9
Nominal Thickness (in)	0.313
Measured Thick. (in)	0.305
BHN	532
Penetrator:	.50 AP M2
Obliquity:	30
Date:	7-May-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
6464	1972	601	PP	
6465	2179	664	CP	
6466	2127	648	CP	+
6467	2068	630	CP	+
6468	2080	634	CP	+
6469	1941	592	PP	
6470	1989	606	PP	-
6471	2031	619	PP	-
6472	2054	626	PP	-

Low CP	2068
High PP	2054

	(ft/s)	m/s
V50	2058	627
Std Dev	47	14
Vel Spread	138	42
ZMR	0	0

Plate Type:	ATI 500
Nominal Thickness (mm)	9.5
Nominal Thickness (in)	0.375
Measured Thick. (in)	0.381
BHN	512
Penetrator:	.50 AP M2
Obliquity:	30
Date:	5-Feb-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
6138	2281	695	PP	
6139	2477	755	CP	
6140	2376	724	CP	+
6141	2300	701	PP	-
6142	2413	736	CP	+
6143	2348	716	PP	-
6144	2388	728	PP	-
6145	2413	736	CP	+

Low CP	2376
High PP	2388

	(ft/s)	m/s
V50	2373	723
Std Dev	43	13
Vel Spread	113	34
ZMR	12	4

Plate Type:	ATI 500
Nominal Thickness (mm)	12.7
Nominal Thickness (in)	0.500
Measured Thick. (in)	0.517
BHN	512
Penetrator:	.50 AP M2
Obliquity:	30
Date:	6-Feb-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
6146	2644	806	CP	+
6147	2544	776	CP	+
6148	2497	761	PP	
6149	2525	770	PP	-
6150	2559	780	PP	-
6151	2561	781	PP	-
6152	2659	811	CP	+

Low CP	2544
High PP	2561

	(ft/s)	m/s
V50	2582	787
Std Dev	56	17
Vel Spread	134	41
ZMR	17	5

Plate Type:	ATI 500
Nominal Thickness (mm)	15.9
Nominal Thickness (in)	0.625
Measured Thick. (in)	0.514
BHN	
Penetrator:	14.5mmAPIB32
Obliquity:	30
Date:	12-Mar-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
200825854	2355	718	CP	+
200825853	2373	723	PP	-
200825852	2438	743	CP	+
200825851	2400	732	PP	-
200825850	2421	738	CP	+
200825849	2472	754	CP	

Low CP	2355
High PP	2400

	(ft/s)	m/s
V50	2396	730
Std Dev	43	13
Vel Spread	83	25
ZMR	45	14

Plate Type:	ATI 500
Nominal Thickness (mm)	15.9
Nominal Thickness (in)	0.625
Measured Thick. (in)	0.607
BHN	
Penetrator:	14.5mmAPIB32
Obliquity:	30
Date:	24-Mar-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
200825814	2601	793	CP	
200825815	2435	742	CP	+
200825816	2371	723	PP	-
200825817	2409	734	PP	-
200825818	2446	746	CP	+
2008258419	2425	739	PP	-
2008258420	2461	750	CP	+

Low CP	2435
High PP	2425

	(ft/s)	m/s
V50	2424	739
Std Dev	31	9
Vel Spread	90	27
ZMR	0	0

Plate Type:	ATI 500
Nominal Thickness (mm)	19.5
Nominal Thickness (in)	0.750
Measured Thick. (in)	0.742
BHN	
Penetrator:	14.5mmAPIB32
Obliquity:	30
Date:	12-Mar-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
200825861	2810	857	CP	+
200825860	2753	839	PP	-
200825859	2727	831	PP	-
200825858	2796	852	CP	+
200825857	2776	846	CP	+
200825856	2696	822	PP	-

Low CP	2776
High PP	2753

	(ft/s)	m/s
V50	2760	841
Std Dev	43	13
Vel Spread	114	35
ZMR	0	0

Plate Type:	ATI 500
Nominal Thickness (mm)	25.4
Nominal Thickness (in)	1.000
Measured Thick. (in)	0.996
BHN	
Penetrator:	14.5mmAPIB32
Obliquity:	30
Date:	13-Mar-08

Shot #	Velocity (ft/s)	Velocity (m/s)	Result	
200825956	2924	891	PP	-
200825957	2924	891	CP	
200825958	2937	895	CP	
200825959	2901	884	CP	
200825960	2901	884	CP	+
200825961	2871	875	CP	+
200825962	2819	859	PP	-
200825963	2798	853	CP	+
200825964	2793	852	PP	-

Low CP	2798
High PP	2924

	(ft/s)	m/s
V50	2851	869
Std Dev	55	17
Vel Spread	131	40
ZMR	126	38