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Test Report T68-4-1

METALLURGICAL ANALYSIS OF 5.56mm BULLET, COPPER PLATED-LEAD CORED

BY

DANIEL CAROSIELLO

October 1967

UNITED STATES ARMY
FRANKFORD ARSENAL
PHILADELPHIA, PA.

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ABSTRACT

Samples of 5.56mm bullets, copper coated and lead cored, representing two production lots (Lots A & B), were analyzed. The purpose of the analysis was to ascertain metallurgical properties and characteristics of each lot which relate to quality and possibly to method of manufacture. The testing procedures included chemical, metallographical, electron microprobe and hardness analyses. The results indicated that the electroplating quality of Lot B was superior to that of Lot A, especially with respect to adhesion and strength of coating. The electroplating techniques used in the manufacture of each lot were different as evidenced by Lot A having one continuous layer of copper and Lot B having a banded structure of three distinct layers of copper. Although the lead-antimony substrates of each lot were very similar chemically, it was demonstrated from the relative differences in hardness and hardness patterns that bullets of Lot B underwent more work-hardening than those of Lot A.

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INTRODUCTION

Two lots of 5.56mm bullets, which were copper plated and lead cored, were submitted for metallurgical analysis. The purpose of the analyses was to ascertain metallurgical properties and characteristics of each lot which relate to quality and possibly to method of manufacture. The lots as-received were labeled "0.010 in. thick copper" and "0.014 in. thick copper". In this analysis, these lots were designated as Lot A and Lot B, respectively.

PROCEDURES AND RESULTS

The analytical procedures for evaluating the two lots were as follows:

a. Chemical analysis

b. Metallographic examination

c. Electron probe microanalysis

d. Dimensional analysis

e. Hardness survey

CHEMICAL ANALYSIS

The chemical analysis of the copper jacket and lead-antimony core of Lots A and B were as follows:

Copper Jacket -

Element	Lot A	Lot B
Copper	99.99%	99.93%
Lead	ND	<0.01%
Iron	<0.005%	<0.005%
Zinc	ND	ND
Tin	ND	ND
Nickel	ND	0.05%
Aluminum	ND	ND
Manganese	ND	ND
Bismuth	ND	ND
Antimony	<0.005%	ND
Silicon	ND	<0.005%
Silver	<0.005%	<0.005%

Lead-Antimony Core -

Element	Lot A	Lot B
Antimony	1.06%	0.85%
Copper	0.1/0.3%	0.1/0.3%
Arsenic	0.05/0.15%	ND
Bismuth	<0.005%	<0.005%
Iron	<0.01%	<0.01%
Silver	<0.01%	<0.01%
Tin	ND	ND
Zinc	ND	ND
Nickel	ND	ND
Cobalt	ND	ND
Calcium	ND	ND
Lead	Remainder	Remainder

METALLOGRAPHIC EXAMINATION

Samples from each lot were examined metallographically in planes transverse to the bullet axis at different locations along its length and in planes longitudinal through the bullet axis. No intermediate layers or other phases were found to be present at the Pb:Cu interface. Poor adhesion, however, was observed between the copper coating and lead substrate in samples of Lot A. This condition was characterized as intermittent separations along this interface. Figure 1 shows one of these separations on an unpolished area of the interface. The area is on a plane transverse to the bullet axis close to the base. The reason for the unpolished condition was that polishing, even if kept minimal, either tended to smear the soft lead over the discontinuity or formed a step at the interface which obliterated it completely.

The copper jacket of Lot A in Figure 2 appeared as a single layer deposit. The copper deposit exhibited a fine nodular type structure throughout practically the entire jacket. The initially deposited portion of the copper, however, had some remotely scattered columnar grain networks present with axes perpendicular to the lead-antimony substrate.

The copper jacket of Lot B had a banded structure of three distinct layers of deposited copper. Figure 2 shows these layers as compared to the single deposited layer of Lot A. The outer layer of Lot B appears much lighter than the inner layers. This condition was attributed to surface reflection due to difference in layer orientation, the actual microstructures of each layer being very similar, that is, a uniform distribution of small nodules was noted in each layer.

ELECTRON PROBE MICROANALYSIS

Electron probe microanalysis revealed the absence of an intermediate layer at the Pb-Sb:Cu interface in both Lots A and B. An electron image of this interface is shown in Figure 3. The hardness indentation which appears in the copper matrix at the lower right hand corner was used as a reference marker for indicating specimen position. Copper rich areas were detected in the lead core of both lots. Figure 4 shows these areas in an X-ray image of Cu Kα radiation with the copper phase being easily distinguishable in the dark lead matrix. An electron image of a specimen in Lot A appears in Figure 5. The arrow at the top of the photograph points to a discontinuity at the Pb-Sb:Cu interface, a condition which was noted previously in metallographic examination. Sulfur was found to be uniformly distributed in the lead core of both lots. In addition, ScKα radiation showed the presence of uniformly distributed scandium, a rare earth metal, in the copper layer of both lots. Because of the inexplicable detection of scandium, the specimen was scanned with the microprobe spectrometer for each Sc Bragg angle. An X-ray radiation response was observed at the appropriate Bragg angles for ScKα and Kβ radiation.

DIMENSIONAL ANALYSIS

The copper plating thickness of several samples which were selected randomly from Lots A and B was measured. Measurements were made at planes longitudinal and transverse to the bullet axis. The results showed that the plating thickness of each lot was very consistent. Lot A had a copper plating thickness of 0.010 in. and Lot B had a plating thickness of 0.014 in. These thicknesses corresponded to those originally designated for the lots.

The thicknesses of the three distinct layers of the banded copper exhibited in Lot B were also measured. The following average thickness values were obtained for each layer.

Outside Layer - 0.0041 in.
Middle Layer - 0.0055 in.
Initial Layer - 0.0044 in.

