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DEVELOPMENT AND BALLISTIC TESTING OF A NEW CLASS OF AUTO-TEMPERED HIGH HARD STEELS UNDER MILITARY SPECIFICATION MIL-DTL-46100E

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Abstract

The US 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 US 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™ 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 paper documents the development of ATI 500-MIL™ plate and subsequent ballistic testing and inclusion into the specification as Class 2 auto-tempered HHA steel.

Introduction

The U.S. armor community is currently engaged in accelerated efforts to deliver light-weight 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 US armor community has increased the availability of quenched and tempered armor steels by updating current steel military specifications and the most important 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 HHA specification allows modern continuous processing technologies to be used efficiently as well as introducing a new class of auto-tempered high hard steels.

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 US 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 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 US Army will be releasing a new ultrahigh 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 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 paper documents the development of ATI 500-MIL™ plate and subsequent ballistic testing and inclusion into the specification as Class 2 auto-tempered HHA steel.

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 post-operation heat treatments for restorations of ballistic properties were successfully alleviated. These post-process 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 stability of the armor.

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

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 (max)	0.005 (max)	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/lbs (J)**	**Yield Strength ksi (MPa)**	**Tensile strength ksi (MPa)**	**Elongation (%)**
ATI 500-MIL™	477-534	20 (27)	150 (1034)	260 (1792)	13

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 0.5mm (0.020") 2024 T3 aluminum witness plate 152.6mm (6.00") 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 fps) shall be permitted between the lowest and highest velocities employed in determination of ballistic limits. The data for the ATI 500-MIL™ steels are compared to the base line ballistic acceptance data of MIL-DTL-46100E.

TEST PROJECTILES

The eight ATI 500-MIL™ plates tested for First Article certification ranged in thickness (nominal) from 0.1875" (4.8 mm) up to 1.000" (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 8mm (0.315") thickness.

Table 3. Thickness Ranges and Corresponding Test Projectiles for First Article Testing

Nominal thickness range, in (mm)	Obliquity, degrees	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 Grains (g)	Length in. (mm)	Diameter in. (mm)	Weight Grains (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)

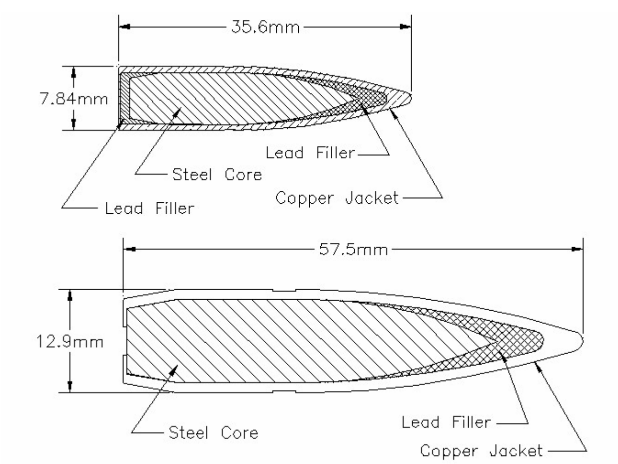

Figure 1. The 0.30-Cal APM2 and 0.50-Cal APM2 Test Projectiles

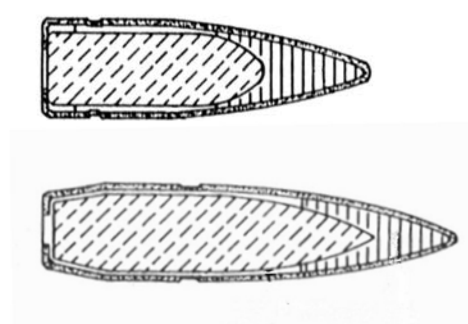

Figure 2. The 14.5-mm BS41 (top) and B32 Test Projectiles (Bottom)

