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Ballistic Testing of Australian Bisalloy Steel for Armor Applications

by Dwight D. Showalter, William A. Gooch, Matt S. Burkins, Victoria Thorn, Stephen J. Cimpoeru, and Russell Barnett

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Aberdeen Proving Ground, MD 21005-5069

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) and Australian Defence Science and Technology Organisation (DSTO) have ballistically baselined a range of armor steels (277-321HB to 477-534HB) manufactured by the Australian company, Bisalloy Steels. Plate was tested in thicknesses from 10 mm to 20 mm and ARL and DSTO ballistically tested the plates against 0.30 calibre and 0.50 calibre armor piercing projectiles, 0.50 calibre and 20 mm Fragment Simulating Projectiles (FSPs) and the 14.5 mm BS41. Ballistic performance was compared for armor steels over a range of hardnesses and toughnesses, and results compared with the minimum ballistic requirements of MIL-A-12560H and MIL-A-46100D.

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BALLISTIC TESTING OF AUSTRALIAN BISALLOY STEEL FOR ARMOR APPLICATIONS

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The U.S. Army Research Laboratory (ARL) and Australian Defence Science and Technology Organisation (DSTO) have ballistically baselined a range of armor steels (277-321HB to 477-534HB) manufactured by the Australian company, Bisalloy Steels. Plate was tested in thicknesses from 10 mm to 20 mm and ARL and DSTO ballistically tested the plates against 0.30 calibre and 0.50 calibre armor piercing projectiles, 0.50 calibre and 20 mm Fragment Simulating Projectiles (FSPs) and the 14.5 mm BS41. Ballistic performance was compared for armor steels over a range of hardnesses and toughnesses, and results compared with the minimum ballistic requirements of MIL-A-12560H and MIL-A-46100D.

INTRODUCTION

The U.S. and Australia are engaged in a cooperative effort under a joint Defense Project Agreement [1] to assess light-weight armor technologies that deliver optimized performance against a range of battlefield threats, including armor piercing (AP) and fragmentation threats. Such protection has to be provided at realistic areal densities for an affordable price. Quenched and tempered steel is still quite competitive as an armor material for many ballistic applications and is the subject of the present study.

Two of the most common armor steel grades in use are MIL-A-12560H Class 1 Rolled Homogenous Armor (RHA) with a hardness range of 241-388HB [2] and MIL-A-46100D High Hardness Armor (HHA) with a hardness range of 477-534HB [3]. Both of these specifications had their origins in World War II and had not changed markedly since. The former has been modified recently (September 2000) to become more of a unified specification, incorporating a new class of wrought armor plate, Class 4, which is heat treatable to higher hardness ranges than Class 1. This new class is divided into two sub-classes, defined by whether the armor plate is for a structural or non-structural application.

An Australian company, Bisalloy Steels Pty Ltd, produces a wide range of quenched and tempered steel grades of varied hardness and toughness which are very lean in alloy content and are starting to be used in a number of armor applications. The present study assesses the performance of these steels against a range of test projectiles, including Fragment Simulating Projectiles (FSPs), 0.30 Cal. APM2, 0.50 Cal. APM2 and 14.5 mm BS41, which will support the data obtained from the earlier assessment of steel produced by Swedish Steel SSAB [4].

An additional aim is to add to the data set that is gradually being accumulated on how ballistic performance varies with steel hardness and toughness. This will aid the further development and application of unified armor steel specifications that control armor steel properties over a wide range of steel hardness, Australian DEF(AUST) 8030 [5] and UK DEF STAN 95-24 [6] being good examples of such specifications. Table 1 compares these specifications, the U.S. Military Specifications and the Bisalloy steel grades.

DEF(AUST) 8030 is a unified armor steel specification, which controls the mechanical and chemical properties over a full range of functional rolled homogenous armor steel classes. It is a performance-based specification, allowing a contractor the freedom to choose an armor steel that best meets their needs while defining ballistic performance quality assurance requirements and, importantly, ensuring that the structural integrity of the resulting armored structure will also meet a minimum standard [7].

Table 1. Armor Classes.