Total Thickness - 0.0140 in.

HARDNESS SURVEY

Vickers microhardness tests were made on the copper jacket at loads of 500 grams. Brinell hardness was determined on the lead core using a 2mm dia. ball and a load of 5 kg applied with a Vickers hardness tester. The hardness values appearing in this report for the copper jacket are Rockwell B converted from the VPH readings. The lead core hardnesses are direct Brinell readings. The following results were obtained.

Copper Jacket -

Hardness tests were performed in the copper jacket perpendicular to the bullet axis in a pattern shown in Figure 6 for both lots. Three specimens per lot were tested using this procedure. Hardness tests were also made on transverse sections in directions parallel to the axis and further hardness tests were performed on the peripheral surface of the bullet between the cannelure and the base. The location of these hardness indentations are shown in Figure 7. Tables I and II present the results of the hardness tests made at these locations, respectively.

In Lot A (see Figure 6 and Table I), the readings obtained perpendicular to the axis indicated that adjacent to the outer surface along the copper jacket, the base of the bullet was much softer (RB 26) than the nose (RB 60) or sidewalls (RB 57 and 54). The same behavior pattern was noted in the middle sector of the jacket, but with hardness values increasing somewhat to RB 50 at the base, RB 62 at the nose and RB 61 and 59 at the sidewalls. The inmost readings were comparable to the middle sector results, the base measuring RB 53 and the nose and sidewalls RB 61 and RB 60.

When considering the three impressions at the different locations independently, the average values at the sidewalls showed that the hardness of the copper jacket increased only slightly from the outer sector inward towards the lead substrate. This was also true of the nose region where no significant difference was noted from the surface inward. The hardness of the base, however, showed the readings just below the surface to be softer (RB 26) than the inner portions of the jacket (RB 50 and 53).

Generally, in summarizing the results in Lot A, the nose was slightly harder than the sidewalls, whereas the base was significantly softer.

In Lot B (see Figure 6 and Table I), the outer layer was harder at the nose (RB 84) and base (RB 84) than at the sidewalls (RB 78). In the middle layer, the base (RB 77) and nose (RB 78) were harder than the sidewalls (RB 70 and 71). The inmost layer was harder at the nose (RB 70) and base (RB 72) than locations along the sidewalls (RB 57 and 56).

When considering the three impressions at the different locations independently, the average values at the sidewalls showed a significant decline in hardness in the copper jacket with a high hardness near the surface to a softer region near the substrate. The values ranged from RB 78 to RB 57 and 56. This behavior was also evident at the nose and base regions, the hardnesses varying from RB 84 to 70 and from RB 84 to 73, respectively.

Results of hardness tests in the copper jacket, parallel to the bullet axis in Lot A (see Figure 7 and Table II), showed very slight differences in hardness from the outer sector inward to the substrate either at the sidewall or nose areas. The sidewall from nose to cannelure was in the range RB 49-51 and from cannelure to base RB 54-58. The average hardnesses at the different locations along the bullet did vary somewhat, however, the sidewalls in front and behind the cannelure averaging RB 50 and RB 56, respectively.

The hardness of Lot A transverse to the bullet axis (see Figure 6 and Table I) as compared to the hardness parallel to the axis (see Figure 7 and Table II) showed that a difference in hardness existed at the sidewall section between the nose and cannelure, the average transverse hardness being RB 59, while the parallel direction hardnesses averaged RB 50. The direction of indent did not appear to have any effect on hardness at other locations of the bullet jacket.

In Lot B (see Figure 7 and Table II), the results parallel to the axis showed that at the sidewalls and nose, there existed a definite hardness gradient from a harder outer sector inward to a softer area immediately adjacent to the lead substrate. The sidewall between the nose and cannelure varied from RB 83 to RB 58, while the sidewall between the cannelure and base varied from RB 80 to RB 65. The hardness gradient in the latter location is illustrated in Figure 8. The size of each hardness indentation is shown increasing from the surface inward. The average hardness, however, at the different locations varied only slightly, the sidewall values averaging RB 71 and RB 73.

The hardness results of Lot B transverse to the bullet axis (see Figure 6 and Table I) versus results parallel to the axis (see Figure 7 and Table II) showed direction of indent had practically no effect on the hardness results of the side-walls, that is, there was little difference due to direction of testing.

In Lot A, the peripheral hardnesses (see Table II) on the surface of the copper jacket were significantly greater than the hardness tests made at right angles immediately below the surface; i.e. at the outer sector, both perpendicular or parallel to the bullet axis. The peripheral hardness ranged from averages of RB 63 to RB 69 while the cross-sectional hardnesses, very near to the surface, averaged RB 54.

In Lot B, the same comparison of peripheral vs. subsurface hardness showed no significant difference between the peripheral hardness of RB 83 as compared to RB 78 and RB 80.

<u>Lead-Antimony</u> Core -

In comparing the hardness of Lots A and B (see Figure 9 and Table III), Lot B core was generally harder than the Lot A core. The hardness of the core centers, however, according to impression Nos. 4 and 7 in each lot, coincided in both perpendicular and longitudinal directions to the bullet axis, the Brinell hardness values (BHN) averaging 7.1 and 6.3, respectively. It should be noted that these impressions were located away from the copper jacket in a region where the effects of any strain hardening would be minimal, e.g., strain hardening that might result in resizing of the bullet.

Impressions numbered 2 and 3 (see Figure 9 and Table III) in each lot which were located immediately under the cannelure exhibited somewhat higher hardnesses than the other impressions in each respective lot.

Impressions Nos. 1 and 5 in Lot A compared closely to the hardness at the core center. The averages were BHN 6.9 and 7.5 to BHN 7.1 at the center. In Lot B, Nos. 1 and 5 were higher than the core center hardness of BHN 7.1, averaging BHN 7.9 and 8.2, respectively.

