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TERMINAL BALLISTICS OF STEEL/ALUMINUM COMPOSITES. PART I. CALIB--ETC(U)
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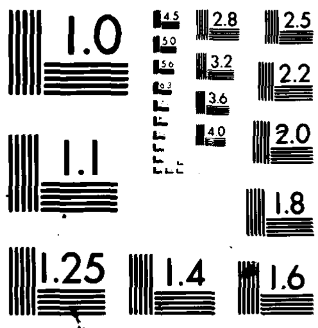

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ABSTRACT

The small caliber AP ballistic performance of two hardened 4300 series alloy steels is studied. Both alloys satisfy specification AMS 6359C for aircraft-quality steel plate, except one has a modified carbon content of 0.46 to 0.48 weight percent; AMS 6359C specifies a carbon content of 0.38 to 0.43. The AMS 6359C alloy is tested in monolithic plate form; the higher carbon alloy is tested as frontal plate in steel/aluminum laminate designs.

Steel/aluminum composites of modified 4340 alloy steel heat treated to a hardness level of HRC 55 to 60 and backed with armor grade 5083 aluminum are tested with the caliber .30 AP M2 projectile. Limit velocity data is generated for composites of unit weight 13.5 to 20 lb/ft^2 and variable weight fraction steel. Ballistic tests are conducted both at ambient conditions and subzero temperature. Comparative limit velocity data is generated with the caliber .30 AP M2 projectile for monolithic plates of AMS 6359C 4340 steel hardened to HRC 50 to 55 and current production high-hardness steel (MIL-A-46100).

CONTENTS

INTRODUCTION

Background

The terminal ballistic performance of steel-faced aluminum composites for defeat of AP penetrators has been the topic of several past investigations. These include an early exploratory effort[1] and two more recent studies[2,3] performed in support of specific weapons systems. No study attempted to optimize the performance of steel/aluminum composites or develop general understanding or principles on the ballistic behavior of such systems.

Reference 1 studied steel/aluminum composites of unit weight 20 lb/ft^2 with the caliber .30 AP M2 projectile and 20-mm fragment-simulating projectile at 0° obliquity and the caliber .50 AP M2 projectile at 45° obliquity. Composites consisted of a frontal steel plate of one of three types of rolled homogeneous steel backed with a plate of 2024-T4, 5083, or 7075-T6 aluminum alloy. The composites showed no gain in ballistic performance over an equal unit weight of rolled homogeneous steel.

Reference 2 examined steel-faced aluminum laminates for hardening the armored reconnaissance scout vehicle (ARSV). Armor composites consisted of a frontal plate of dual-hardness steel (MIL-S-46099), high-hardness steel (MIL-A-46100), or 4350 electroslag remelted steel in the HRC 57 to 59 hardness range and a backup plate of 5083 (MIL-A-46027) or 7039 (MIL-A-46063) aluminum alloy. The nominal thickness of the steel frontal plate ranged from 3/16 inch to 5/8 inch in the case of dual-hardness composites and from 1/4 inch to 1/2 inch for high-hardness and 4350 laminates. A backup plate of nominal thickness 1/2 inch or 3/4 inch was used for all targets. Limit velocity data was obtained with the caliber .30 AP M2 and 14.5-mm API BS41 projectiles; the latter is a simulant for the Soviet 14.5-mm API BST tungsten carbide core projectile.

The ARSV effort examined the terminal ballistic effects of a number of variables including frontal steel type, backup aluminum alloy, steel/aluminum distribution, threat type, and impact obliquity. The limited number of experiments allowed only limited functional relations. The study did show, however, that steel/aluminum composites with a hard frontal component such as the electroslag remelted 4350 steel or dual-hardness steel provide 20 to 40 percent weight savings over rolled homogeneous steel (MIL-A-12560) for the caliber .30 AP M2 threat at 0° obliquity, while composites with a frontal component of high-hardness steel yield, at most, a 21.5 percent weight savings over homogeneous steel.

Reference 3 examined the terminal ballistic performance of five steel/aluminum laminate designs for hardening the improved TOW vehicle (ITV) launcher assembly. The objective of this work was to determine the feasibility of facing the aluminum launcher assembly with 4340 steel to provide launcher protection equivalent to the aluminum hull of the M113 carrier. Each of the five armor designs consisted of a frontal plate of aircraft-quality 4340 composition steel satisfying AMS 6359C adhesively bonded to a 5083 aluminum alloy plate satisfying military specification MIL-A-46027. Heat treatment

1. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor Materials (U).* Army Materials and Mechanics Research Center, AMRA MS 64-07, September 1964 (Confidential Report).
2. VAN CANEGHEM, R. J. *Armor, Steel and Aluminum Plate and Appliques for ARSV (U).* TECOM Report No. APG-MT-4370, December 1973 (Confidential Report).
3. DeLUCA, E., PRIFTI, J. J., and RYDER, P. T. *Terminal Ballistic Data of Steel/Aluminum Composite Armors for Improved TOW Vehicle Launcher.* Army Materials and Mechanics Research Center, AMMRC SP 77-7, July 1977.

of the frontal plate was selected to reach hardness levels in the range of HRC 52 to 57. The nominal thickness of the steel frontal plate ranged from 1/8 inch to 1/4 inch; the nominal thickness of the aluminum backup plate ranged from 3/8 inch to 3/4 inch. Terminal ballistic experiments were conducted on each of the five composite designs with the caliber .30 AP M2 projectile, the 20-mm fragment-simulating projectile, and the Soviet 12.7-mm API B32 projectile; the 14.5-mm API BS41 projectile was used against one of the heavier composites.

While each of the ITV launcher armor designs was well characterized ballistically, the resulting data base was not sufficient to show the effect of composite unit weight or steel/aluminum weight ratio on terminal ballistic performance. The study did attempt to model the effect of composite armor makeup on limit velocity; however, the limited data base flawed this effort.

Except for the electroslag remelted 4350 steel, the ARSV study dealt with conventional steel armor. The ITV study introduced commercially available high-strength steel as an armor candidate; this material displayed distinct advantages over both high-hardness and dual-hardness steels. In particular, high-strength steel hardened above HRC 54 showed promise for the development of steel/aluminum composites that could provide reliable, cost-effective armor of the "dual-hardness" type. Such hybrid armor would lend itself to applique armor for improved survivability of in-service vehicles as well as form the basis for armor design of advanced combat vehicles.

This work is an outgrowth of two studies on ballistic hardening of ground equipment - the ITV launcher study discussed above and a study conducted for the ground-launched cruise missile (GLCM) system. It combines data obtained for both applications to obtain a more complete understanding of the terminal ballistic performance of steel/aluminum composite armor. Also, data is provided for an optimal steel/aluminum design that shows the potential of such composites as ballistically reliable, cost-effective substitutes for dual-hardness steel.

Objectives

The primary objective of this work is to show that steel/aluminum composites of modified 4340 alloy steel and armor grade aluminum provide an important extension to the class of metallic materials for AP penetrator defeat. For example, it is shown that a modified 4340 steel/5083 aluminum laminate can be designed to perform at the level of dual-hardness steel for AP type threats. A secondary purpose is to show that aircraft-quality 4340 alloy steel offers excellent potential for use in lightweight armor systems, in particular, as a ballistically superior replacement for high-hardness and rolled homogeneous steels.

The objectives are pursued through (a) a study of steel/aluminum weight ratio and composite unit weight on the terminal ballistic performance of a class of steel/aluminum laminates, (b) demonstration of a modified 4340 alloy steel/5083 aluminum laminate that combines the terminal ballistic performance of dual-hardness steel for AP penetrators with the ballistic reliability and material cost of aluminum armor, and (c) generation of limited comparative data on the AP terminal ballistics of 4340 composition and high-hardness steels. The work is conducted with the caliber .30 AP M2 projectile as a model for a class of small arms AP penetrators.