Armor Class According to DEF(AUST) 8030	Hardness Equivalences (HB)			
	DEF(AUST) 8030[1]	U.S. Military Specification Approx. Nominal Equivalent Grade	DEF STAN 95-24 Approx. Nominal Equivalent Grade	**BISALLOY STEELS GRADES**
Class 1	Not Explicitly Specified	No Equivalent	No Equivalent	**Bisplate 80A (235-293)**
Class 2	2A: 260-310 2B: 280-330	MIL-A-12560H Class 2 <31.8 mm (277-321)	Class 1 (262-311)	**Bisplate High Impact Armor (HIA) Class 2 (277-321)**
Class 3	340-390	MIL-A-12560H Class 1 <12.7 mm (341-388) 12.7 to <19.1 mm (331-375) 19.1 to <31.8 mm (321-375) 31.8 to <50.5 mm (293-331)	Class 2 <9 mm (341 min) 9 to <15 mm (311 min) 15 to <35 mm (285 min) 35 to <50 mm (262 min)	**Bisplate High Impact Armor (HIA) Class 1 (290-390)**
Class 4	370-430	MIL-A-12560H Class 4B (381 max)	No Equivalent	**Bisplate High Toughness Armor (HTA) (370-430)**
Class 5	420-480	MIL-A-12560H Class 4A (442 min)	Class 3A 5 to <50 mm (420-480)	**Bisplate Ultra High Toughness Armor (UHTA) (420-480)**
Class 6	470-535	MIL-A-46100D	Class 3 <15 mm (470-540) 15 to <35 mm (470-535)	**Bisplate High Hardness Armor (HHA) (477-534)**
Class 7	530-605	No Equivalent	Class 4 <15 mm (530-605) 15 to <50 mm (495-605)	No Equivalent
Class 8	560-655	No Equivalent	Class 5 (560-655)	No Equivalent

[1]Each hardness range in DEF(AUST) 8030 applies for all thicknesses from 3-35 mm, unless otherwise specified.

STEEL MECHANICAL PROPERTIES AND CHEMISTRY

The collaborative research undertaken by ARL, DSTO and Bisalloy was designed to evaluate the ballistic performance of the current range of armor grade steels produced by Bisalloy Steels. The five grades assessed, HIA Class 2, HIA Class 1, HTA, UHTA and HHA, were manufactured to closely align with the main military standards of interest, namely DEF(AUST) 8030, DEF STAN 95-24 and the U.S. Military Specifications as per Table 1. These fine grained steels are vacuum degassed and calcium treated and specifically designed to optimize ballistic performance whilst maintaining good fabrication qualities and excellent weldability.

The chemical compositions for Bisplate armor grades are outlined in Table 2 below.

Table 2. Chemical Compositions of Bisplate Armor Grades.

Grade	C max	Si max	Mn max	P max	S max	Cr max	Ni max	Mo Max	B max
HIA Classes 1 & 2	.32	.50	.80	.025	.005	1.20	.50	.30	.0020
HTA	.32	.50	.80	.025	.005	1.20	.50	.30	.0020
UHTA	.25	.50	.80	.025	.005	1.20	.35	.30	.0020
HHA	.32	.50	.80	.025	.005	1.20	.50	.30	.0020

All grades are quenched and tempered through a modern Drever roller quench facility to achieve optimum levels of hardness and toughness. Mechanical properties are listed in Table 3, below.

Table 3. Mechanical Properties Specifications of Bisplate Armor Grades.

Grade	Thickness (mm)	Brinell Hardness (BHN)	Charpy V-notch @ -40C/-40F (10 x 10 mm) transverse[2]
HIA Class 2	5-50	277-321	Min 40J
HIA Class 1[3]	5-50	290-390	Min 20J
HTA	5-50	370-430	Min 17J
UHTA	8-20	420-480	Min 16J
HHA	6-60	477-534	Min 16J

[2]Charpy V-Notch test in accordance with AS 1544.2 or BS EN 10045-1 as per DEF(AUST) 8030.
[3]Hardness ranges to comply with variable hardness range requirements depending on thickness as per MIL-A-12560H.

TEST DATA

Tables 4-7 show the nominal thickness; Brinell hardness (HB); angle of obliquity with zero being normal to the target; V_{50} ballistic limit; standard deviation (σ); and the mass efficiency (E_m) of the test coupons. A maximum likelihood method was used to determine the ballistic limits and standard deviations when there was a zone of mixed results, otherwise the ballistic limits were obtained by averaging. Tight velocity spreads for ballistic limit determinations were not able to be obtained in all circumstances.

The coupons tested against armor piercing projectiles, Table 4 and 5, display increasing ballistic protection as the hardness increases. This is in contrast to the Fragment Simulating Projectile (FSP) data in Table 6, which shows how the ballistic limit drops markedly as the hardness increases.

