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BALLISTIC PROPERTIES OF DELAMINATING ARMOR

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ABSTRACT

Composite armor plate was fabricated by hot-rolling stacks of 1/4-inch steel plates bonded with foils of aluminum, copper and nickel, and iron screens. Very little delamination occurred during handling or processing. Delamination to the desired extent did occur during penetration by a .50-cal sphere. A 5/16-inch plate of delaminating armor had a limit velocity of approximately 2690 feet per second. For the same limit, a plate of 24ST weighing 11 percent less per unit area or a plate of solid armor weighing 12 percent more would be required.

PROBLEM STATUS

This is a final report; unless otherwise advised by the Bureau of Aeronautics, the Laboratory will consider the problem closed thirty days from the mailing date.

AUTHORIZATION

NRL Problem M01-20R
(BuAer Nr. AR-28 62338, Request No. TED NRL-AR-2801)
NR 411-200

BALLISTIC PROPERTIES OF DELAMINATING ARMOR

INTRODUCTION

Military requirements dictate the use of armor plate in combat aircraft. Improvements in armor performance are essential if the present weight is to continue to provide adequate protection against new weapons. Attempts to improve ballistic effectiveness of steel armor deserve particular attention because it is the material most likely to be utilized as armor in case of the need for rapid expansion of combat aircraft production.

The classical approach to steel armor improvement has been based on attempts to find plates with particular combinations of composition and microstructure which have optimum resistance to penetration. Another approach was suggested by previous NRL work on plastics showing that bonded plates which delaminated during penetration were superior to solid plates of equivalent weight in defeating simulated fragments. Hodge and Joyce[1] pointed out that in some cases uncontrolled inclusions and laminations increase limit-velocity results because they change the mode of deformation of armor.

In view of the work on plastics and the general experience with "dirty" armor, a study was initated to determine whether or not bonded steel plates which delaminated during penetration would have better ballistic properties than solid homogeneous steel plates.

EXPERIMENTAL PROCEDURE

Alloy steels AISI 8630 and STS 564 were selected as base plates for fabrication into delaminating armor. Foils of aluminum, copper, and nickel were studied as continuous bonding media, while strips of copper foil or steel screens in various wire and mesh sizes were utilized for investigations of discontinuous bonding. Table 1 lists the various bonding materials used.

Stacks of five six-inch-square, one-quarter-inch-thick plates,plus the intermediate bonding materials, were sealed by welding the edges in order to minimize oxidation of the internal surfaces during heating for rolling. The stacks were rolled to 5/16 inch at approximately 2000°F. Exceptions were those bonded with copper; the latter were rolled at about 1700°F to prevent separation.

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[1] Hodge, J. M., and Joyce, H. V., "A Study of Ballistic and Metallurgical Characteristics of Steel Aircraft Armor," Carnegie-Illinois Steel Corp. Research Report, Pittsburgh, June 1948. Contract No. N173-S-11392 (Confidential)

TABLE 1
Summary of Delaminating Tests of Laminated Armor

Steels	Composition of Steels C	Mn	Ni	Cr
STS	0.32	0.23	2.87	1.44
8630	0.30	0.91	0.61	0.52

Comp	Steel Hardness B.H.N.	Bonding Agent Material	Bonding Agent Thickness	Mesh	Extent of Delamination during Penetration*	Remarks
STS	250	None			None	‖to rolling direction.
STS	250	None			None	Half‖ and half ⊥ to rolling direction.
STS	250	Ni foil	0.005		None	
8630	As rolled	Steel screen	0.025	$4\frac{1}{2}$	Fair	
8630	"	"	0.025	9	Fair	
8630	"	"	0.025	16	Poor	
8630	"	"	0.050	4	Fair	
8630	"	"	0.050	7	Fair	Partially delaminated during quenching.
8630	"	"	0.050	10	Fair	
8630	"	"	0.072	$3\frac{1}{2}$	Good	
8630	"	"	0.072	6	Poor	
8630	"	"	0.072	8	Poor	
8630	"	Cu screen	0.054	7	Good	Delaminated during rolling at 1850°F.
8630	"	Cu foil	0.002		Good	Cu foil in cross strips; 20% of area of plate before rolling.
8630	"	"	0.002		Good	
8630	"	"	0.002		Good	
8630	"	"	0.004		Good	
8630	"	Al foil	0.004		Good	