TEST PROGRAM

Armor Materials

Target specimens for this work were of two general types: monolithic steel plate and laminates made up of a plate each of steel and aluminum. The composite armor experiments represent the more extensive part of this investigation.

Two steels were used in the monolithic experiments: hardened 4340 alloy satisfying specification AMS 6359C and high-hardness steel satisfying military specification MIL-A-46100. Each of the laminate targets consisted of a frontal plate of hardened steel adhesively bonded to a backup component of 5083 aluminum. Frontal steel plates for the composite armor satisfied specification AMS 6359C except for an important modification in carbon content. Backup plates were 5083 aluminum alloy satisfying military specification MIL-A-46027 or 5083-H321 aluminum rolled to practices of MIL-A-46027. The chemical analysis and source for each of the 4340 composition steels used in this work are shown in Table 1.

Table 1. CHEMICAL ANALYSES OF 4340 ALLOY STEEL PLATE - WEIGHT PERCENT

Heat	Source	Use	Analysis	C	Mn	P	S	Si	Cu	Ni	Cr	Mo
B9492	I	M	Producer	0.39	0.67	0.013	0.024	0.28	0.11	1.75	0.83	0.25
			AMMRC	0.40	0.69	0.007	0.019	0.29	0.08	1.79	0.74	0.26
B0157	I	M	Producer	0.40	0.71	0.013	0.018	0.27	0.10	1.95	0.85	0.25
			AMMRC	0.41	0.73	0.009	0.020	0.28	0.07	1.97	0.83	0.24
B0499	I	M	Producer	0.40	0.73	0.010	0.018	0.29	0.08	1.76	0.84	0.24
			AMMRC	0.41								
48473	A	M	Producer	0.41	0.75	0.010	0.012	0.26	0.14	1.80	0.82	0.21
			AMMRC	0.41								
C5084	I	C	Producer	0.43	0.66	0.009	0.017	0.31	0.12	1.90	0.80	0.26
			AMMRC	0.46	0.67	0.008	0.014	0.29	0.09	1.88	0.74	0.26
51957	A	C	Producer	0.47	0.63	0.010	0.019	0.22	0.23	1.74	0.78	0.24
			AMMRC	0.48	0.66	0.005	0.022	0.20	0.24	1.73	0.77	0.26

M - Steel used strictly for monolithic plate experiments.
C - Steel used as frontal plate in composite targets.

The high-hardness steel plates were tested as-received without any further heat treatment or surface preparation. The condition specified for high-hardness steel in MIL-A-46100 is as-heat treated with surfaces not pickled and average surface hardness in the range of HB 477 to HB 534.

Specification AMS 6359C requires the 4340 plate to be hot rolled, annealed if necessary, descaled, and oiled with hardness equal to or less than HRC 25. The 4340 steel was received in this condition except for the plates of heat 51957 which were not descaled and included a normalize and temper modification with maximum hardness HRC 30. Reduction in plate thickness was accomplished before heat treatment by Blanchard grinding; equal amounts of material were removed from both sides of the plate. Grinding also served to clean the plate surfaces. Plates of heat 51957, not reduced below the as-rolled thickness, were grit blasted to remove all surface scale before heat treatment; all other 4340 plates not reduced in thickness were heat treated as-received. Heat treatment for the 4340 steel included austenitizing at 1550°F for approximately 1/2 hour, oil quenching, tempering at 325°F or 250°F for two hours, followed by air cooling. Plates of heat C5084 were oil quenched after tempering; this variation in practice is not considered significant for the purposes of this study.

The starting material for the rear or backup component of each composite target was a nominal 12" × 12" × 3/4" 5083 aluminum alloy plate satisfying MIL-A-46027 or a nominal 12" × 12" × 3/8" 5083-H321 plate rolled to the practices of MIL-A-46027. The MIL-A-46027 aluminum plates used in laminates with backup component thickness less than 3/4" were milled an equal amount on both sides to final size.

The steel and aluminum components of each composite were laminated to form a nominal 12" × 12" target. The steel frontal plate was joined to the aluminum backup plate with a synthetic rubber adhesive of the polysulfide type (MIL-S-8802, class A-2). This is a temperature-resistant (-65°F to 250°F) two-component synthetic rubber used primarily as a sealing compound; class A-2 designates a brushable material with a two-hour application time. The interface sides of the steel and aluminum components were cleaned before bonding by lightly grit blasting, followed by a solvent wash. Excess adhesive was then applied to the clean surface of each plate and the components clamped together with C-clamps. This procedure was used to reduce the interplate gap resulting from component plate distortion and generally resulted in a uniform, adhesive interlayer of 25- to 50-mil thickness. The adhesive was allowed to cure a minimum of 48 hours at room temperature before testing the composite.

Table 2 lists all test items and includes data on component source and target makeup. The average hardness displayed in Table 2 for each 4340 plate is the Rockwell C hardness scale equivalent to the plate average Knoop hardness. The Knoop hardness was obtained by averaging the readings in one or more Knoop (500-gram load) microhardness scans across the plate thickness; microhardness readings in each scan were generally taken at 0.25-mm intervals.

Ballistic Procedure

Figure 1 is a schematic diagram of the laboratory arrangement for the terminal ballistic experiments. Test projectile launch was conducted in conventional fashion

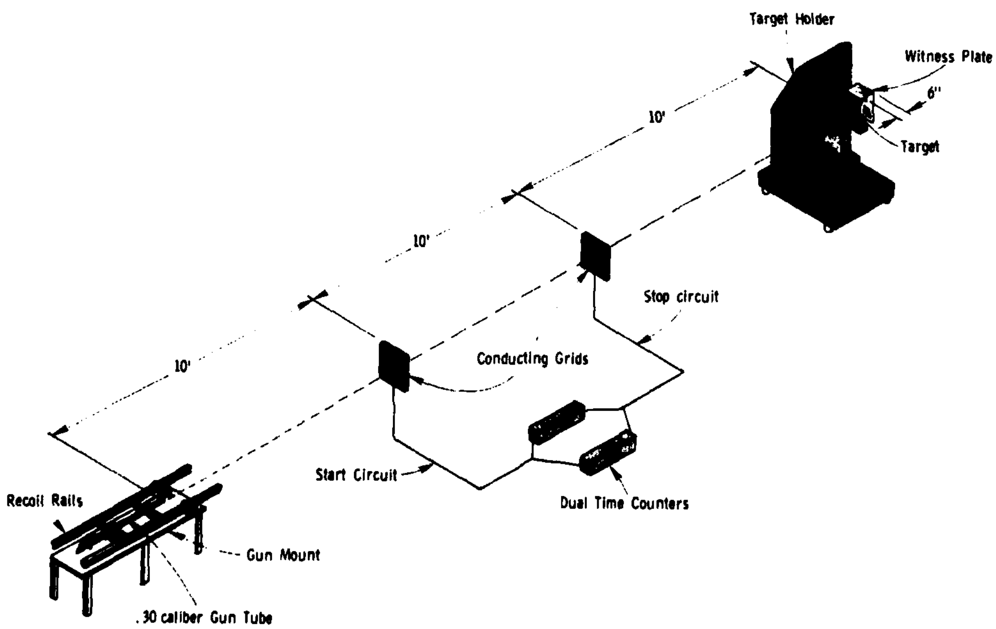


Figure 1. Terminal ballistic test schematic.

