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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL. 710/476

A Preliminary Study of the Effect of Shot Blasting Upon The Ballistic Characteristics of the M1 Steel Helmet

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DATE 28 February 1944

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MEMORANDUM REPORT WAL 710/476

Partial Report on Problem B-7.2

28 February 1944

A Preliminary Study of the Effect of Shot Blasting Upon The Ballistic Characteristics of the M1 Steel Helmet

SUMMARY

Shot blasting experiments were conducted upon a group of helmets using roughly spheroidal chilled steel shot of No. 14 mesh at an air pressure of 45 pounds per square inch. It was found that shot blasting the entire exterior surface of the helmet has an adverse effect upon the ballistic properties as determined with caliber .45 ball ammunition, reducing the ballistic limit and causing brittle failures. Shot blasting the entire interior surface of the helmet or shot blasting both the interior and exterior surfaces produces no appreciable change in the ballistic properties as compared to the as-received helmets. It is believed that any treatment which will leave the interior surface of the helmet in tension will adversely affect the ballistic properties. The original residual stresses induced by cold forming are generally tensile on the exterior surface of the helmet and compressive on the interior surface and are thus favorably disposed to resist ballistic attack, although unfavorably disposed from the viewpoint of resistance to service cracking.

Experiments involving variations in the severity of the shot blasting, size of the shot blasting particles, and the shot blasting of the local areas most susceptable to service cracking should be performed to determine the optimum conditions which would provide the helmet with least tendency to crack combined with best ballistic resistance.

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INTRODUCTION

1. In compliance with a request by telephone from the Office, Chief of Ordnance, this arsenal has initiated experiments to determine the advisability of applying the shot blasting process to the helmet shell for the purpose of redistributing the residual stresses in such manner as to prevent service cracking. The examination of several hundred helmets returned from the field revealed the existence of three areas displaying a marked tendency

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to crack. Locating positions around the circumference of the helmet by starting at the middle of the visor as zero degrees and rotating clockwise, the three areas are as follows: (1) the visor, extending from 320° to 40°, where the cracks generally extend vertically upwards from the rim; (2) the right rear of the helmet, from 130° to 170°, where the cracks occur vertically in a region extending from 1" to 3" above the rim; and (3) the left rear of the helmet, from 190° to 240°, where the cracks occur similarly to those in the right rear of the helmet.

2. Hardness surveys taken on numerous helmets indicate that the regions most susceptable to cracking have been cold worked to the greatest extent, having hardnesses in excess of Rockwell C 50[1]. Preliminary stress determinations made on several helmets show that the interior surface of the helmet shell is generally in compression and the outer surface in tension. Residual stresses, induced by the cold forming operation, have been found to be as high as 85,000 pounds per square inch, and are highest in the regions where the majority of service cracking occurs.

3. The disposition of the residual stresses are very unfavorable from the viewpoint of crack formation, the tensile forces in the outer skin of the helmet shell and in the visor being dangerously high. It was thought that if the outer skin could be put into compression by the application of shot blasting, the tendency to crack could be eliminated or at least greatly reduced. Before advocating the shot blasting procedure, it is first necessary to determine the effect of shot blasting upon the ballistic properties of helmets and to determine the effect, if any, of residual stresses and their distribution upon the ballistic characteristics of helmet steel.

Shot Blasting Procedure

4. The only shot blasting equipment available at this arsenal consists of a unit manufactured by the W. W. Sly Manufacturing Company of Cleveland, Ohio, having an air pressure that can be varied from 45 to 100 pounds per square inch. The grit consists of roughly spheroidal chilled steel shot of No. 14 mesh supplied by the same company. Preliminary experimentation with pieces of flat helmet sheet in the as quenched (annealed) condition indicated that shot blasting for a relatively short time at a pressure of 45 pounds per square inch was capable of producing severe deformation, causing the sheet to curl up, with the shot blasted surface being convex.