*Good signifies separation of every bond and absence of tearing or spawling.
Fair signifies separation of three or four bonds and some tearing but no spawling.
Poor signifies separation of less than two bonds and extensive tearing or spawling.

TABLE 2
Heat Treatment of 1/4-Inch Homogeneous Steel Armor

Composition C	Mn	Cr	Mo	Ni	Va	S	P	Si
0.30	0.49	1.08	0.62	0.12	0.14	0.012	0.018	0.16

Treatment	B.H.N.	Austenitizing Temp. (°F) (1/2 Hr)	Cooling Procedure After Austenitizing	Tempering Temp. (°F)	Tempering Time (hr)	Cooling Procedure After Tempering	Micro-structure*
1	229	1600	Furnace cooled @ 750°F/hr	Not tempered		None	P
2	229	1600	Oil Quenched	1300	3	Furnace Cooled	T.M.
3	350	†					T.M.
4	212	1600	Oil Quenched	1300	$3\frac{1}{2}$	Water Quenched	T.M.
5	250	1600	Oil Quenched	1300	2	Water Quenched	T.M.
6	311	1600	Oil Quenched	1225	1	Water Quenched	T.M.
7	363	1600	Oil Quenched	1200	1	Water Quenched	T.M.

* P = Pearlite
T.M.= Tempered Martensite
† Used as received from Jessop Steel Company

Solid homogeneous plates (1/4 and 3/8 inch thick) of the compositions listed in Table 1 were tested for comparison with the delaminating armor.

Heat Treatment

The composite plates were heat-treated to a Brinell hardness of 250 for comparison of the bonding materials. Each samp was:

Austenized at 1550°F for 1/2 hour,
Quenched in oil at room temperature,
Tempered at 1150°F for 4 hours,
Quenched in water.

Seven heat treatments (Table 2) were used to prepare the 1/4-inch homogeneous steel plates for ballistic tests of the relation between hardness and limit velocity. Five plates were used for each treatment.

Comparisons of ballistic properties were made with delaminating armor and with 1/4- and 3/8-inch solid steel armor plates heat-treated to a Brinell hardness of 212 as follows:

Austenized at 1600°F for 1/2 hour,
Quenched in oil at room temperature,
Tempered at 1300°F for 3-1/2 hours,
Quenched in water.

Ballistic Tests

Ballistic tests were made on 6 x 6-inch solid and composite specimens in a ballistic pendulum using a hard .50-cal sphere[2] fired from a smooth-bore gun. Suitable blast deflectors were employed. Projectile velocities, controlled by varying the powder charge, were calculated from measurements of the deflection of the accurately weighed pendulum.

The plate was backed by several pieces of 1/2-inch-thick plywood. Limit velocity was designated as the highest projectile velocity at which the plug from the plate hit the first piece of plywood and bounced off.

RESULTS

The delaminating characteristics of the composite plates are shown in Table 1. All except those bonded with nickel foil delaminated to some extent. The most complete delamination occurred with copper foil or aluminum foil. There was a slight tendency for the plates bonded with the heaviest wire screen to delaminate during quenching.