Table 2. TEST ITEMS

Target	Type	Source	Heat	Average Thickness* (in.)	Average Hardness (HRC)	Unit Wt. (lb/ft²)
a. Monolithic Steel Plate						
M1	MIL-A-46100	A	50120	0.263	Note†	10.73
M2		A	50120	0.268		10.93
M3		A	50120	0.272		11.10
M4		A	51372	0.328		13.38
M5		A	51372	0.330		13.46
M6		A	51372	0.335		13.67
M7		U	-	0.391		15.95
M8		U	-	0.393		16.03
M9	4340‡	I	B9492	0.257	53.1	10.49
M10		I	B0157	0.259	53.8	10.57
M11		I	B0157	0.259	54.4	10.57
M12		A	48473	0.261	51.3	10.65
M13		I	B0499	0.301 (G)	54.2	12.28
M14		I	B0499	0.303 (G)	54.1	12.36
M15		I	B0499	0.372 (G)	54.7	15.18
M16		I	B0499	0.372 (G)	54.6	15.18
M17		I	B0499	0.523	51.8	21.34
M18		I	B0499	0.524	53.6	21.38

	4340‡ Steel Frontal Plate				Aluminum Backup Plate		
Target	Source	Heat	Average Thickness* (in.)	Average Hardness (HRC)	Type	Average Thickness (in.)	Composite Wt.** (lb/ft²)
b. Steel/Aluminum Composites							
C1	I	C5084	0.126 (G)	56.3	MIL-A-46027	0.500	12.05
C2	A	51957	0.209	58.6	5083-H321	0.375	13.71
C3	A	51957	0.271	56.7	MIL-A-46027	0.194	13.74
C4	A	51957	0.212	58.9	5083-H321	0.373	13.80
C5	A	51957	0.214	59.1	5083-H321	0.373	13.88
C6	A	51957	0.213	56.5	MIL-A-46027	0.376	13.89
C7	A	51957	0.214	58.0	5083-H321	0.374	13.90
C8	A	51957	0.218	56.9	MIL-A-46027	0.374	14.06
C9	I	C5084	0.189 (G)	53.7	MIL-A-46027	0.497	14.58
C10	I	C5084	0.256	54.7	MIL-A-46027	0.373	15.60
C11	A	51957	0.214	56.5	MIL-A-46027	0.502	15.67
C12	I	C5084	0.257	55.9	MIL-A-46027	0.500	17.40
C13	I	C5084	0.189 (G)	53.7	MIL-A-46027	0.751	18.09
C14	I	C5084	0.190 (G)	55.5	MIL-A-46027	0.752	18.14
C15	I	C5084	0.182 (G)	56.4	MIL-A-46027	0.779	18.20
C16	A	51957	0.188 (G)	55.9	MIL-A-46027	0.772	18.34
C17	I	C5084	0.257	56.3	MIL-A-46027	0.627	19.20
C18	A	51957	0.222	56.5	MIL-A-46027	0.777	19.80
C19	A	51957	0.210	57.3	MIL-A-46027	0.251	12.04
C20	A	51957	0.211	56.8	5083-H321	0.374	13.78
C21	A	51957	0.212	59.6	5083-H321	0.371	13.78
C22	A	51957	0.212	59.6	5083-H321	0.374	13.82
C23	A	51957	0.214	57.7	MIL-A-46027	0.378	13.95
C24	A	51957	0.217	57.1	5083-H321	0.374	14.02
C25	A	51957	0.213	57.0	5083-H321	0.374	13.86
C26	A	51957	0.215	57.1	5083-H321	0.371	13.90
C27	A	51957	0.212	56.9	5083-H321	0.371	13.78

Frontal components of C19 to C27 tempered at 250°F for 2 hours.

*G - Plates ground to final size.
†Average surface hardness for MIL-A-46100 is specified in the range HB477 to HB534.
‡Heat treatment of the 4340 steel includes austenitized at 1550°F for 1/2 hr, oil quenched, tempered at 325°F for 2 hours except as noted, and air cooled.
**Unit weight does not include adhesive interlayer.

with a .30 caliber rifled tube. The caliber .30 AP M2 projectile was used virtually throughout; this is a nominal 166-grain projectile with a hardened steel core (HRC 61 to 66) of nominal mass 81 grains. Data for each test round included the velocity of the projectile at impact (strike velocity) and the record as to whether impact resulted in a partial or complete penetration of the target. Strike velocity was obtained from measurement of flight time over a fixed distance (base length). Flight time was measured by silver-line conducting paper grids (break screens) connected in parallel to duplicate time counters of 0.1-μsec accuracy; a base length of ten feet was used for strike velocity determination. Targets were held during ballistic impact by inserting top and bottom edges into two-inch-deep horizontal steel channels (arms) spaced approximately twelve inches apart and cantilevered from a tracked target holder. Wooden wedges were used to firm the target panel in the channels. The impact point on the target was varied by horizontal and vertical translation of the target holder. Perforation of a 0.020-inch-thick 2024-T3 aluminum plate, placed parallel to and six inches behind the target, served to define complete penetration of the target; a partial penetration is defined as an impact that does not result in a complete penetration. All tests were conducted at zero degree obliquity under controlled environmental conditions of 72°F ± 5°F and 50% to 60% relative humidity unless otherwise noted.

BALLISTIC TEST RESULTS

Monolithic Steel Plate

The terminal ballistic data obtained in this work is contained in the appendix. Measurements taken on the 18 monolithic steel plates (M1 to M18) and 27 composite targets (C1 to C27) are contained in this data file. A sufficient number of test rounds was obtained for each target to provide an estimate of the target ballistic limit velocity. In this study, limit velocity (V_L) is defined as the arithmetic mean of an even number of strike velocities, half of which result in complete penetration of the target, half in partial penetration, and all of which fall within 150 ft/sec of each other. The average must also include the lowest strike velocity that results in complete penetration.* Strike velocities used in the limit velocity calculation for each target are noted in the appendix.

The calculated limit velocity for each of the monolithic steel targets is listed in Table 3. This data illustrates the comparative AP terminal ballistics of high-hardness steel satisfying military specification MIL-A-46100 and 4340 composition steel manufactured to specification AMS 6359C. Although caliber .30 AP M2 terminal ballistic data for high-hardness steel has been published in the past,[4] the high-hardness data of Table 3 was generated for this study. This is to preclude any variation in high-hardness ballistics resulting from change in production practice. The high-hardness data of this work represents material manufactured under current practice.

The data of Table 3 is plotted in Figure 2 along with linear, least-squares representations for each steel data set. Two observations are immediate. The first is the performance variability of high-hardness steel against the AP projectile; this scatter in limit velocity is typical for high-hardness steel and AP penetrators. More important is the demonstrated improvement both in the level and reproducibility of limit velocity offered by 4340 steel over high-hardness material for plates up to 1/2 inch in thickness.

*The definition of V_L is quite similar to that of protection ballistic limit V_{50}.

4. MASCIANICA, F. S. *Ballistic Technology of Lightweight Armor - 1979 (U).* Army Materials and Mechanics Research Center, AMMRC TR 79-10, February 1979 (Confidential Report).

Improved AP ballistics of the 4340 alloy is attributed to its higher level of average hardness. It is postulated that the superior ballistic performance for the 4340 steel illustrated in Figure 2 extends, in general, to all threats of the AP variety making aircraft-quality 4340 steel an attractive candidate for replacement of high-hardness steel in armor applications.

Table 3. LIMIT VELOCITY FOR MONOLITHIC STEEL PLATE

Test Projectile - Caliber .30 AP M2 at 0° Obliquity

Target	Type	Average Hardness (HRC)	Average Thickness (in.)	Unit Wt. (lb/ft²)	Limit Velocity (fps)
M1	MIL-A-46100	*	0.263	10.73	1588
M2			0.268	10.93	1574
M3			0.272	11.10	1787
M4			0.328	13.38	1761
M5			0.330	13.46	1804
M6			0.335	13.67	2142
M7			0.391	15.95	2065
M8			0.393	16.03	2170
M9	4340 - AMS 6359C†	53.1	0.257	10.49	2220
M10		53.8	0.259	10.57	2168
M11		54.4	0.259	10.57	2218
M12		51.3	0.261	10.65	2269
M13		54.2	0.301	12.28	2313
M14		54.1	0.303	12.36	2274
M15		54.7	0.372	15.18	2621
M16		54.6	0.372	15.18	2397
M17		51.8	0.523	21.34	3190
M18		53.6	0.524	21.38	3188

*Average surface hardness for MIL-A-46100 is specified in the range HB477 to HB534.

†Austenitized at 1550°F for 1/2 hr, oil quenched, tempered at 325°F for 2 hours, and air cooled.