5. The following group of helmets was selected and tested:

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1. See Watertown Arsenal Laboratory Report No. WAL 710/586, "Metallurgical Examination of 20 M1 Helmets Made by the Schlueter Manufacturing Company, Which Cracked After Aging", dated 29 January 1944.

Helmet No.	McCord Lot No.	Steel Source	Mfgr's Heat No.	Condition of Helmet	Treatment at Watertown Arsenal
H3	618B	Carnegie	166839	Finished, Unpainted	Exterior shot blasted
H7	619B	Carnegie	246861	"	none
G6	621A	Sharon	72517	"	Exterior shot blasted
G7	621A	Sharon	72517	"	none
G3	620A	Sharon	72516	"	Interior shot blasted
G4	620A	Sharon	72516	"	Interior and exterior shot blasted
5	608A	Sharon	--	Finished, Painted	none
6	608A	Sharon	-	"	none

The shot blasting was performed with an air pressure of 45 pounds per square inch, the nozzle being moved slowly around the helmet until the entire surface was blasted. After shot blasting, the liners fitted the helmets as well as before, indicating very little permanent deformation of the helmet shell. The visors of all helmets which were shot blasted on their exterior surfaces were slightly bent downwards, but not enough to interfere with either the fit of the liners or visibility.

Ballistic Testing

6. After shot blasting, the helmets were subjected to ballistic testing with caliber .45 ball ammunition at a range of 25 feet. Velocities were varied by changing the powder load, and were recorded by means of an Aberdeen chronograph. Insofar as possible the helmets were impacted in the vertical area extending from 1½" to 3⅛" up from the rim where the thickness lies between 0.040" and 0.044". The detailed ballistic data is contained in Appendix A and is summarized in Table I. Photographs of the helmets after the ballistic testing are shown in Figures 1, 2, and 3.

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TABLE I

Ballistic Data of Experimental Helmets

Helmet No.	Treatment at Watertown Arsenal	Ballistic Limit Ft./Sec.	Remarks
H3	Exterior shot blasted	Below 658	Brittle behavior, pieces blown out upon complete penetration.
H7	As received	777	Ductile behavior, pieces folded back upon complete penetration.
G6	Exterior shot blasted	Below 847	Brittle behavior, pieces blown out upon complete penetration. Also excessive cracking.
G7	As received	907	Ductile behavior.
G3	Interior shot blasted	897	Ductile behavior
G4	Interior and exterior shot blasted	882	Ductile behavior

Discussion of Ballistic Results

7. Helmets H3 and H7 from McCord, Lots 613B and 619B, fabricated from Carnegie-Illinois Steel Corp., Heats 166839 and 246861, are distinctly inferior to the rest of the helmets because of poor steel quality. The following data are taken from Table III of Watertown Arsenal Laboratory Memorandum Report No. WAL 710/575[2].

Helmet No.	Magnetic Traverse - inches
H3	8.5
H7	11.0
G6	1.5
G7	0.5
G3	1.0
G4	1.0

2. Watertown Arsenal Laboratory Memorandum Report No. WAL 710/575, "Metallurgical Examination of Defective and Satisfactory Helmets and Helmet Steel Stock Furnished by the McCord Radiator and Manufacturing Company, Detroit, Michigan, dated 23 December 1943.

The results of the magnetic test indicate that helmets H3 and H7 contain surface decarburization, a factor which has been found responsible for reduced ballistic properties.

8. Poor ballistic properties and brittle behavior were encountered in both helmets which had been shot blasted on their exterior surfaces, while no deleterious changes occurred in the helmets shot blasted on the interior surface and on both interior and exterior surfaces. It is believed that the stress pattern is to a large extent responsible for the observed ballistic characteristics. In the cold formed condition the interior surface of the helmet shell is in compression and the exterior surface in tension. These residual stresses are so disposed as to resist bullet penetration, because penetration is occasioned by tensile failure of the back surface of the attacked area. The original compression of the rear surface must first be overcome before failure will occur. The high residual stresses induced in Hadfield manganese steel helmets by the cold-forming operation may account for some of the superiority of manganese steel helmets over heat treated magnetic steel helmets of comparable thickness, which, being heat treated after forming, are relatively stress free.