The ballistic performance of 1/4-inch solid, homogeneous armor at various hardnesses and microstructures is shown in Figure 1. Detailed information obtained from each shot is given in Table 3. Pearlite is definitely inferior to the microstructures developed after

[2] SKF grade 1 ball bearing

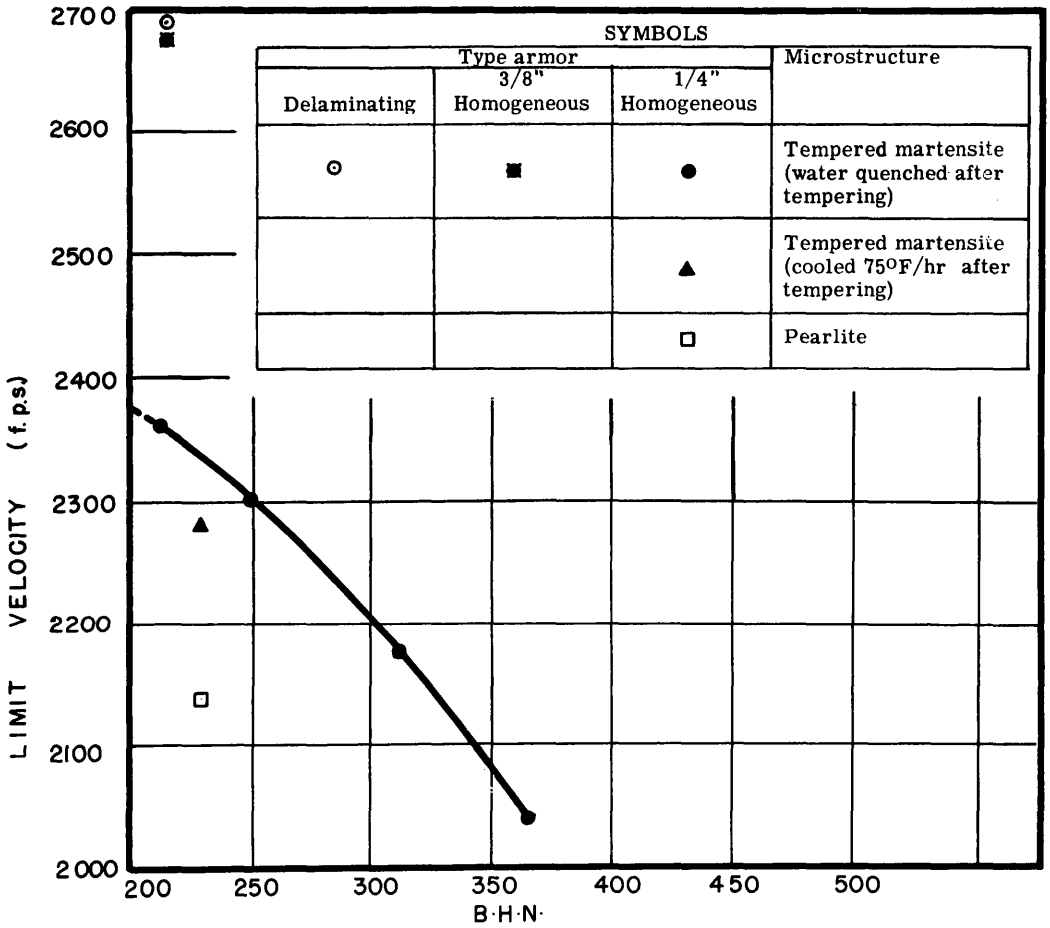

Figure 1 - Limit velocity (protection) against a .50-cal sphere projectile

tempering martensite. As is observed in tests with fragments,[3] the sphere penetration resistance decreases with increased hardness. Optimum hardness was the softest which could be produced, viz., 212 B.H.N. The performance of 3/8-inch homogeneous armor at 212 B.H.N. is also shown in Figure 1.

Since the plates bonded with copper exhibited the best delaminating characteristics, they were heat-treated to the optimum hardness and tested ballistically. The results are shown in Table 4. A shot near the limit velocity caused a bulge approximately the size of the diameter of the sphere. The extent of the bulge and degree of delamination are exhibited in Figure 2. Figure 3 shows a 6 x 6-inch plate in which all shots were fired between 2350 and 2740 feet per second. Performance of subsequent shots was not impaired by previous delaminations or by impacts near the edge. In Figure 4 cross sections through complete penetrations of delaminating and solid armor are shown. It can be seen that a much greater volume of deformed metal is present after delamination. The restraint present in the solid armor is reduced by the separation of each bond. Each successive plate in the delaminating armor flows more freely than a similar element in solid plate.