In Lot A, the hardness perpendicular and parallel to the bullet axis compared closely at the base (Nos. 1 and 6) and showed little difference at the nose, (Nos. 5 and 8); the base difference was BHN 6.9 perpendicular and BHN 7.0 parallel and the nose difference BHN 7.5 perpendicular and 8.0 parallel.

In making the same directional comparison in Lot B, Nos. 1 and 6 at the base varied slightly; BHN 7.9 to 7.7 and at the nose Nos. 5 and 8 the difference was a little greater, BHN 8.2 to 7.5.

DISCUSSION

The results of this evaluation indicated that in 5.56mm bullets, representing the two production Lots A and B, the structural soundness of Lot A was inferior to that of Lot B. Poor adhesion was noted in Lot A between the copper coating and the lead substrate in areas between the cannelure and base of the bullet. Several factors are known to cause poor adhesion, but to ascertain precisely the reasons for this condition is beyond the scope of this investigation, since it would necessitate an extensive study of the many variables involved in electroplating and other processes in the manufacture of the bullet.

There was a definite difference in the manner in which the copper was deposited in Lot A as compared to Lot B. The banded structure of Lot B was typical of electrodeposits resulting from periodic reversal of current during deposition, whereas the single deposit of Lot A was probably done under a single set of plating conditions.

Regarding crystal size and shape of the structures under analysis, the salient features were, for the most part, very fine grain, nodular types with no obvious preferred direction of growth. The composition of the plating bath most likely was a factor producing such a structure during deposition. It should be mentioned also that such structures usually exhibit minimal anisotropy.

The electron probe analysis confirmed the findings in the metallographic examination of the copper coating, that is, at the lead substrate interface of both lots, there was no intermediate layer or phase.

The presence of copper in the lead core is possible by diffusion from the surface during electroplating of copper. (Copper was readily detected since it is practically insoluble in lead.)

The detection of sulfur in the lead core by the electron probe, at first, was somewhat surprising since commercial lead alloys are sulfur-free. A possible explanation of its presence may be from sulfur in the atmosphere which reacted during exposure in the metallographic preparation of the sample.

There was no explanation for the scandium detected in the copper jacket by the electron probe.

The hardness survey showed that copper plating in Lot B was much harder than that of Lot A. The hardness pattern of the three layers of Lot B, wherein a hardness gradient existed, that is, the layers becoming gradually softer inward to the core, was believed to be attributable to variation in the current density in depositing each layer, the outer layer having a relatively higher current density and then the inner layers progressively less. Of course, other conditions such as bath temperature and addition agents might have affected this hardness behavior also. The hardness behavior of Lot B was nevertheless different from that of Lot A when considering the similarity in locations of hardness impressions. The readings in Lot A showed little variation from the surface inward to the core (base excluded). The peripheral hardness of Lot A was relatively high, however, a condition which probably resulted from the finishing operation.

The hardness results obtained in the lead cores of both lots showed the areas immediately below the cannelure to be harder than the other locations within the core. This condition was undoubtedly due to work hardening imparted to the lead substrate in these areas during the forming of the cannelure groove. It was noted that the hardness impressions furthest from the surface located midway along the bullet axis were softer than the other impressions. There was an exception in Lot A where impressions near the base corresponded to the core center hardness.

The hardness of the copper jacket at the base of each lot showed Lot A was softer at the base than the remainder of the jacket, whereas Lot B was harder than the remainder of its jacket. Perhaps the reason for this relative difference in hardness could be explained when considering hardness of the lead substrate at the base. In Lot A, (see Table III) the lead substrate is relatively soft when compared to other locations in close proximity to the copper jacket, that is at the cannelure, the sidewalls, and nose of the bullet. The effects of work-hardening, if any, were minimal at the base region. In Lot B, the hardness of the base substrate is relatively higher than the mid-axial region. The latter location is practically unaffected by any work hardening. This condition in combination with the high hardness of the copper jacket at this base strongly suggests that this lot had experienced some degree of work hardening. This was further corroborated by the higher hardness of the lead core of Lot B at the nose section as compared to Lot A, in relation to the core center hardnesses.

CONCLUSIONS

1. There was a definite difference in the quality of the bullets of the lots analyzed. Lot A was inferior to Lot B as evidenced by the findings in metallographic examination and electron probe microanalysis. Poor adhesion of the copper jacket to the lead substrate was noted between the cannelure and base of the bullet of Lot A. Lot B showed good adhesion of coating.

2. There was an obvious difference in method of manufacture between Lots A and B. Lot A had a single layer of copper deposited, whereas Lot B showed a banded structure consisting of three distinct layers of copper.

3. The difference in coating hardness between Lots A and B was attributable to plating procedures. These might include such factors as current density, temperature of plating solution, presence of addition agents, etc.

4. The difference in basis metal hardness between lots A (soft) and B (hard) was probably due to higher work hardening of the Lot B base section since the core chemistries of both lots were very similar, as well as the hardnesses at the apparent centers of the bullets.

5. The sidewall hardness of the copper jacket in Lot A, perpendicular to bullet axis, was significently higher than the hardness in the sidewall parallel to the axis, indicating some degree of anisotropy existed in this lot.