9. Shot blasting the exterior surface of a helmet puts that surface into compression. If the superimposed stresses are sufficiently large, the interior surface of the helmet shell will be put into tension. With this stress distribution, i.e. compression on the outside and tension on the inside, the bullet is aided in its penetration, resulting in a lowering of the ballistic limit. The transition from ductile to brittle behavior may be traceable to the fact that the change in stress pattern is effective in increasing the strain rate. When the inside surface is in tension, the fracture stress will be reached before much deformation has occurred. The bullet speed will not, consequently, have been appreciably lowered, and thus a high strain rate will be maintained to the point of fracture, resulting in brittle failure. With the inside surface in compression, the fracture stress will be reached only after considerable deformation has occurred. The velocity of the bullet will be reduced by the cushioning action of the deforming metal; and when the fracture stress is reached, the strain rate will have been reduced sufficiently to allow ductile failure. Experiments with the shot blasting equipment available at this arsenal indicate that even at the minimum air pressure of 45 pounds per square inch the shot blasting is very severe, and in all probability, too severe for optimum benefit in the helmet application. Apparently, any shot blasting treatment which will result in the interior surface being in tension will have a harmful effect upon the ballistic properties of helmets.

10. Shot blasting the interior surface of the helmet shell produced no appreciable change in the ballistic properties. If any favorable increase in compressive stress occurred it was compensated for by a decrease in the effective fracture strength of the inside surface. Shot blasting both the exterior and interior surfaces also produced no changes in ballistic properties. Both surfaces of the helmet were put into compression and the interior of the sheet into tension. Apparently, as long as the interior remains in compression, the ballistic properties remain satisfactory.

11. To substantiate the contention that the stress distribution plays a prominent part in determining the ballistic properties of Hadfield manganese steel helmets, two finished helmets from McCord Lot 608A were ballistically tested. These helmets were part of a group previously sent to this arsenal for metallurgical examination because of age cracking. The cracking was traced to a combination of highly stressed material and notches existing at a constant position in the visor edges. The steel was free of metallurgical defects. One shot was fired at identical spots on each helmet, using caliber .45 ball ammunition. The powder load, the same for each bullet, was intended to produce a velocity approximately 100 feet per second below the expected ballistic limit of satisfactory quality helmets. Helmet No. 6 was impacted on the outside surface, while helmet No. 5 was fired at so that the bullet struck the same spot on the inside surface of the helmet shell, see Figure 4. A partial penetration was produced in helmet No. 6 whereas a complete penetration, with brittle behavior, resulted in helmet No. 5, see Figure 5.