Table 4. V_{50} Data for 0.30 Cal. APM2.

Target	Actual Thickness (mm)	Brinell Hardness (HB)	Obliquity (deg.)	V_{50} (m/s)	σ	E_m
HIA Class 2	10.3	300	0	643	10.1	0.93
HIA Class 1	10.2	363	0	664	11.9	0.99
HTA	10.3	400	0	699	12.8	1.07
UHTA	10.1	450	0	708	7.6	1.11
HHA	10.4	512	0	702	12.1	1.06
HTA	12.1	403	0	763	6.4	1.07
UHTA	12.0	444	0	777	9.0	1.12
HHA	11.9	530	0	826	7.0	1.25

Table 5. V_{50} Data for 0.50 Cal. APM2.

Target	Actual Thickness (mm)	Brinell Hardness (HB)	Obliquity (deg.)	V_{50} (m/s)	σ	E_m
HIA Class 2	10.3	300	0	490	12.8	1.04
HIA Class 1	10.2	363	0	508	14.9	1.11
HTA	10.3	400	0	495	9.4	1.05
HTA	12.0	403	0	512	12.5	0.95
UHTA	12.0	444	0	463	12.8	0.83
HHA	11.9	530	30	734	16.7	1.15
HTA	19.9	372	0	705[5]	47	0.97
UHTA	19.9	444	0	715[5]	5	1.00
HHA[4]	19.5	477	0	751[5]	81	1.11

[4]Shattergap problem at 0°obliquity, this result is using data obtained for intact projectiles.
[5]Data analysed using Maximum Likelihood Method.

Table 6. V_{50} Data for 0.50 Cal. FSP.

Target	Actual Thickness (mm)	Brinell Hardness (HB)	Obliquity (deg.)	V_{50} (m/s)	σ	E_m
HIA Class 2	10.3	300	0	945	22.9	1.02
HIA Class 1	10.2	363	0	913	21.3	0.99
HTA	10.3	400	0	774	18.6	0.79
UHTA	10.1	450	0	708	7.2	0.70
HHA	10.4	512	0	726	6.9	0.71
HTA	12.1	403	0	868	8.3	0.78
UHTA	11.8	444	0	835	9.4	0.76
HHA	11.9	530	0	835	10.4	0.75

Table 7. V_{50} Data for 14.5 mm BS41 and 20 mm FSP (19.6 mm actual plate thickness).

Target	Threat	Brinell Hardness (HB)	Obliquity (deg.)	V_{50} (m/s)	σ	E_m
HHA	14.5 mm BS41	477	30	801	13.4	1.63
HHA	20 mm FSP	477	0	845	4.2	0.81

COMPARISON WITH U.S. ARMOR SPECIFICATIONS

For armor to be accepted into service in the U.S., it must meet MIL-A-12560H or MIL-A-46100D. This test program also included tests to ensure the ballistic limit met or exceeded that required in the standards for the particular steels. Some of the tests were conducted at 30° obliquity because the HHA often induces shattergap problems with 0.30 Cal and 0.50 Cal APM2 ammunition, the acceptance tables in MIL-A-46100D implicitly acknowledging this issue. As can be seen in Table 8, all three combinations tested to the specifications *passed*.

Table 8. Comparison of results with MIL-A-12560H and MIL-A-46100D.

Target	Threat	Actual Thickness (in.)	Obliquity (degrees)	Minimum Ballistic Limit (fps)	Actual Ballistic Limit (fps)
HHA	0.50 Cal APM2	0.469 (11.9 mm)	30	2354[6] (718 m/s)	2408 (734 m/s)
HHA	14.5 mm BS41	0.770 (19.6 mm)	30	2292[6] (699 m/s)	2627 (801 m/s)
HIA Class 1	0.30 Cal APM2	0.402 (10.2 mm)	0	2146[7] (654 m/s)	2183 (664 m/s)

[6]MIL-A-46100D.
[7]MIL-A-12560H.