TABLES

Table I. Results of Hardness Tests - Hardness Impressions Made in Copper Jacket Perpendicular to Bullet Axis (see Fig. 6)

Lot A -

Rockwell B Values[1]

Between nose and cannelure	Between cannelure and base	Nose section	Base section	
54	51	57	21	--adjacent to surface
59	57	59	16	
59	53	63	42	
57	57	Avg. 60	Avg. 26	
51	54			
59	53			
Avg. 57	Avg. 54			
63	60	59	42	--middle sector
59	59	65	53	
65	62	62	54	
64	57	Avg. 62	Avg. 50	
54	59			
59	57			
Avg. 61	Avg. 59			
63	60	62	56	--inmost sector
56	60	62	50	
62	59	60	54	
60	62	Avg. 61	Avg. 53	
63	57			
57	62			
Avg. 60	Avg. 60			

Table I cont'd

Lot B -

Rockwell B Values[1]

Between nose and cannelure	Between cannelure and base	Nose section	Base section	
				-- outer layer
80	79	83	83	
75	74	85	85	
79	85	83	83	
85	83	Avg. 84	Avg. 84	
72	75			
77	72			
Avg. 78	Avg. 78			
				-- middle layer
69	69	78	77	
71	72	80	78	
71	72	77	77	
72	73	Avg. 78	Avg. 77	
69	69			
68	69			
Avg. 70	Avg. 71			
				-- inmost layer
53	57	68	68	
62	60	73	78	
56	59	69	72	
59	50	Avg. 70	Avg. 73	
56	50			
53	57			
Avg. 57	Avg. 56			

(1) Rockwell B scale values were converted from Vickers (VPH) readings.

Table II. Results of Hardness Tests - Location of Hardness Indentations Peripherally on Copper Jacket Surface and Longitudinally to Axis in the Jacket (see Fig. 7)

	Rockwell B Values[1]					
	Between nose and cannelure	Between cannelure and base	Nose[2] section	Base[2] section	Peripheral near base	
Adjacent to surface - Lot A	53	54	57	21	64	68
	42	53	59	16	62	68
	53	54	63	42	63	71
	49	56	Avg. 60	Avg. 26	63	70
	Avg. 49	Avg. 54			Avg. 63	Avg. 69
Adjacent to surface - Lot B	85	82	83	83	85	83
	83	79	85	85	84	82
	82	79	83	83	82	83
	83	80	Avg. 84	Avg. 84	82	82
	Avg. 83	Avg. 80			Avg. 83	Avg. 83
Middle sector - Lot A	56	56	59	42		
	40	57	65	53		
	56	56	62	54		
	50	54	Avg. 62	Avg. 50		
	Avg. 51	Avg. 56				
Middle sector - Lot B	71	74	78	77		
	72	74	80	78		
	72	73	77	77		
	72	73	Avg. 78	Avg. 77		
	Avg. 72	Avg. 74				
Inmost sector - Lot A	50	56	62	56		
	51	57	62	50		
	53	60	60	54		
	50	57	Avg. 61	Avg. 53		
	Avg. 51	Avg. 58				
Inmost sector - Lot B	57	67	68	68		
	59	65	73	78		
	53	65	69	72		
	62	63	Avg. 70	Avg. 73		
	Avg. 58	Avg. 65				

(1) Rockwell B scale values are converted from VPH values.

(2) These results appear in Table I and are included in this table for comparison.

Table III. Results of Hardness Tests - Hardness Impressions made Perpendicular and Longitudinal to the Bullet Axis of the Lead Core (see Fig. 9).

Brinell Hardness -- 5Kg Load, 2mm Ball

Impression No. (transverse)	Sample #1	Sample #2	Sample #3	Average	Impression No. (longitudinal)
Lot A - 1	6.7	7.0	7.0	6.9	6 --- 7.0
2	7.7	7.9	8.2	7.9	7 --- 6.3
3	8.3	8.1	8.1	8.2	8 --- 8.0
4	7.3	7.1	7.0	7.1	
5	7.7	7.5	7.3	7.5	
Lot B - 1	8.2	7.1	8.3	7.9	6 --- 7.7
2	9.7	8.4	9.2	9.1	7 --- 6.3
3	9.9	8.6	9.3	9.3	8 --- 7.5
4	7.4	6.7	7.3	7.1	
5	9.1	6.2	9.3	8.2	