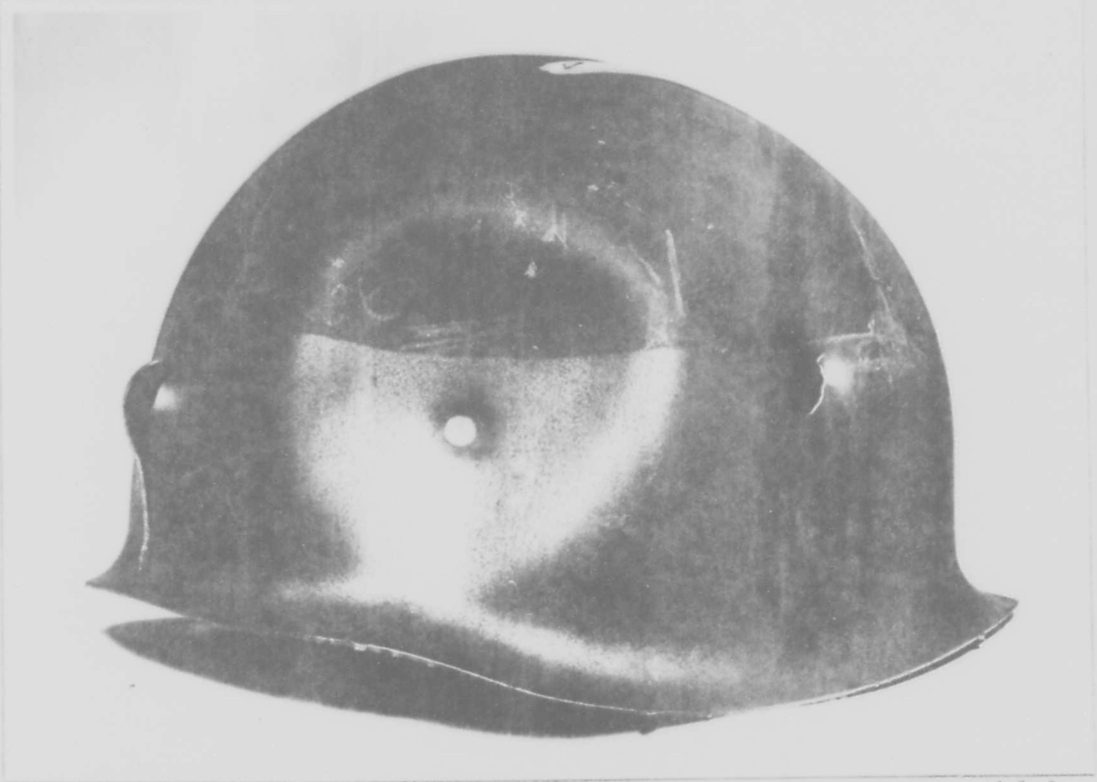
12. Obviously, the above experiment did not involve only a comparison of the effect of stress distribution upon ballistic properties, since the additional factor of differences of curvature exists. When helmet No. 6 was impacted on the outside surface, the deformation was distributed over a large portion of the area adjacent to the impact. This was due to the structural shape of this region of the helmet which permits the bending inwards of a large portion of the arch. In the case of helmet No. 5 which was impacted from the inside, the shape is such that deformation is restricted to a much smaller area than previously, tending to produce failure more readily. The brittle failure of helmet No. 5 is, however, a strong indication of the effect of the stress distribution upon the ballistic characteristics of thin sheets of a material whose ductility has been greatly reduced by cold deformation. When good quality manganese steel helmets are penetrated by caliber .45 ball ammunition, the metal tears and a piece is folded back as the bullet passes through. The complete separation of circular sections much larger than the diameter of the projectile is indicative of brittle behavior.