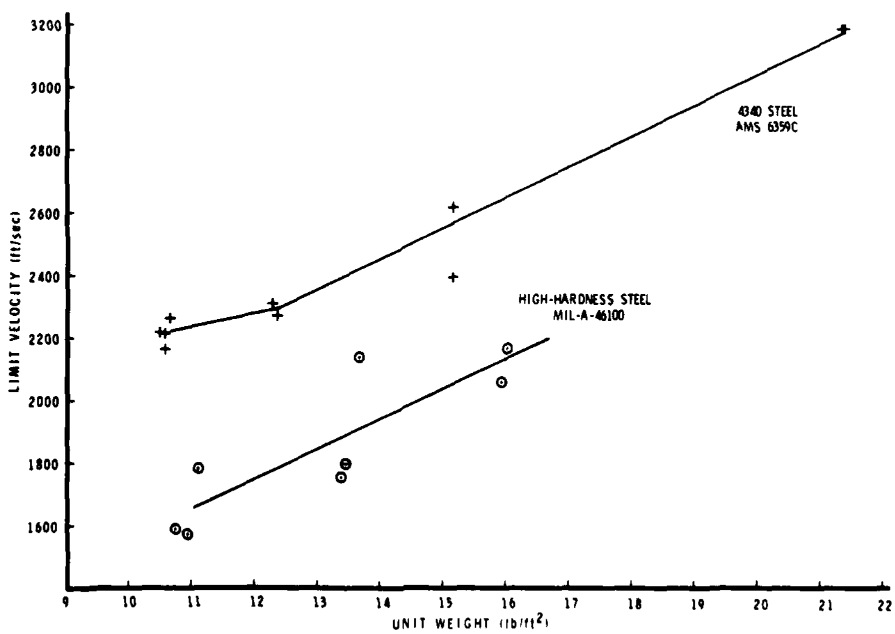
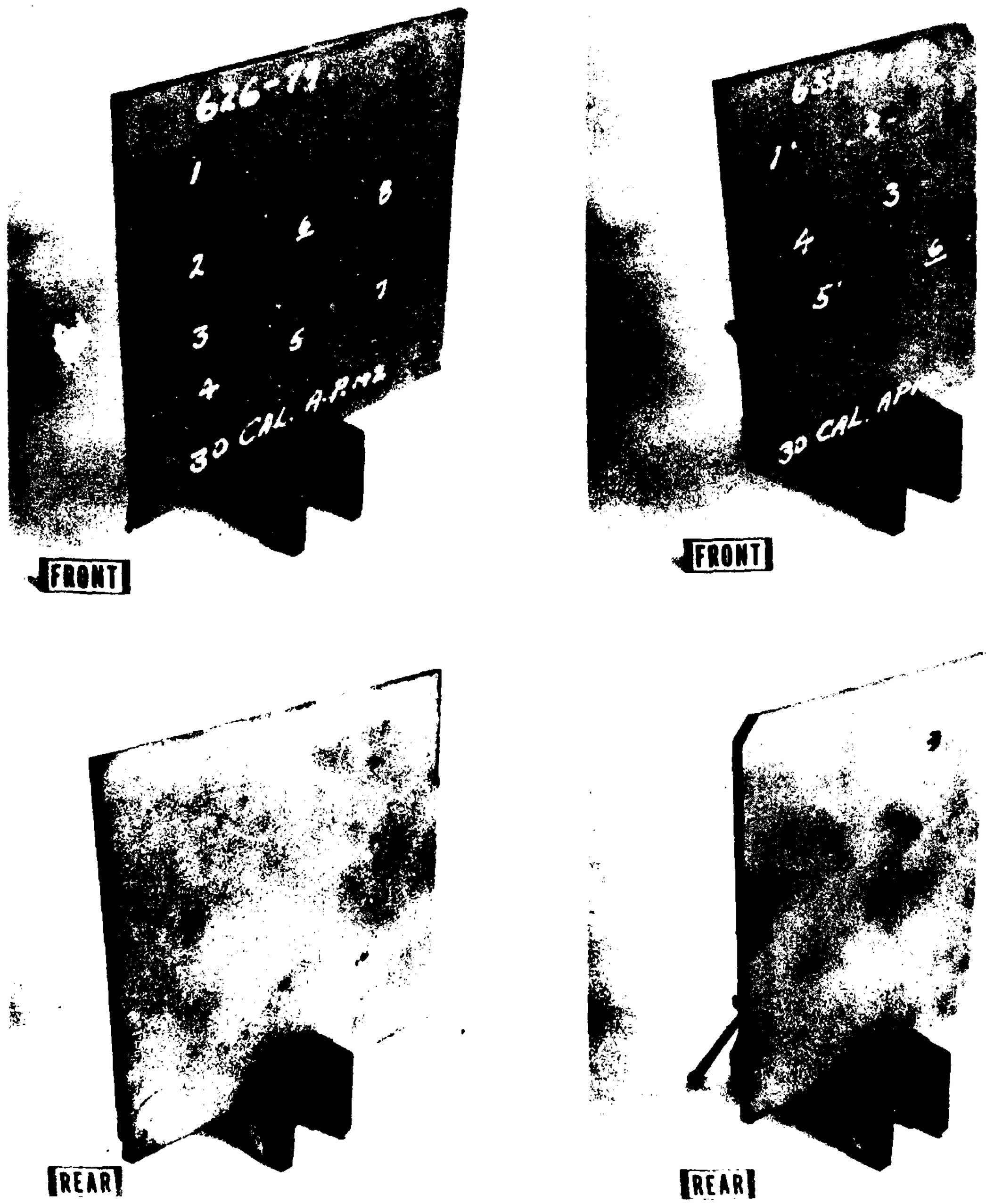


Figure 2. Limit velocity data for monolithic steel (caliber .30 AP M2 projectile at 0° obliquity).

Front and rear profile views of two monolithic steel targets after impact are shown in Figure 3, a high-hardness plate (M4) and a 4340 plate (M16). The front views show no difference in plate failure; the rear views indicate only minor differences with the high-hardness plate displaying more tendency toward ductile-type failure.



High-hardness steel (MIL-A-46100)

4340 steel (AMS 6359C)

Figure 3. Monolithic steel targets after ballistic impact (caliber .30 AP M2 projectile at 0° obliquity).

Composite Armor

The calculated limit velocity for each of the steel/aluminum composite targets tested at room temperature is shown in Table 4. The data is in two sets corresponding to the temper of the steel frontal plate; within each set, the targets are arranged in increasing order of composite unit weight.

Table 4. LIMIT VELOCITY FOR STEEL/ALUMINUM COMPOSITE ARMOR
Test Projectile - Caliber .30 AP M2 at 0° Obliquity

Target*	Plate Thickness Steel/Aluminum (in.)	Steel Plate Average Hardness (HRC)	Composite Wt. (lb/ft^2)	Limit Velocity† (fps)
C1	0.126/0.500	56.3	12.05	1997
C2	0.209/0.375	58.6	13.71	2720
C3	0.271/0.194	56.7	13.74	2595
C4	0.212/0.373	58.9	13.80	2682
C4	0.212/0.373	58.9	13.80	2692
C5	0.214/0.373	59.1	13.88	2842
C6	0.213/0.376	56.5	13.89	2728
C7	0.214/0.374	58.0	13.90	2770
C8	0.218/0.374	56.9	14.06	2773
C9	0.189/0.497	53.7	14.58	2579
C10	0.256/0.373	54.7	15.60	2800
C11	0.214/0.502	56.5	15.67	2830
C12	0.257/0.500	55.9	17.40	2815
C13	0.189/0.751	53.7	18.09	2698
C14	0.190/0.752	55.5	18.14	2783
C15	0.182/0.779	56.4	18.20	2618
C16	0.188/0.772	55.9	18.34	2802
C17	0.257/0.627	56.3	19.20	2923
C18	0.222/0.777	56.5	19.80	3032
C19	0.210/0.251	57.3	12.04	2659
C20	0.211/0.374	56.8	13.78	2741
C21	0.212/0.371	59.6	13.78	2800
C22	0.212/0.374	59.6	13.82	2802
C23	0.214/0.378	57.7	13.95	2805
C24	0.217/0.374	57.1	14.02	2834

*Steel frontal plates satisfy specification AMS 6359C with a modified carbon content (0.46 to 0.48 weight percent). Temper for steel frontal plate of targets C1 to C18 is 325°F for two hours; frontal component of C19 to C24 tempered at 250°F for two hours.
†Ballistic tests conducted at room temperature.