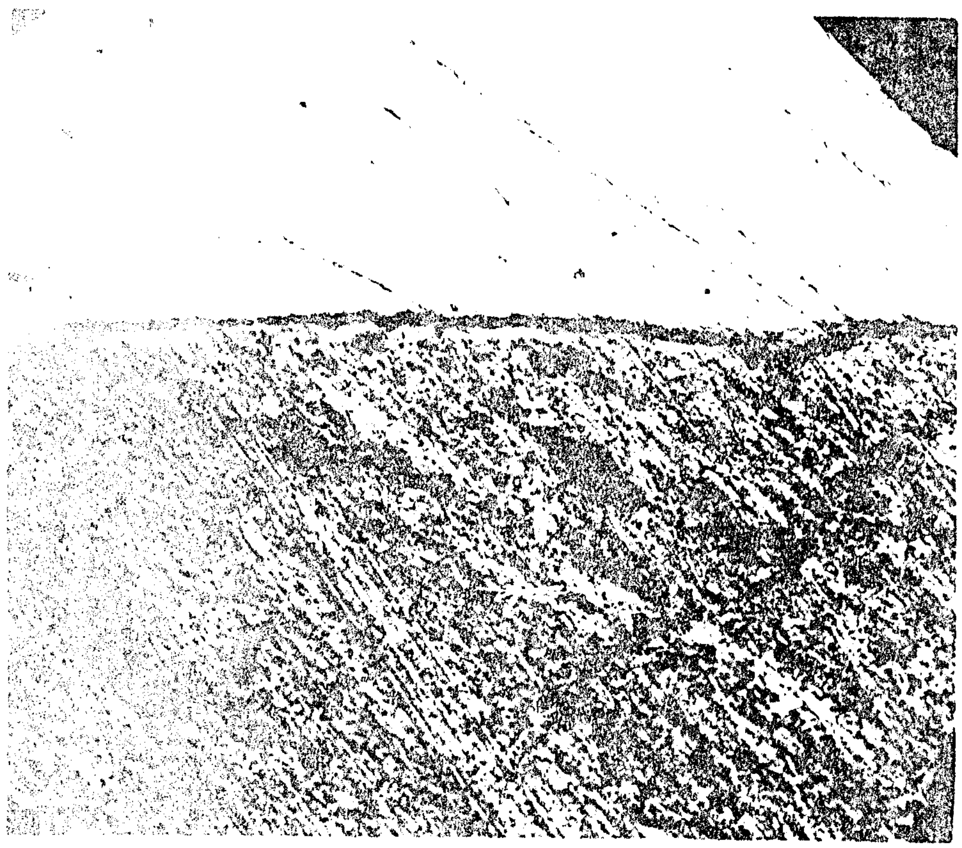
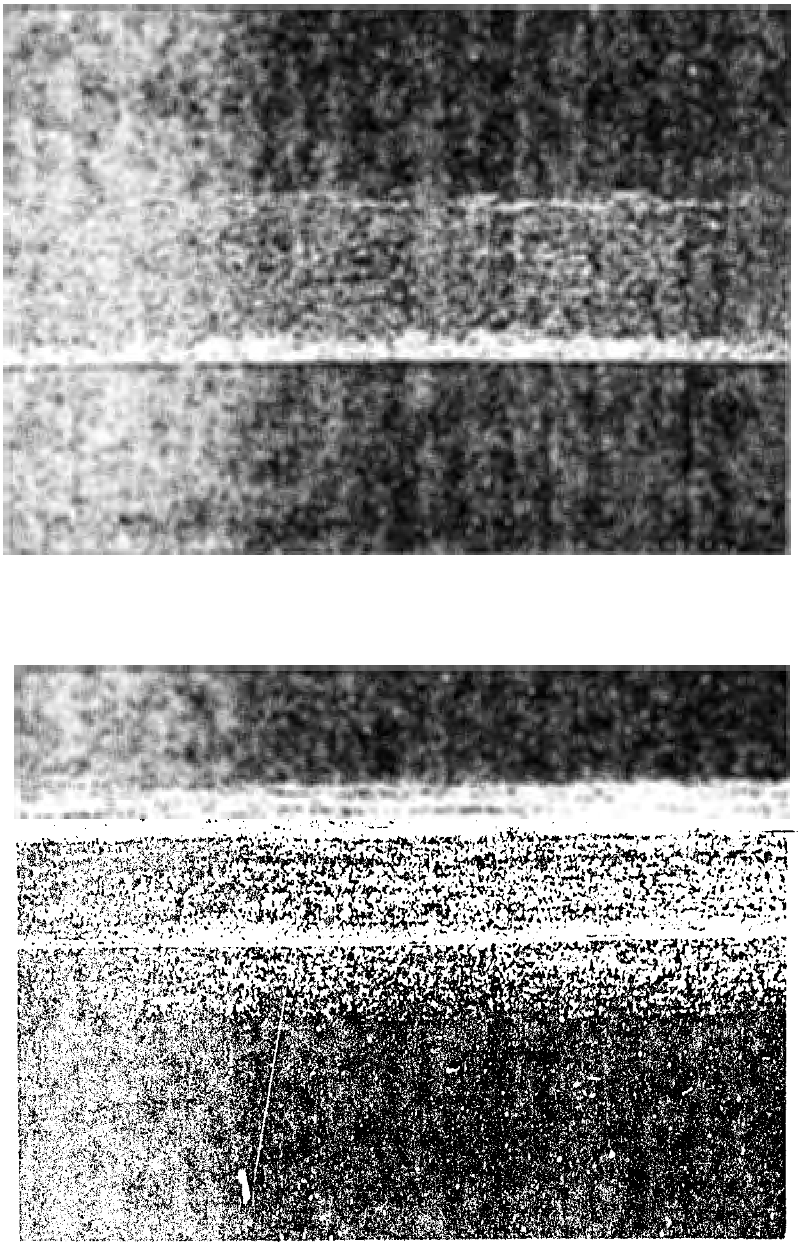


Figure [illegible]. Narrow separation at Pb-Sb (top): Cu (bottom) interface indicating unbonded area. Sample represents 0.010 in. Cu plated 5.56mm bullet.
Unetched & Unpolished
X300



LOT A — Cu / Pb

LOT B — Cu / Pb

Figure 2. Top photomicrograph shows single deposit of copper on lead substrate of Lot "A". Bottom photomicrograph shows a three layered copper deposit on lead substrate of Lot "B".

Etchant: Dual-- (1) $K_2Cr_2O_7:NaCl:H_2SO_4:H_2O$
(2) $NH_4OH:H_2O_2$

X100

Figure 3. Electron image of Pb-Sb: Cu interface with hardness indentation in Cu layer.