[3] Private communication from C. Levine, Bureau of Aeronautics, Navy Department

TABLE 3
1/4-inch Homogeneous .30% C Armor Under Sphere Ballistic Test*
Sphere = 0.50 Cal (SKF Ball Bearing)

Treatment	Microstructure	Velocity	Rest Positions of Ball and Plug		Armor Appearance Back of Hole
			Ball	Plug	
	Pearlite	2455	2nd P.W.	2nd P.W.	C.S.
1	229 B.H.N.	2190	1st P.W.	1st P.W.	S.S.
		2060	R.A.	B.P.W.	C.S. Jagged 3/8" hole
		2120	R.A.	B.P.W.	C.S. Jagged 3/8" hole
		2160	R.A.	1st P.W.	C.S. Jagged
	Tempered	2300	B.P.W.	1st P.W.	N.S.
	Martensite	2262	R.A.	B.P.W.	S.S. One Quadrant
2	229 B.H.N.	2288	R.A.	B.P.W.	S.S. One Quadrant
		2370	F.A.	2nd P.W.	N.S.
	Tempered	2092	R.A.	1st P.W.	Back Hole only 1/4" wide
	Martensite	2160	F.A.	1st P.W.	N.S.
3	As Received	2182	B.A.	B.P.W.	Back Hole only 1/4" wide N
	Jessop Steel	2170	R.A.	1st P.W.	N.S.
	Ave. B.H.N. 350	2185	B.A.	B.P.W.	N.S.
	Tempered	2472	F.A.	2nd P.W.	N.S.
	Martensite	2220	R.A.	B.P.W.	N.S.
4	B.H.N. 212	2245	R.A.	B.P.W.	N.S.
		2388	F. 1st P.W.	1st P.W.	N.S.
		2325	B.P.W.	B.P.W.	N.S.
		2310	B.P.W.	B.P.W.	N.S.
		2330	B.P.W.	B .020" Al	N.S.
	Tempered	2430	1st P.W.	1st P.W.	S.
	Martensite	2350	1st P.W.	1st P.W.	N.S.
5	B.H.N. 250	2330	1st P.W.	1st P.W.	N.S.
		2250	B.P.W.	B.P.W.	N.S.
		2195	R.A.	B.P.W.	N.S.
	Tempered	2110	F.A.	B.P.W.	N.S.
	Martensite	2115	F.A.	B.P.W.	N.S.
6	B.H.N. 311	2235	F.A.	1st P.W.	N.S.
	Tempered	2110	B.A.	1st P.W.	N.S.
	Martensite	2192	F.A.	1st P.W.	N.S.
7	B.H.N. 363	2040	B.A.P.	B.P.W.	N.S.
	3/8-inch Homogeneous Armor				
	Tempered Martensite	2605	R.A.	None	Bulged. Cracked about 50% of periphery
4	B.H.N. 215	2555	R.A.	None	Metal sheared about 1/4" out from plate
		2700	F.A.	Pen 0.20" Al into P.W.	N.S.
		2640	F.A.	B.020" Al	N.S.

*P.W. = Plywood
R.A. = Retained by Armor
B. = Bounced Off
F. = Fragmented
BAP = Bounced After Penetration
S. = Spawling in Back of Hole
C.S. = Spawling Entire Periphery
S.S. = Slight Spawling
N.S. = No Spawling
Pen = Penetrated

TABLE 4
Ballistic Results on Cu-Bonded Laminated Steel Armor

Velocity (ft/sec)	Position of Rest		Armor Appearance
	Projectile	Plug	
2405	R.A.	None	Bulged approximately 1/4 inch
2350	R.A.	None	Near plate edge visible delamination at edge. Large bulge
2552	R.A.	None	Plate delaminated. Bulged out so that trailing edge of ball is even with back of plate
2640	R.A.	None	Delamination evident in slight tear in plate back. Bulged greater than diameter of sphere
2740	1st P.W.	Stuck in .020" Al. Very small size	Bulged to 1/2 inch
2635	B.020" 24STS	B.020" 24STS	Bulged to 1/2 inch