Recall that the steel component of each composite satisfies specification AMS 6359C except for carbon content, and that heat treatment included austenitizing at 1550°F for 1/2 hour, oil quenching, tempering for two hours at either 325°F or 250°F, and air cooling. The steel frontal component of targets C1 to C18 was tempered at 325°F and that of C19 to C24 at 250°F. This is considered an important variation. A further distinction is that composites with frontal component tempered at 325°F contain a steel plate from one of two sources. The major difference in sources (heats C5084 and 51957) is carbon content. Chemical analysis of samples from three plates of each heat showed a carbon weight percent of 0.46 for C5084 and 0.48 for 51957. This two-point difference in carbon and its effect on average hardness level is ignored for the purposes of this work. That is, the variation in limit velocity for targets C1 to C18 is attributed strictly to steel/aluminum distribution and composite unit weight.

The limit velocities in Table 4 for composite targets C2 to C18 (frontal steel plate tempered at 325°F) are plotted in Figure 4. The data has been grouped into three sets for this plot according to the thickness of the steel plate. The three data sets correspond to composites with steel plate thickness of 0.182 inch to 0.190 inch, 0.209 inch to 0.222 inch, and 0.256 inch to 0.271 inch. The figure also contains a linear, least-squares representation for each of the three data sets.

Figure 4 implies that for fixed unit weight of steel/aluminum composite, the caliber .30 AP M2 limit velocity is not monotonic with weight fraction steel but is maximal for some steel/aluminum weight ratio. This is demonstrated in Figure 5 which shows the variation in limit velocity with weight percent steel for two steel/aluminum composites of 15 and 18 lb/ft^2. The limit velocities of Figure 5 for composites with a non-zero weight percent steel are taken from the straight lines of Figure 4; limit velocity for a composite of zero weight percent steel (100 weight percent aluminum) is taken as the ballistic limit of 5083 aluminum alloy (MIL-A-46027).[4]

The variation in limit velocity with steel/aluminum weight ratio for a composite of given weight as illustrated in Figure 5 is in contradistinction to the statement that "for fixed composite weight, limit velocity is a monotonically increasing function of weight fraction steel for each AP threat."[3] The limited data of Reference 3 precluded the notion of a ballistically optimal steel/aluminum weight ratio for fixed weight of composite.

Limit velocity maxima in steel/aluminum composite armor for optimal values of the steel/aluminum weight ratio is the central result of Figure 4. There are corollaries to this observation. For example, Figure 4 shows that an increase in limit velocity does not necessarily accompany an increase in composite unit weight. In fact, the limit

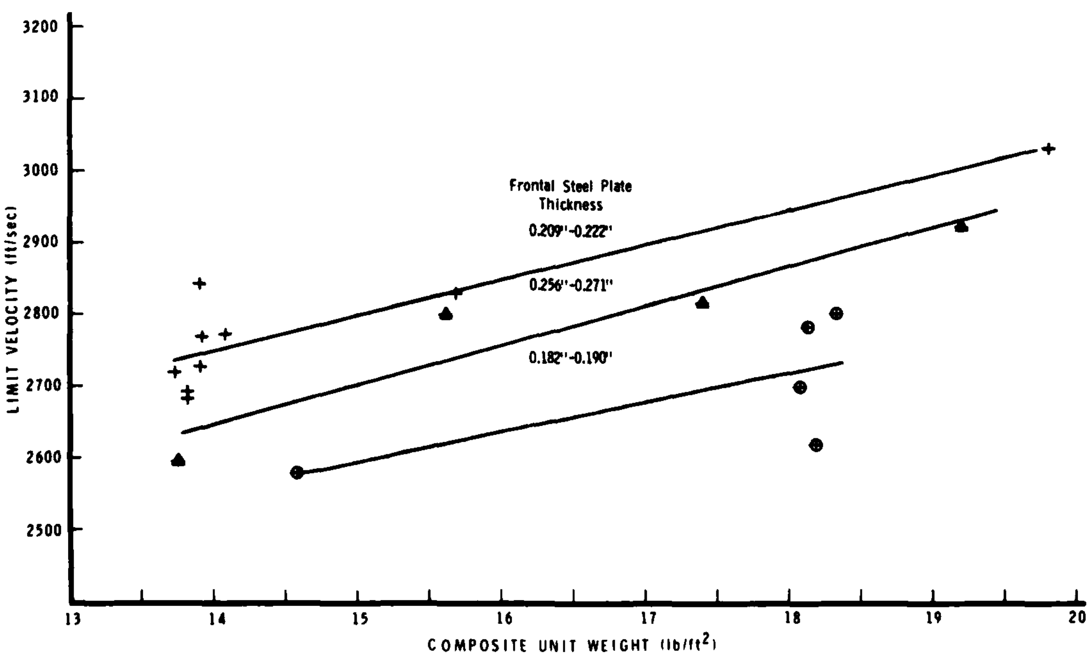


Figure 4. Limit velocity data for steel/aluminum composites (caliber .30 AP M2 projectile at 0° obliquity).

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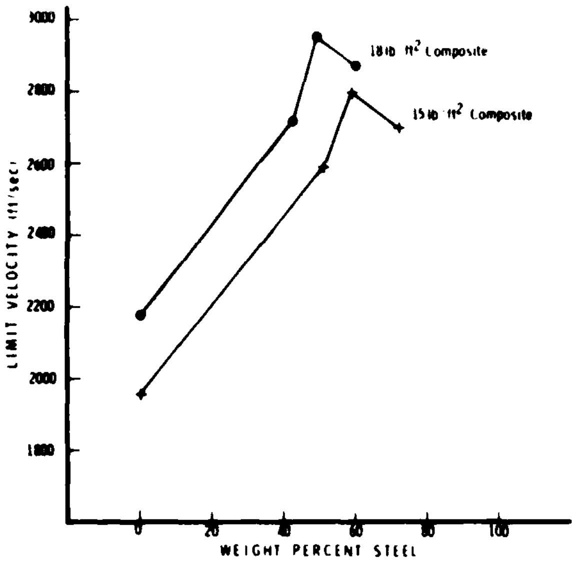

Figure 5. Variation in limit velocity with weight percent steel for steel/aluminum composites of fixed unit weight (caliber .30 AP M2 projectile at 0° obliquity).

velocity could decrease with increase in unit weight. Also, the weight percent steel in a steel/aluminum composite must decrease as unit weight increases in order to maintain the optimal level of AP ballistic performance. This is clearly seen in Figure 5. Finally, Figure 4 implies that composites of steel and aluminum can be made to ballistically out-perform the monolithic constituents at equal unit weight.

The steel/aluminum composites under discussion employ the dual-hardness mechanism for AP penetrator defeat, that is, a hard, frontal component to break up the penetrator followed by a secondary component that supports the frontal plate for the initial interaction and then deforms to capture the resulting debris. This principle has been well exploited for both metallic armor (e.g., dual-hardness steel) and nonmetallic armor (e.g., composite of ceramic and reinforced plastic). In any case, the hardness of the frontal component plays a major role in the effectiveness of dual-hardness armor.

One of the more efficient (protection/unit weight) composites examined in this work is the nominal 14 lb/ft^2 design with a 3/8-inch-thick aluminum backup. This design was studied more extensively than others because of potential application to GLCM. To improve performance of this design by further hardening of the frontal component, a target set was fabricated with the steel plate tempered at a reduced temperature of 250°F. These are targets C20 to C24 listed in Table 4. The effect of the change in temper is seen by studying the subsets of Table 4 contained in Table 5.