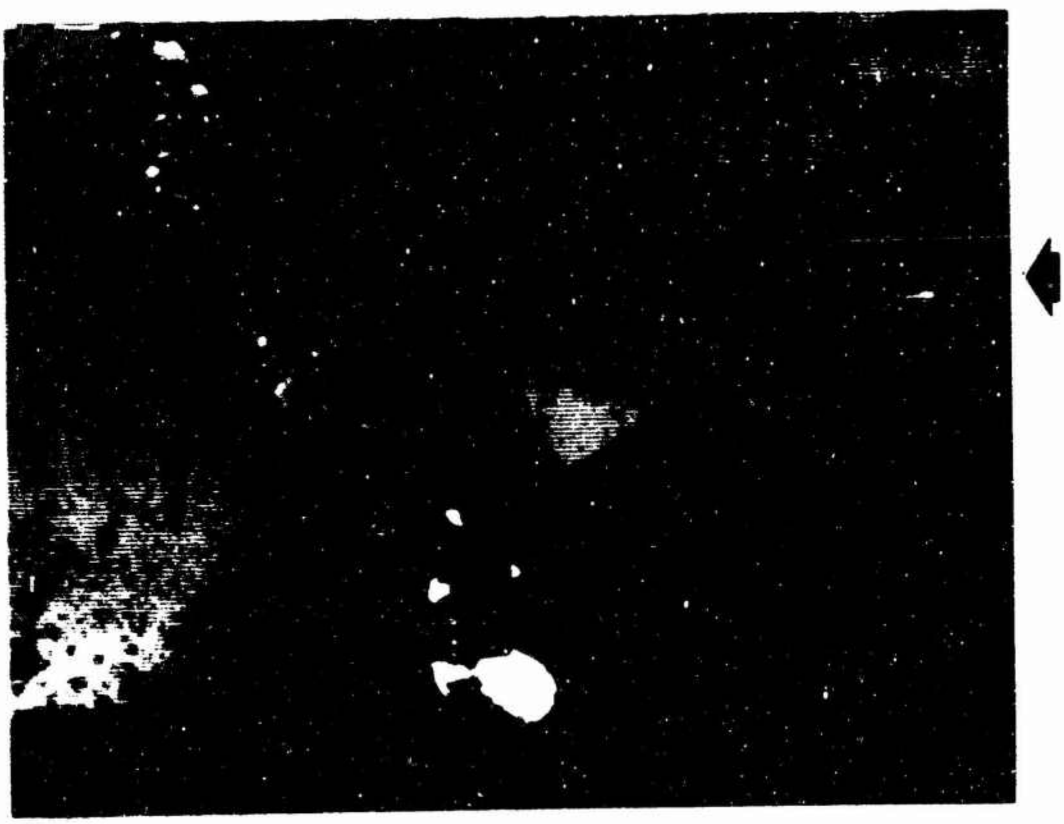
X375

Pb ; Sb Cu

Figure 4. X-ray image of Cu K_{α} radiation showing Cu-rich areas in Pb-Sb matrix.

X375

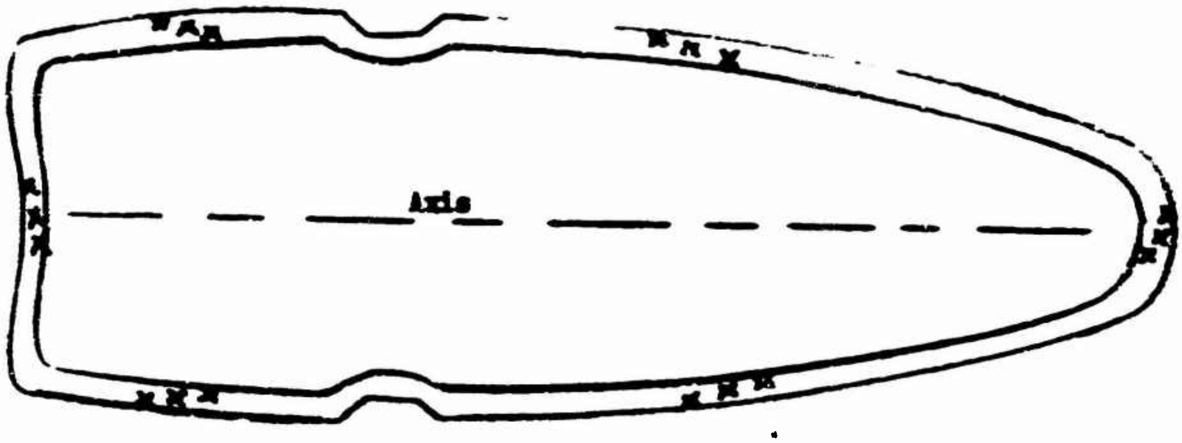
Pb ; Sb



Cu

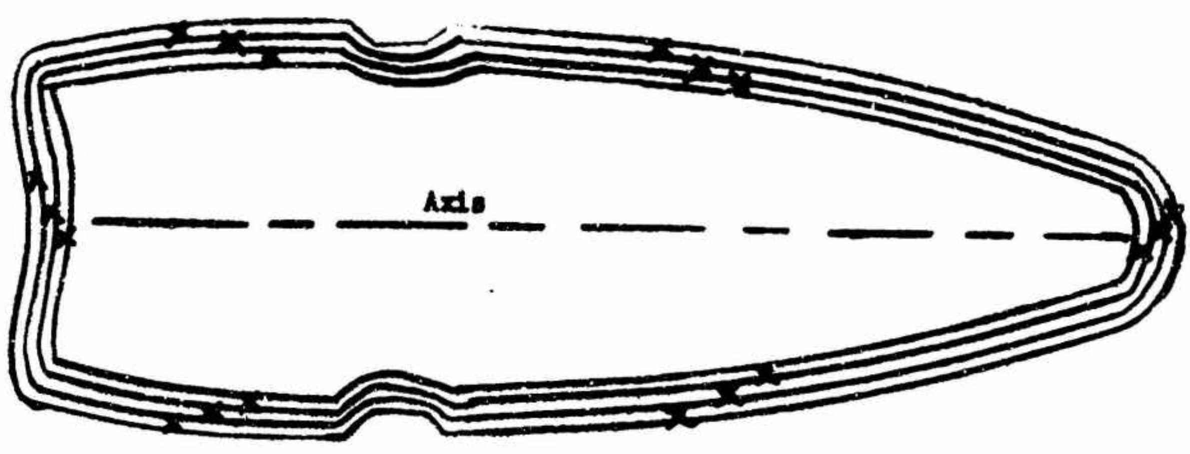
Figure 5. Electron image of Pb-Sb: Cu interface with arrow pointing to crack.

X375



LOT "A" SAMPLE

X — Indicates hardness impression



LOT "B" SAMPLE

Figure 6. Location of hardness indentations in test bullets of lots A & B.