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 and the data is shown in Table 5 for each test projectile. Figures 3-6 plot the V_{50} velocities versus 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 Thick. 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)	14.5mm B32	0.614 (15.6)	30	2396 (730)	43 (13)
0.625 (15.88)*	14.5mm B32	0.607 (15.4)	30	2424 (739)	32 (9)
0.750 (19.05)	14.5mm B32	0.742 (18.8)	30	2760 (841)	43 (13)
1.000 (25.40)	14.5mm BS41	0.966 (24.5)	30	2851 (869)	56 (17)

* Retest

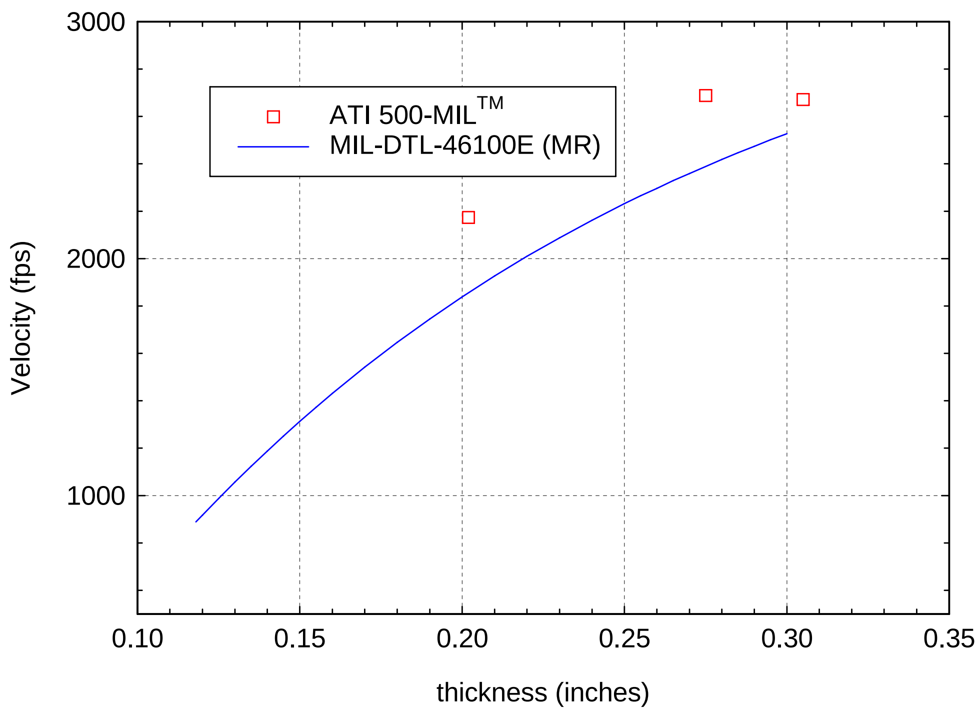

Figure 3. ATI 500-MIL™ Plate Thickness versus V_{50} Velocity for the 0.30-Cal APM2 @ 30° Obliquity