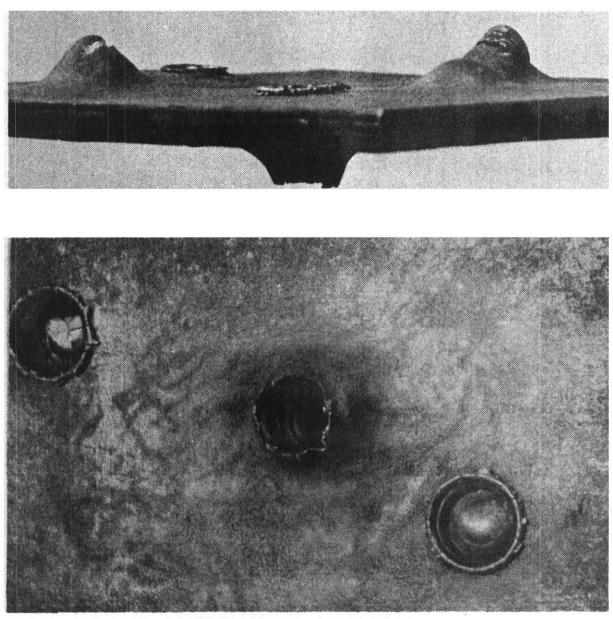

Figure 2 - (Top) Extent of bulge in delaminating armor. (Bottom) Extent of delamination (center hole)