A sample mean of 2744 ft/sec is obtained for the limit velocity for targets that incorporate the 325°F temper frontal plate; the sample mean for targets that incorporate a steel component tempered at 250°F is 2796 ft/sec. The difference in mean limit velocity for the two data sets of Table 5 cannot be proven statistically significant. However, a good indication that the lower temper indeed leads to improved performance is the number of impacts with strike velocity equal to or less than 2800 ft/sec that result in complete penetration, namely, 36.6 percent (15 of 41) for the 325°F temper and 3.8 percent (1 of 26) for the 250°F temper.

It is of interest to note that the protection limit velocity for 14 lb/ft^2 of dual-hardness steel against the caliber .30 AP M2 projectile is suggested as 2820 ft/sec.[4]

Table 5. LIMIT VELOCITY FOR A STEEL/ALUMINUM COMPOSITE OF VIRTUALLY CONSTANT DESIGN

Test Projectile - Caliber .30 AP M2 at 0° Obliquity

Target*	Plate Thickness Steel/Aluminum (in.)	Composite Wt. (lb/ft^2)	Limit Velocity† (fps)
Set 1			
C2	0.209/0.375	13.71	2720
C4	0.212/0.373	13.80	2682
C4	0.212/0.373	13.80	2692
C5	0.214/0.373	13.88	2842
C6	0.213/0.376	13.89	2728
C7	0.214/0.374	13.90	2770
C8	0.218/0.374	14.06	2773
		Mean = 13.86	Mean = 2744
			Standard Deviation = 55.5
Set 2			
C20	0.211/0.374	13.78	2741
C21	0.212/0.371	13.78	2800
C22	0.212/0.374	13.82	2802
C23	0.214/0.378	13.95	2805
C24	0.217/0.374	14.02	2834
		Mean = 13.87	Mean = 2796
			Standard Deviation = 33.9

*Steel component for targets of Set 1 tempered at 325°F for two hours; steel component for targets of Set 2 tempered at 250°F for two hours.
†Ballistic tests conducted at room temperature.

Composite Armor at Subzero Temperature and Interlayer Effects

A series of ballistic experiments was conducted at subzero temperature to (a) test the steel/aluminum armor for breakup or shatter of the hardened steel frontal plate and (b) measure the limit velocity for a nominal 14 lb/ft^2 steel/aluminum composite. The experimental procedure included cooling the composite target to a uniform temperature of approximately -60°F, holding at this temperature overnight, mounting in a chamber at room temperature, allowing the target surface temperature to reach -40°F, and firing the test round. Surface temperature was monitored at all times with a Chromel/Alumel thermocouple attached to the steel face of the composite. Each round required the same temperature conditioning of the target before impact.

The test procedure for cold impact was applied to a set of steel/aluminum composites using the caliber .30 AP M2 steel core penetrator. A single round was fired at each of five nominal 14 lb/ft^2 composite targets at -40°F. The set included members with steel frontal component tempered both at 325°F and 250°F. Each of the composites used in these experiments had been previously tested at room temperature to determine limit velocity. Strike velocity for the -40°F impact was selected to be near the composite limit velocity. Results of the single-shot experiments are contained in Table 6.

In addition to single-shot experiments on a set of different composites at -40°F, a sufficient number of caliber .30 AP M2 test rounds were fired at a single steel/aluminum composite to determine its limit velocity at -40°F. This is a nominal 14 lb/ft^2

Table 6. TEST RESULTS FOR STEEL/ALUMINUM COMPOSITES AT -40°F*
Test Projectile - Caliber .30 AP M2 at 0° Obliquity

Target†	Plate Thickness Steel/Aluminum (in.)	Composite Wt. (lb/ft^2)	Strike Velocity (fps)	Result‡
a. Single Shot Experiments				
C2**	0.209/0.375	13.71	2609	1
C6**	0.213/0.376	13.89	2665	0
C7**	0.214/0.374	13.90	2731	0
C21††	0.212/0.371	13.78	2754	0
C22††	0.212/0.374	13.82	2696	0
Target	**Plate Thickness Steel/Aluminum (in.)**	**Composite Wt. (lb/ft^2)**	**Limit Velocity (fps)**	
b. Limit Velocity Measurement				
C25††	0.213/0.374	13.86	2817	

*Temperature of steel plate surface at impact.
†See Table 5 for target limit velocity at room temperature.
‡Complete penetration of target is denoted by 1, partial penetration by 0.
**Steel frontal plate tempered at 325°F for two hours.
††Steel frontal plate tempered at 250°F for two hours.

composite with a 0.213-inch-thick steel frontal component tempered at 250°F. The calculated limit velocity for this composite at -40°F is contained in Table 6; individual test round data is contained in the appendix.

The ballistic behavior of steel/aluminum composites at -40°F appeared identical in all respects to that witnessed at room temperature. Target C25 (0.213-inch steel tempered at 250°F backed with 0.374-inch aluminum for a unit weight of 13.86 lb/ft^2) showed a limit velocity of 2817 ft/sec at -40°F. Compare this with a mean limit velocity of 2796 ft/sec for the set of steel/aluminum composites of similar design tested at room temperature (Table 5).

Impact of steel/aluminum composites at -40°F with the caliber .30 AP M2 projectile revealed no apparent problems associated with brittle fracture or shatter of the hardened steel face. This was the case for composites with steel frontal plate tempered at both 325°F and 250°F. Furthermore, steel component integrity was maintained under multi-hit impact at -40°F as demonstrated by composite C25.

Figure 6 contains front and rear profile views of composite target C21 after ballistic impact; the target has received seven impacts at room temperature and a single impact at -40°F with the caliber .30 AP M2 projectile.

A final phase of the work on steel/aluminum composites dealt with the role of adhesive interlayer on ballistic performance. Specifically, two steel/aluminum composites of the design studied in Table 5 (steel temper 250°F) were tested under extreme conditions of adhesive interlayer thickness. The first represented a zero thickness interlayer, that is, the steel and aluminum components were simply clamped together to form a composite with no adhesive bond. A second composite was assembled with an adhesive interlayer of nominal 1/8-inch thickness. The two composites simulate conditions of interlayer thickness that could appear locally in a steel/aluminum armor cover. The limit velocity for each of these assemblies is shown in Table 7; individual test round data is contained in the appendix. The results of these experiments indicate there is little sensitivity of steel/aluminum composite limit velocity to adhesive interlayer thickness from zero up to 1/8 inch, at least for this composite design.

Table 7. LIMIT VELOCITY FOR STEEL/ALUMINUM COMPOSITE ARMOR

Test Projectile - Caliber .30 AP M2 at 0° Obliquity

Target	Plate Thickness Steel/Aluminum (in.)	Composite Wt. (lb/ft^2)	Limit Velocity* (fps)
C26†	0.215/0.371	13.90	2901
C27‡	0.212/0.371	13.78	2738

*Ballistic tests conducted at room temperature.
†No adhesive interlayer between steel and aluminum components.
‡Nominal 1/8"-thick adhesive interlayer between steel and aluminum components.

It is important to note that the aluminum backup component for the composite armor studied in this work plays a critical role in preventing global cracking* and/or shatter of the hardened steel frontal plate. In fact, monolithic 4340 steel plate of nominal thickness 0.2 inch with a modified carbon content of 0.48 (heat 51957) and a two-hour 325°F temper cracked globally when impacted with the caliber .30 AP M2 projectile near the plate limit velocity. Increasing the temper to 350°F for three hours eliminated cracking under caliber .30 AP M2 impact; however, such plates broke up catastrophically when impacted with the Soviet 7.62-mm × 54 Type D ball (lead core) projectile near muzzle velocity (2630 ft/sec). When supported (backed) with an aluminum plate, the steel plate studied in this work did not catastrophically fail under caliber .30 AP M2 attack; this was the case even for steel components with reduced temper of two hours at 250°F.