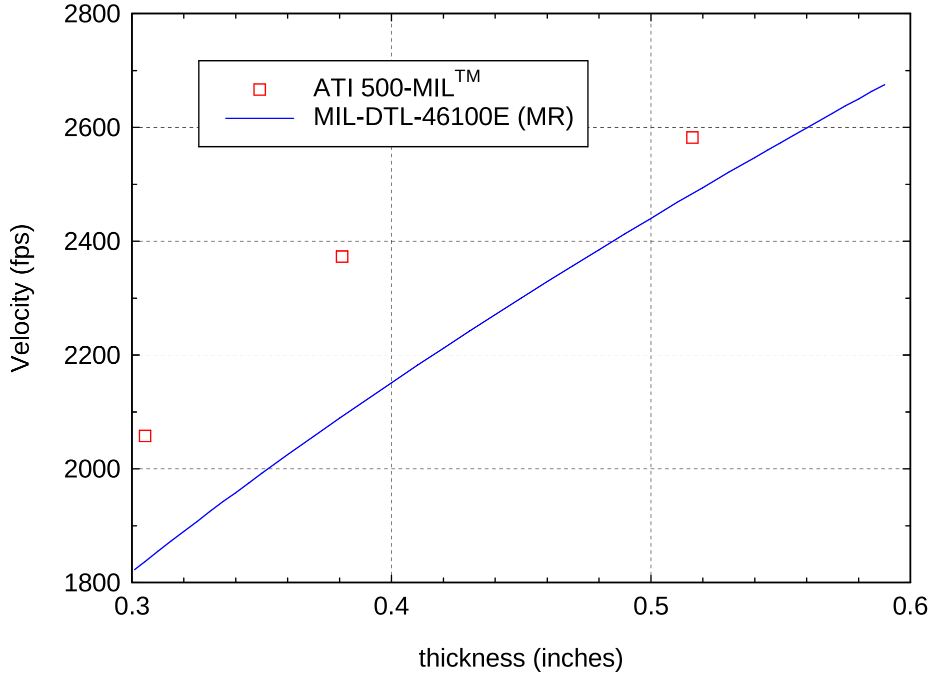

Figure 4. ATI 500-MIL™ Plate Thickness versus V_{50} Velocity for the 0.50-Cal APM2 @ 30^o Obliquity

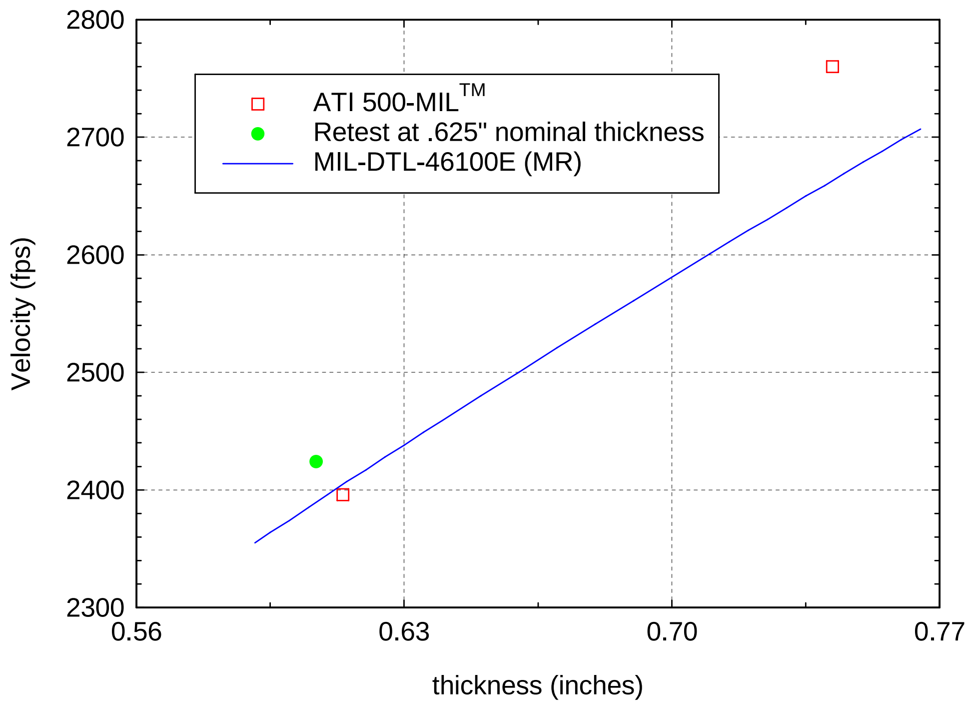

Figure 5. ATI 500-MIL™ Plate Thickness versus V_{50} Velocity for the 14.5mm B32 @ 30^o Obliquity