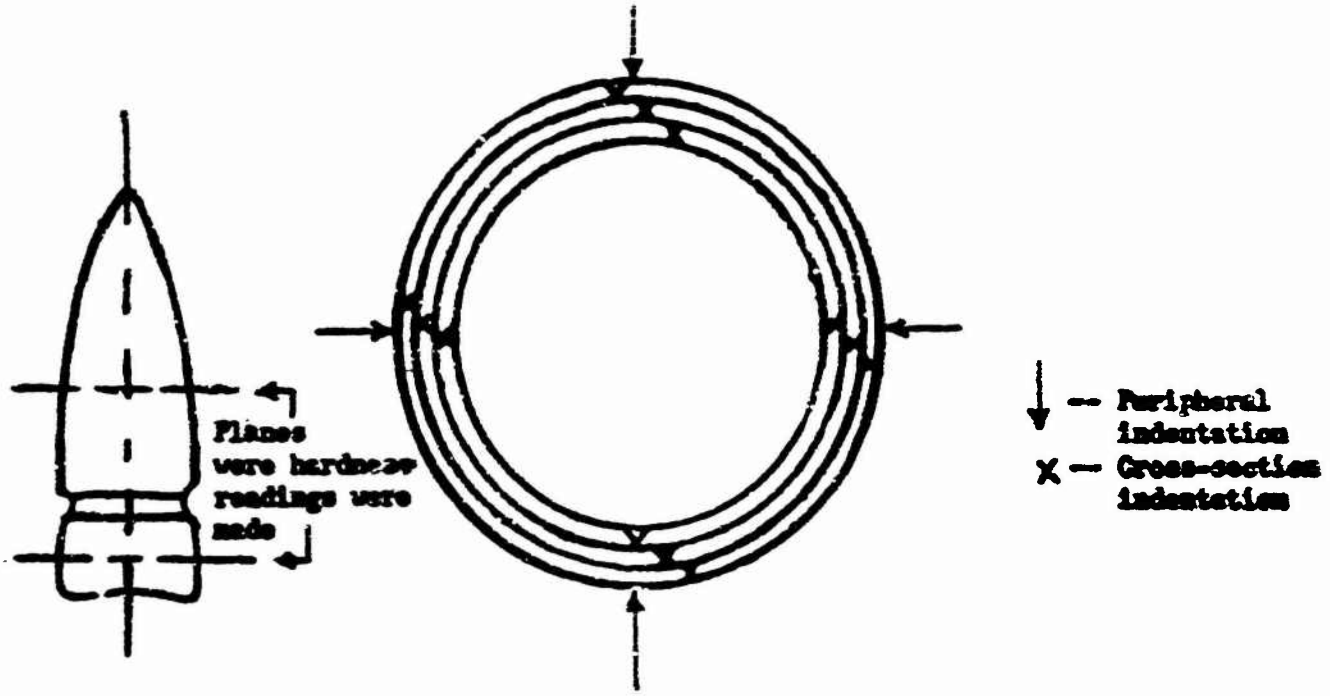


Figure 7. Location of hardness indentations in the copper jacket longitudinal to the bullet axis and peripherally on the surface.

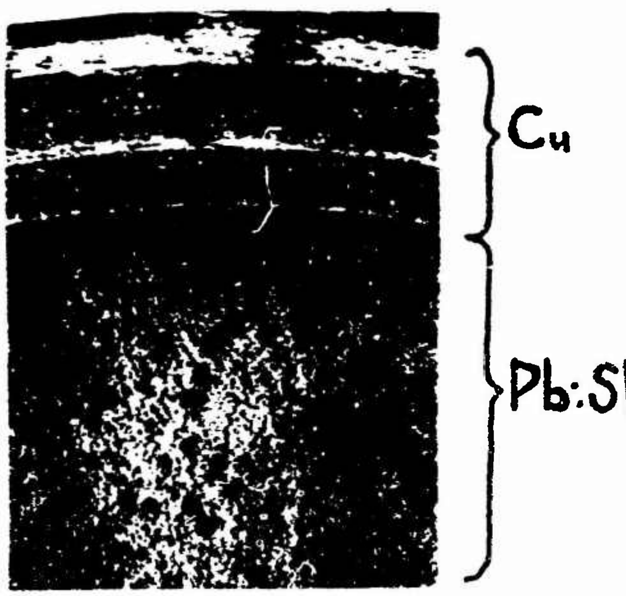


Figure 8. Hardness gradient in 0.014 in. thick copper jacket of 5.56 mm lead cored bullet of Lot B shown by increasing size of Vickers hardness indentations from outer surface towards Pb:Sb core. X75