To further test the susceptibility of steel frontal plate to breakup, a single-shot experiment was conducted on composite C27 with the Soviet 7.62-mm Type D ball projectile. The steel and aluminum plates of target C27 are separated by 1/8-inch adhesive, a "worst-case" condition for steel component support. Furthermore, the shot was conducted with the target at -40°F. A strike velocity of 2740 ft/sec resulted in partial penetration of the target with no signs of face global cracking or breakup.

Figure 7 shows front and rear profile views of composite C27 after ballistic impact. Seven impacts with the caliber .30 AP M2 projectile at room temperature and a single shot with the 7.62-mm Type D ball at -40°F show no more than expected damage of the composite structure.

*Global cracking is used to describe cracks that extend from the impact location to the plate edge or, at least, well beyond the point of impact.

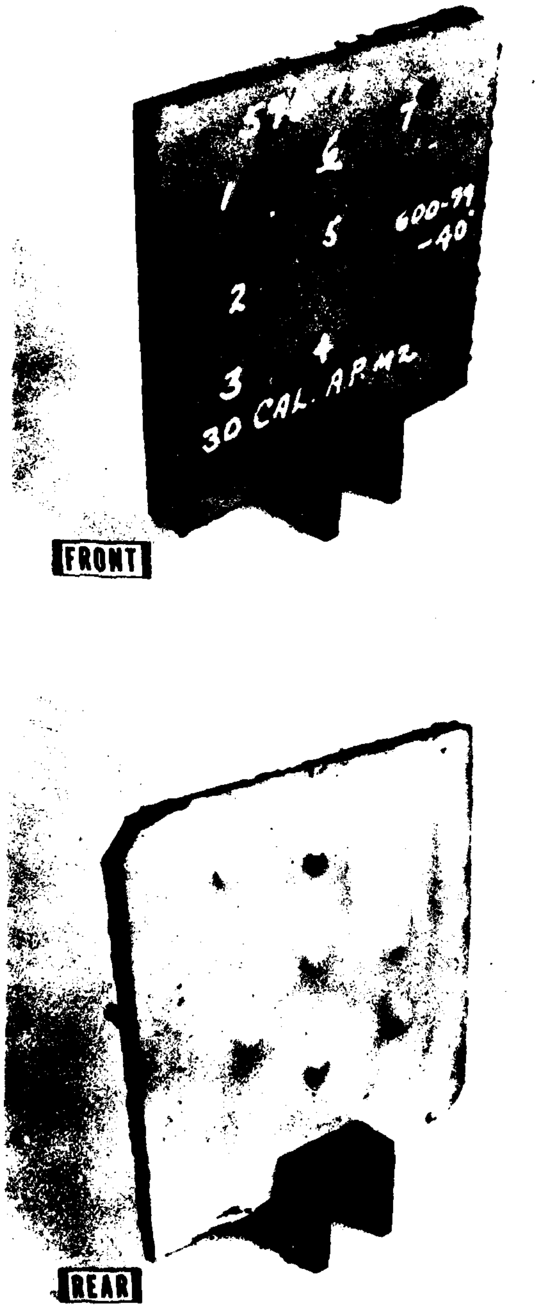

Figure 6. Steel/aluminum composite target C21 after ballistic impact at both room temperature and -40°F (caliber .30 AP M2 projectile at 0° obliquity).

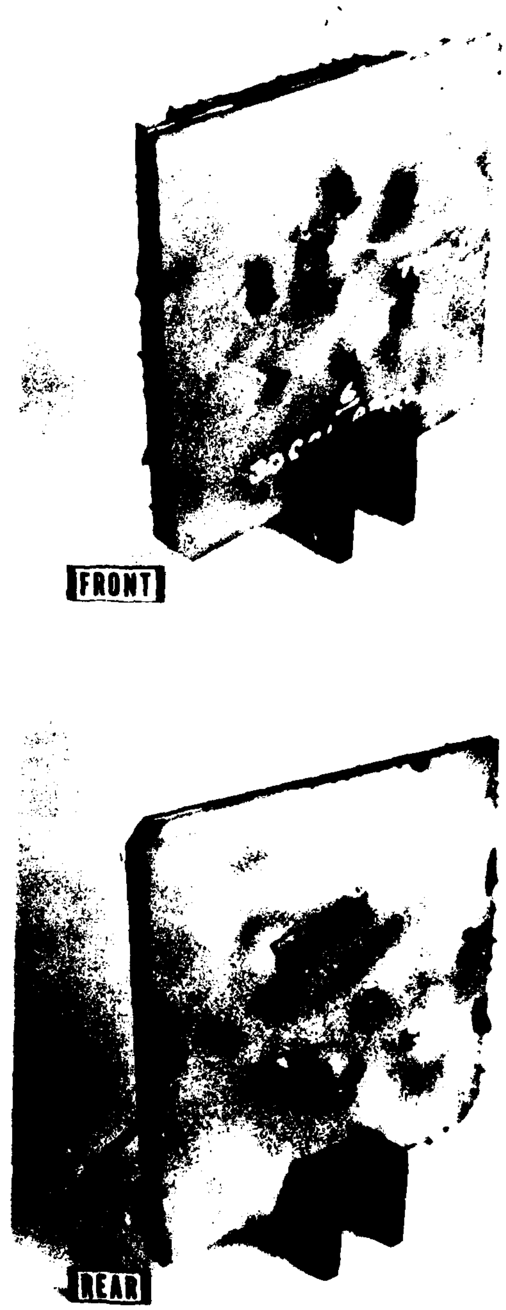

Figure 7. Steel/aluminum composite target C27 after ballistic impact at both room temperature and -40°F (caliber .30 AP M2 projectile and Soviet 7.62-mm Type D ball at 0° obliquity).

CONCLUSIONS

A fundamental conclusion of this work is that aircraft-quality 4340 steel to specification AMS 6359C provides an important addition to the class of low-cost, commercially available steels for AP armor applications. This alloy hardened to HRC 51 to 55 provides improved ballistic performance over high-hardness steel (MIL-A-46100) against small caliber AP threats. This material also offers an effective alternative to both rolled-homogeneous (MIL-A-12560) and high-hardness steels for application as monolithic plate armor or as a component in multiplate armor systems.

Bimetallic composites consisting of carbon-modified 4340 alloy steel (0.46 to 0.48 weight percent carbon) backed with armor grade 5083 aluminum provide a significant addition to the class of armor materials for defeat of AP penetrators. Steel/aluminum laminates of modified 4340 steel and 5083 aluminum perform at the level of dual-hardness steel for the caliber .30 AP M2 projectile. Steel/aluminum laminates can be designed to provide a cost-effective AP armor substitute for dual-hardness steel.

The hardened 4340 steel/5083 aluminum composites display AP limit velocity maxima. That is, for fixed unit weight of composite, AP limit velocity is maximal for some value of the steel/aluminum weight ratio.

Ballistic impact of steel/aluminum composites at room temperature and subzero temperature (-40°F) shows no evidence of brittle fracture or catastrophic failure of the hardened steel frontal plate; this holds for steel hardness up to HRC 60. Furthermore, unlike ceramic-faced composite armor, composites of hardened 4340 steel and 5083 aluminum display excellent multi-hit capability.

High-performance steel-faced aluminum armor is of practical importance because of the wide use of aluminum for combat vehicle hulls. For example, carbon-modified 4340 steel hardened to HRC 55 to 60 can be added to in-service aluminum hull vehicles or designed into advanced vehicles to improve AP survivability.