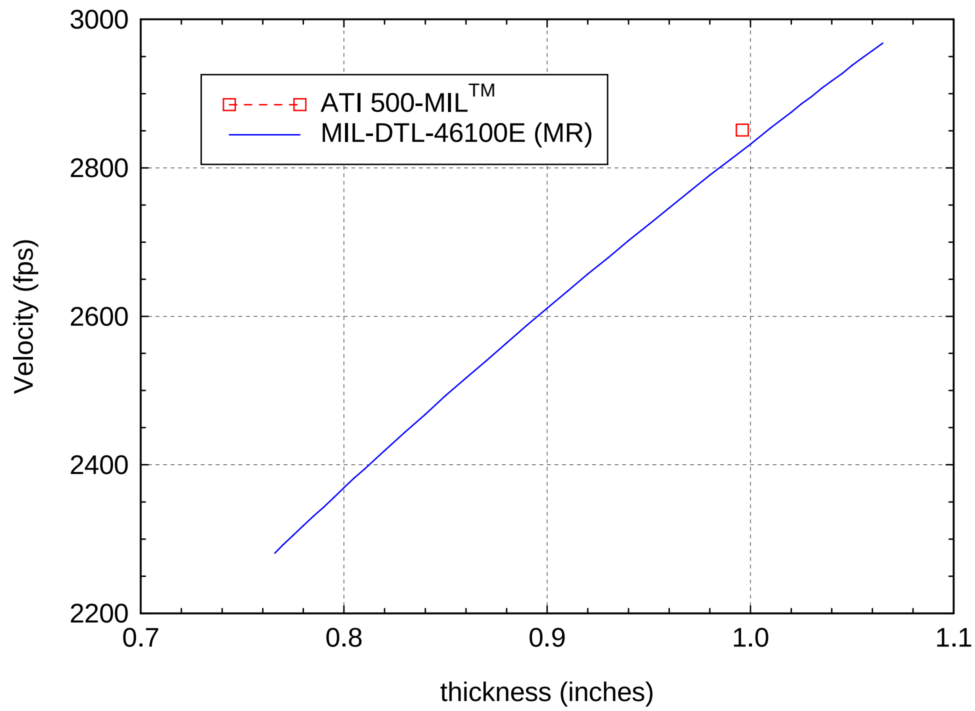

Figure 6. ATI 500-MIL™ Plate Thickness versus V_{50} Velocity
for the 14.5mm BS41 @ 30° Obliquity

The 0.625” thick plate that did not meet the velocity requirement for the first ballistic plate and was retested in accordance with the procedures in the specification. The second plate passed by 35 fps. The effect of the projectile diameter to the thickness of the plate may be a contributing factor on possible plug formation for this thickness for this projectile. At 1.00” 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” is, however, 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” (3mm) and ATI Defense is expected to eventually produce plates between 0.118” - 0.1875”.

CONCLUSIONS

This paper 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.

REFERENCES

[1] U.S. Military Specification, MIL-DTL-46100E (MR), “Armor Plate, Steel, Wrought, High-Hardness”, U.S. Army Research Laboratory, APG, MD, 9 July 2008.

[2] U.S. Military Specification, MIL-A-46099C, “Armor Plate, Steel, Roll-Bonded, Dual Hardness (0.187 Inches to 0.700 Inches Inclusive)”, U.S. Army Materials Technology Laboratory, Watertown, MA, 14 Sept 1987.

[3] E. Rapacki, K. Frank, B. Leavy, M. Keele, and J. Prifti, “Armor Steel Hardness Influence on Kinetic Energy Penetration”, Proceedings, 15th International. Symposium on Ballistics, Jerusalem, Israel, May 1995.

[4] ATI Defense Data Sheet: ATI 500-MIL™ High Hard Specialty Steel Armor, Version 3 (9/3/2008), ATI Defense, Washington, PA.

[5] MIL-STD-662F, Department of Defense Test Standard, U.S. Army Research Laboratory, Weapons & Materials Research Directorate, ATTN: AMSRL-WM-M, APG, MD 21005-5069, 18 December 1997.