EFFECT OF HARDNESS ON BALLISTIC LIMIT FOR ARMOR PIERCING PROJECTILES AND FRAGMENT SIMULATORS

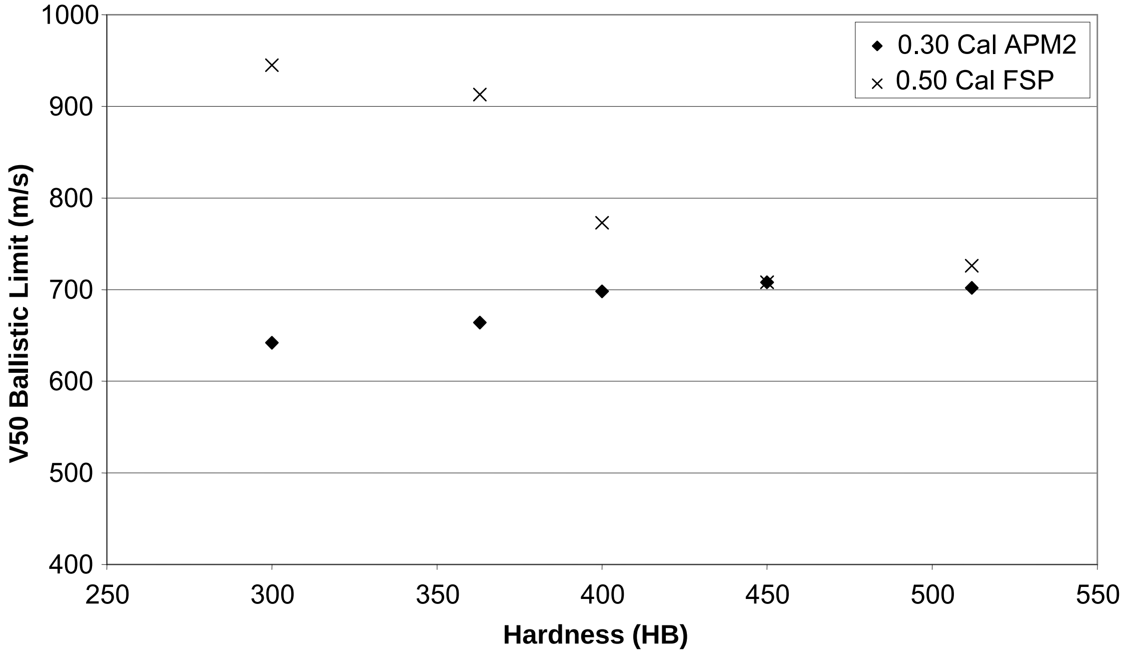

Figure 1. The effect on the V_{50} ballistic limit as the hardness increases for 10 mm Bisalloy plates against 0.30 Cal APM2 and 0.50 Cal FSPs.

From Figure 1 and Tables 4-7 it is evident that plate hardness will affect the ballistic limit achievable for armor steels. 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 Int. Ballistic Symposium [8] and for this reason armor designers are more often incorporating higher strength armor steels in their applique and structural armor solutions. Whilst this phenomenon is true for small arms protection, it does not apply for fragmentation protection. Fragmentation protection decreases significantly with increasing hardness, making the higher hardness armor grades a poor choice for such applications. This is because impacts of blunt fragments cause high strength steels to fail by adiabatic shear plugging [9].

Figure 1 also shows that there is no difference between the ballistic performance of UHTA (~450HB) and HHA (~530HB) and this is also seen for other plate thicknesses in Tables 5 and 6. The UHTA grade has a leaner chemistry, providing improved toughness and weldability compared to HHA. UHTA would be a better choice for structural applications and the more consistent ballistic performance may allow a weight saving in some circumstances.

CONCLUSIONS

The U.S. and Australia completed a cooperative effort to assess armor steel produced by Bisalloy Steels Pty Ltd. A comparison was made between the different grades of Bisalloy steels and various U.S., Australian, and U.K. armor standards. As the hardness of the steel plates increased, the V_{50} ballistic limit of the plates increased against steel-cored, armor-piercing projectiles. For nominal 10 mm plates, the Bisalloy HIA Class 2 plates (277-321HB) provided a V_{50} of 643 m/s against the 0.30 caliber APM2, but the V_{50} increased up to 702 m/s for the HHA grade at 477-534HB. For the 0.50 caliber FSP the trend was reversed with the lowest hardness plates providing the highest V_{50}. The higher strength plates tend to fail by adiabatic shear plugging when subjected to attack by the blunt FSPs. It is also seen in many instances that there is no difference in ballistic performance between UHTA (~450HB) and HHA (~530HB). The UHTA grade is more weldable, has better structural properties and sometimes has more consistent ballistic performance than HHA. Two Bisalloy HHA plates were tested and both passed the requirements of MIL-A-46100D. A single plate of Bisalloy HIA Class 1 armor plate was tested and it passed the requirements of MIL-A-12560H.

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