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APPENDIX. TERMINAL BALLISTIC DATA

Test	Target	Strike Velocity (fps)	Result	V_L (fps)
A. Monolithic Steel Plate				
639-79	M1	1476	0	1588
		1548*	0	
		1551*	0	
		1566*	0	
		1598*	1	
		1613*	1	
		1653*	1	
		1766	0	
		1783	1	
856-78	M2	1538*	1	1574
		1609*	0	
		1665	1	
		1678	1	
		1730	0	
		1776	1	
		1783	1	
		1871	1	
		2002	1	
		2032	1	
		2151	1	
		2201	1	
862-78	M3	1772*	0	1787
		1774*	1	
		1777*	0	
		1826*	1	
		1892	1	
626-79	M4	1709*	0	1761
		1735*	1	
		1766*	0	
		1835*	1	
		1914	1	
		2052	1	
		2089	1	
		2216	1	
635-79	M5	1748*	0	1804
		1809*	0	
		1822*	1	
		1837*	1	
		1846	1	
		1902	0	
		1931	1	
		1953	0	
		2076	1	
863-78	M6	2103*	0	2142
		2129*	1	
		2164*	1	
		2171*	0	
		2189	1	
		2214	1	
638-79	M7	2004*	0	2065
		2018*	1	
		2044*	0	
		2090*	0	
		2110*	1	
		2123*	1	
625-79	M8	2109*	0	2170
		2168*	0	
		2190*	1	
		2213*	1	
		2279	1	
		2318	1	
		2419	1	
		2420	1	
		2515	1	
649-79	M9	2177	0	2220
		2187*	0	
		2199*	1	
		2205*	0	
		2216*	0	
		2232*	1	
		2280*	1	
909-78	M10	2039	0	2168
		2119	0	
		2136*	0	
		2169*	0	
		2176*	1	
		2189*	1	
		2271	1	
854-78	M11	2136	0	2218
		2167	0	
		2185	0	
		2200*	0	
		2204*	0	
		2229*	1	
		2239*	1	
910-78	M12	2037	0	2269
		2266*	0	
		2272*	1	
		2331	1	
		2417	1	
861-78	M13	2281*	0	2313
		2288*	1	
		2322*	0	
		2361*	1	
		2384	1	
		2403	1	
		2535	1	
929-78	M14	2012	0	2274
		2143	0	
		2199	0	
		2212	0	
		2236*	0	
		2267*	0	
		2270*	1	
		2321*	1	
517-79	M15	2587*	0	2621
		2594*	0	
		2627*	1	
		2674*	1	
		2685	1	
		2693	1	
		2743	1	

Test	Target	Strike Velocity (fps)	Result	V_L (fps)
A. Monolithic Steel Plate (continued)				
651-79	M16	2364*	0	2397
		2393*	1	
		2398*	0	
		2431*	1	
		2465	1	
		2545	1	
118-79	M17	2795	0	3190
		2849	0	
		2946	0	
		2982	0	
		3030	0	
		3055	0	
		3171*	0	
		3208*	1	
		3295	1	
652-79	M18	2895	0	3188
		3126*	0	
		3148*	0	
		3184*	1	
		3210*	0	
		3227*	1	
		3230*	1	
		3303	1	
B. Composite Armor at Room Temperature				
373-77	C1	1839	0	1997
		1960*	0	
		1964*	0	
		2014*	1	
		2051*	1	
		2074	1	
		2230	1	
557-79	C2	2650	0	2720
		2680	0	
		2682	0	
		2682*	0	
		2690*	1	
		2696*	0	
		2727*	0	
		2762*	1	
		2765*	1	
457-79	C3	2529*	0	2595
		2572*	0	
		2573*	1	
		2586*	0	
		2650*	1	
		2659*	1	
		2754	1	
558-79	C4	2660*	0	2682
		2665*	0	
		2680*	1	
		2693*	1	
		2696*	0	
		2696*	1	
591-79	C4	2685*	0	2692
		2698*	1	
		2713	1	
		2716	1	
		2718	0	
		2749	1	
588-79	C5	2601	0	2842
		2682	0	
		2782*	0	
		2838*	0	
		2848*	1	
		2899*	1	
422-79	C6	2672	0	2728
		2681	0	
		2704*	0	
		2707*	0	
		2713*	0	
		2717*	1	
		2746*	1	
		2778*	1	
589-79	C7	2711*	0	2770
		2743*	0	
		2755*	0	
		2793*	1	
		2807*	1	
		2812*	1	
498-79	C8	2689	0	2773
		2719	0	
		2741*	0	
		2762*	0	
		2782*	1	
		2807*	1	
518-77	C9	2501*	0	2579
		2557*	0	
		2559*	0	
		2600*	1	
		2616*	1	
		2640*	1	
336-77	C10	2548	0	2800
		2591	0	
		2629	0	
		2663	0	
		2784*	0	
		2816*	1	
456-79	C11	2813*	0	2830
		2829*	0	
		2835*	1	
		2843*	1	
311-77	C12	2488	0	2815
		2788*	0	
		2842*	1	
414-77	C13	2611	0	2698
		2633	0	
		2653*	0	
		2677*	0	
		2694*	1	
		2698*	1	
		2705*	0	
		2763*	1	
374-77	C14	2616	0	2783
		2695	0	
		2753*	0	
		2759*	1	
		2769*	0	
		2850*	1	

Test	Target	Strike Velocity (fps)	Result	V_L (fps)
B. Composite Armor at Room Temperature (continued)				
335-77	C15	2541	0	2618
		2570	0	
		2593*	0	
		2642*	1	
518-79	C16	2659	0	2802
		2740*	0	
		2780*	0	
		2793*	0	
		2805*	1	
		2829*	1	
		2862*	1	
337-77	C17	2893*	0	2923
		2953*	1	
		3037	1	
169-79	C18	2811	0	3032
		2975*	0	
		3009*	0	
		3063*	1	
		3081*	1	
519-79	C19	2642*	0	2659
		2653*	0	
		2665*	1	
		2676*	1	
		2701	1	
		2714	1	
618-79	C20	2683	0	2741
		2709	0	
		2712	0	
		2740*	0	
		2742*	1	
		2765	0	
		2789	0	
		2800	0	
		2843	1	
598-79	C21	2687	0	2800
		2698	0	
		2769	0	
		2773*	0	
		2781*	0	
		2815*	1	
		2830*	1	
596-79	C22	2639	0	2802
		2720	0	
		2751	0	
		2780*	0	
		2800*	0	
		2806*	1	
		2823*	1	
499-79	C23	2693	0	2805
		2764	0	
		2770*	0	
		2800*	0	
		2802*	0	
		2803*	1	
		2813*	1	
		2843*	1	
619-79	C24	2759	0	2834
		2771	0	
		2772	0	
		2795*	0	
		2831*	0	
		2846*	1	
		2865*	1	
C. Composite Armor at Subzero Temperature and Interlayer Effects				
621-79, 630-79	C25 at -40°F	2777*	0	2817
		2779*	0	
		2809*	1	
		2901*	1	
		2921	0	
		2969	1	
		2981	1	
653-79	C26†	2706	0	2901
		2752	0	
		2770	0	
		2874	0	
		2879*	0	
		2898*	1	
		2907*	0	
		2920*	1	
624-79	C27‡	2685*	0	2738
		2736*	0	
		2740*	1	
		2751*	0	
		2756*	1	
		2762*	1	
		2848	1	

*Indicates velocities used in calculation of limit velocity V_L.
†No adhesive interlayer.
‡Nominal 1/8"-thick adhesive interlayer.

NOTE: A zero in the result column indicates partial penetration; a 1 indicates complete penetration.

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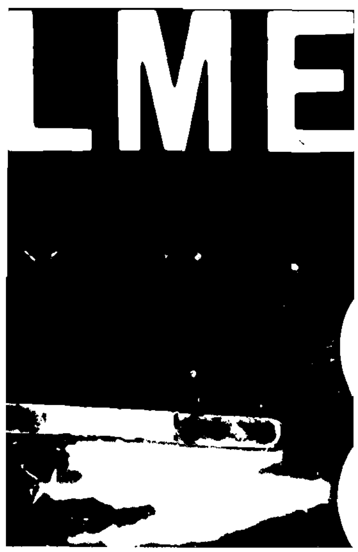
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