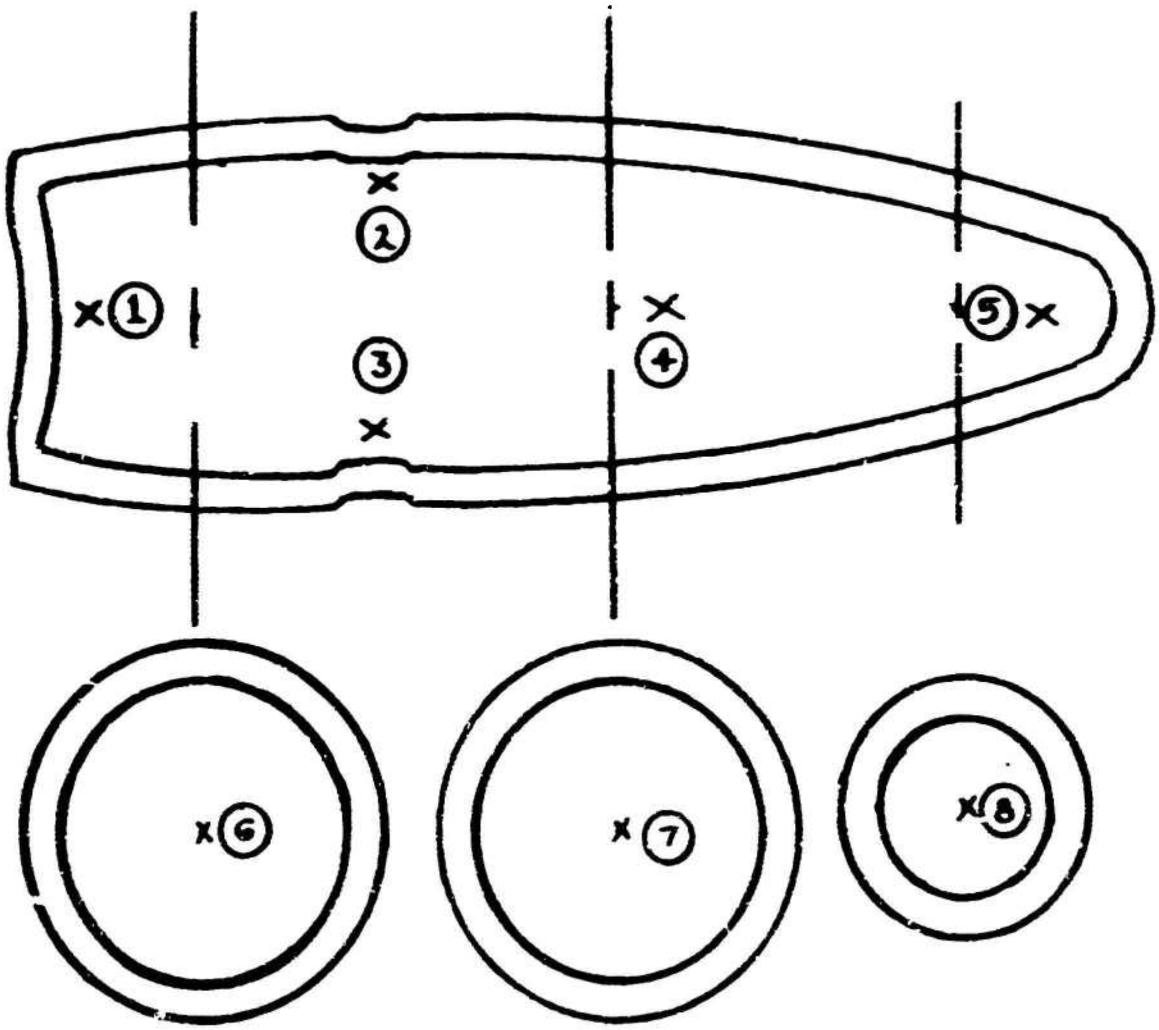


Figure 9. Locations of hardness impressions in lead-antimony core designated by "X". The impressions are perpendicular (Nos. 1 to 5) and longitudinal (Nos. 6 to 8) to the bullet axis.

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1 H. Gultz
1 A. J. Clear

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2 ATTN: AMCIP-PS-QC
1 AMCRD
2 AMCRD-RS-CM
2 AMCQA, Mr. S. J. Lorber

2 Commanding Officer, Harry Diamond Laboratories, Connecticut Ave. and Van Ness Street, N.W., Washington, D. C. 20438

Ballistics Research Laboratories, Aberdeen Proving Ground, Aberdeen, Maryland
1 ATTN: L. DeAngelis, STEAP-SG

Commanding General, U. S. Army Weapons Command, Rock Island, Illinois 61202
1 ATTN: AMSWE-PP
1 AMSWE-RD, Research Division
1 AMSWE-PP, Industrial Mobilization Branch
3 AMSWE-QA, Quality Assurance Office

Commanding Officer, Rock Island Arsenal, Rock Island, Ill. 61202
1 ATTN: 9320, Research and Development
1 5100, Industrial Engineering Division
2 SWERI-QA, Quality Assurance Division
1 SWERI-RDL, V. Vieths

Commanding Officer, Army Materials and Mechanics Center,
Watertown, Massachusetts 02172
2 ATTN: AMXMR-ATL
5 AMXMR-I
1 AMXMR-I, D. E. Driscoll
1 AMXMR-I, Norbert H. Fahey
1 AMXMR-TMS
1 AMXMR-TMT, S. Vigo
1 AMXMR-P, G. Darcy, Jr.
1 AMXMR-EA, O. R. Gericke

25 Commanding Officer, Frankford Arsenal, Philadelphia, Pa. 19137
ATTN: Pitman-Dunn Research Laboratory, Director, L-1000 (1)
Metallurgy Research Laboratory, L-7000 (1)
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Test & Evaluation Laboratory, Q6000 (1)
Basic Materials Evaluation Laboratory, Q6100 (1)
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13. ABSTRACT

Samples of 5.56mm bullets, copper coated and lead cored, representing two production lots (lots A & B), were analyzed. The purpose of the analysis was to ascertain metallurgical properties and characteristics of each lot which relate to quality and possibly to method of manufacture. The testing procedures included chemical, metallographical, electron micro-probe and hardness analyses. The results indicated that the electroplating quality of Lot B was superior to that of Lot A, especially with respect to adhesion and strength of coating. The electroplating techniques used in the manufacture of each lot were different as evidenced by Lot A having one continuous layer of copper and Lot B having a banded structure of three distinct layers of copper. Although the lead-antimony substrates of each lot were very similar chemically, it was demonstrated from the relative differences in hardness and hardness patterns that bullets of Lot B underwent more work-hardening than those of Lot A.

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Copper plating						
Lead-antimony substrate						
Hardness testing						
Electron probe microanalysis						
Ammunition - small caliber						

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