Suggested Shot Blasting Experiments

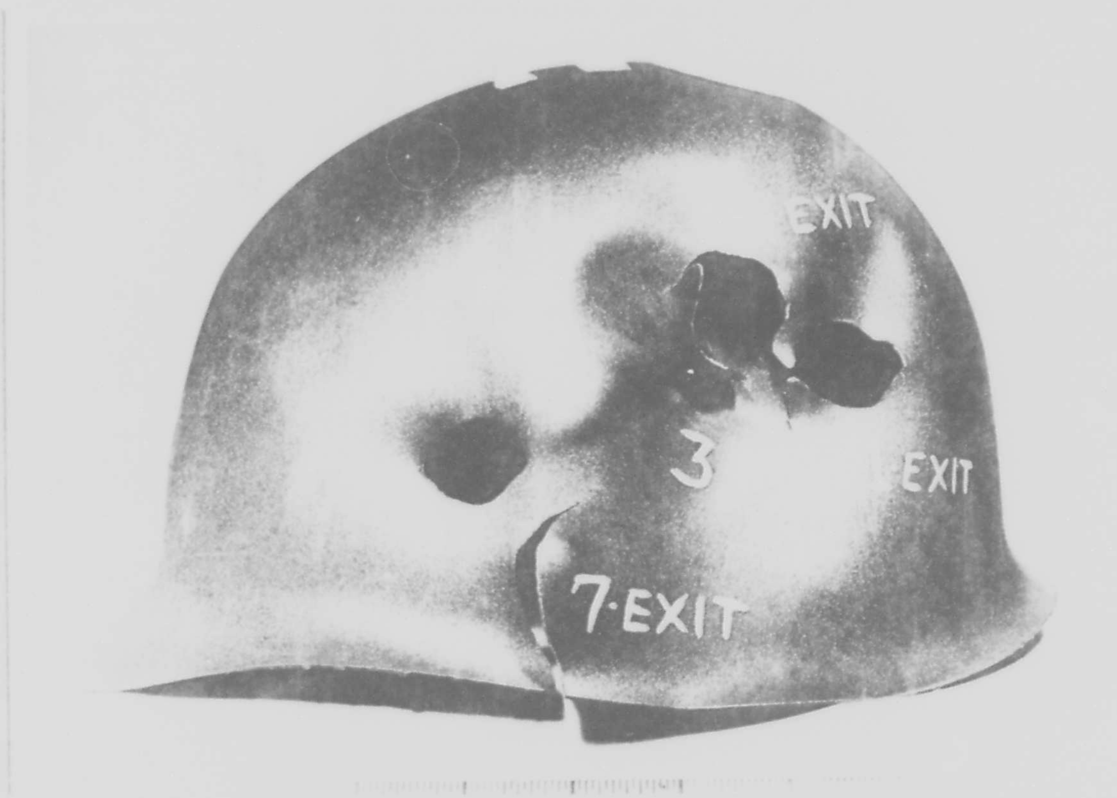
12. The previous experiments cover most of what can be done with the inflexible shot blasting equipment available at this arsenal. From what has been done, however, it is believed that shot blasting shows definite possibilities for application in preventing the service cracking of manganese steel helmets. The shot blasting performed at this arsenal is obviously much more drastic than necessary. Knoop hardness surveys along cross sections of shot blasted helmet steel stock indicate that approximately one third of the thickness has been cold worked by the process. The base hardness of the steel was approximately 210 Knoop[3]. Shot blasting with an air pressure of 45 #/in^2 produced a surface hardness of 450 Knoop. The hardness decreased to 300 Knoop 0.005" below the surface, and 210 Knoop at 0.016" below the surface of the 0.040" thick sheet. Actually, it probably is only necessary

3. The Knoop Hardness Number is approximately equal to the Vickers Pyramid Hardness Number, particularly in the range 200-400 K.H.N.

Helmets After Ballistic Tests with Cal. .45 Ball Ammunition



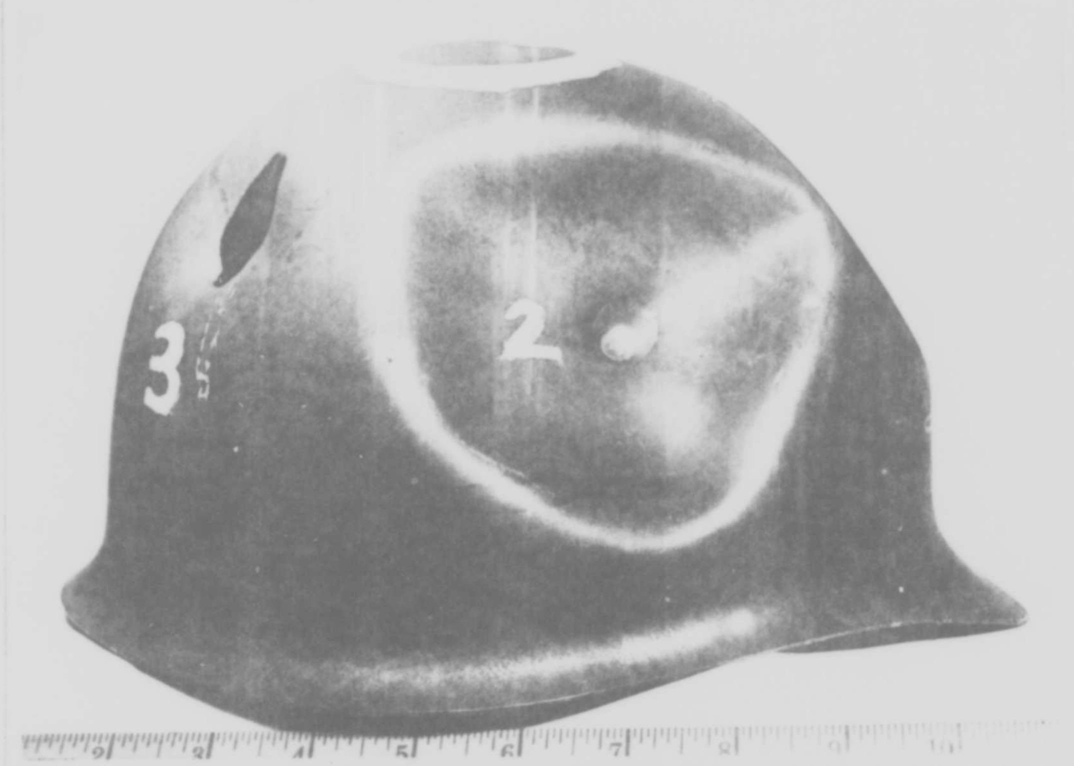
Helmet No. H7. McCord Lot 619B. Carnegie Heat 246861.
Ballistically tested in as-received condition.