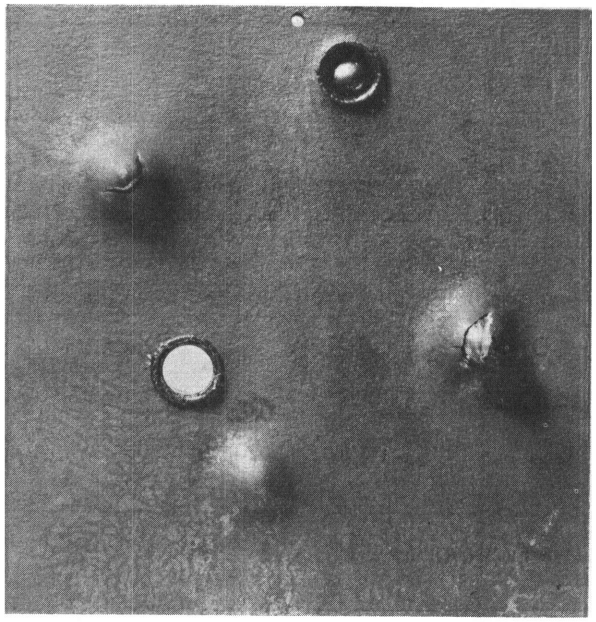

Figure 3 - Condition of plate after firing several shots within a small area

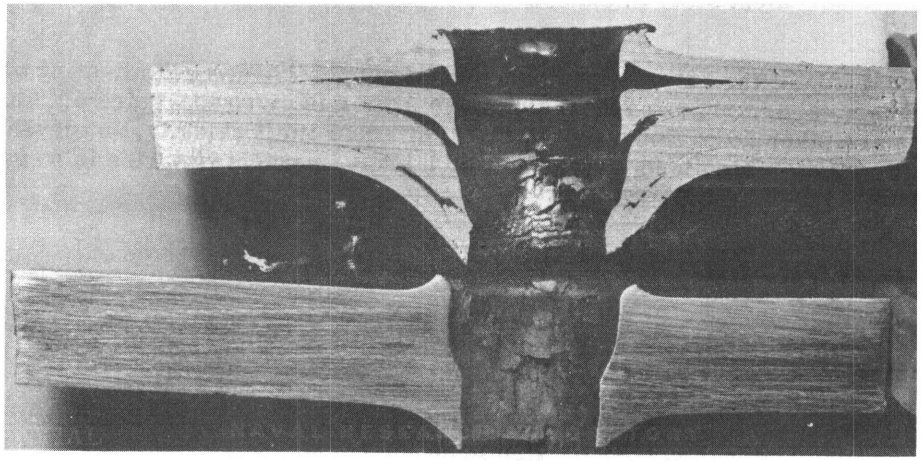

Figure 4 - Cross sections of 5/16-inch delaminating armor and 3/8-inch solid homogeneous armor after penetration with near limit velocity shots (limit velocity is 2690 feet/second for both plates)

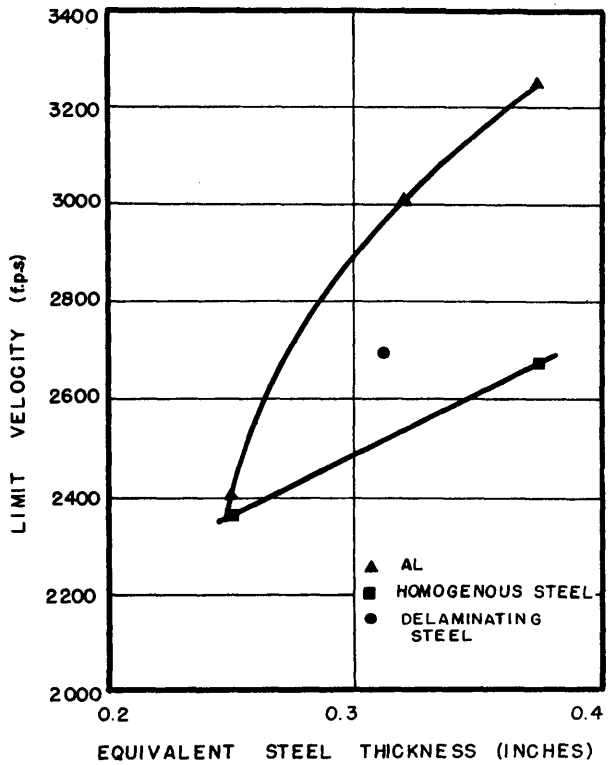

Figure 5 - Comparison of aluminum, homogeneous steel, and delaminating steel armors at equivalent steel thickness

A comparison of the ballistic performance of copper-bonded delaminating armor, solid homogeneous steel armor, and 24ST3 aluminum armor is given in Figure 5. Aluminum armor data are taken from Roberson et al.[4] For equal limit velocity, an eleven percent decrease in weight of aluminum armor and/or a twelve percent increase in weight of homogeneous armor would be required.

SUMMARY AND CONCLUSIONS

1. Composite steel armor can be made which will delaminate locally in the region of a ballistic impact.

2. Although a variety of bonding materials can be used, the best delaminating characteristics are obtained with copper or aluminum foils.

3. Optimum hardness and microstructure for .30% C solid homogeneous armor tested with hard .50-cal spheres is 212 B.H.N. developed after tempering martensite.

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[4] Roberson, R. E., Irwin, G. R., George, W., "Fragment Penetration Resistance Laws in the Theory of Aircraft Vulnerability," NRL Report 3507, 22 July 1949 (Confidential)

4. For protection equal to that provided against .50-cal spheres by 5/16-inch-thick delaminating armor bonded with copper, plates of 24ST aluminum alloy weighing eleven percent less per unit area or plates of solid homogeneous steel armor weighing twelve percent more per unit area are required.

RECOMMENDATIONS

In view of the superior performance of delaminating armor, it is recommended that additional investigations of composite plates be made. Other materials should be studied, such as delaminating aluminum armor, composite plates with various types of steel and aluminum, or steel with other bonding materials. Testing at different hardness levels with a variety of projectiles should be included.

ACKNOWLEDGMENT

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