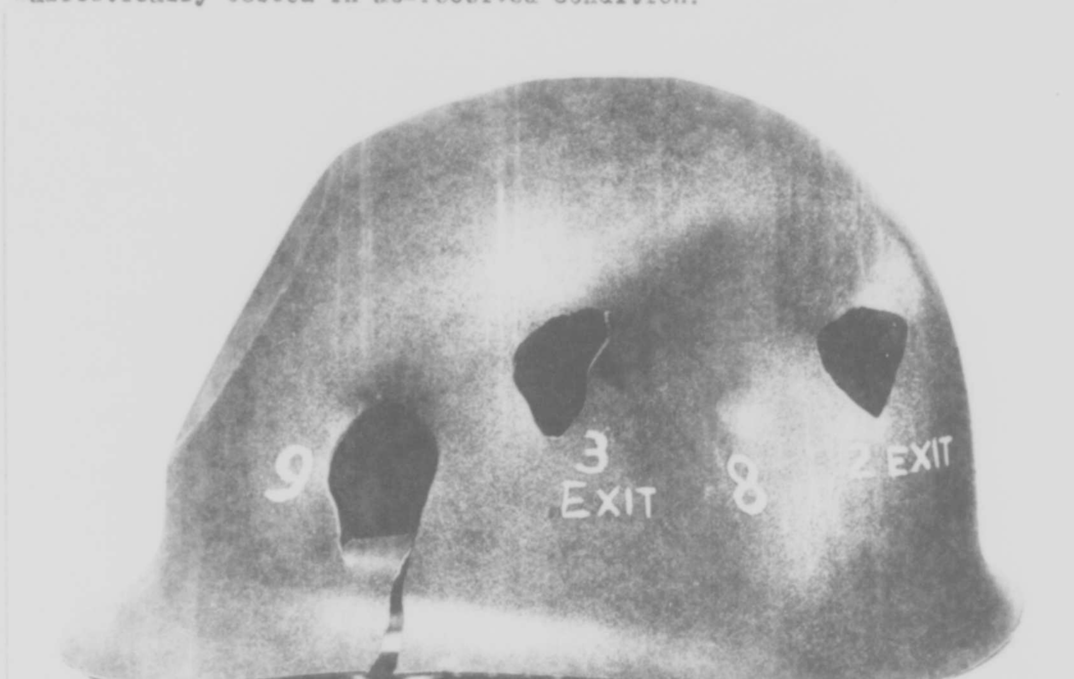
Helmet No. H3. McCord Lot 618B. Carnegie Heat 166839.
Entire exter[illegible]llistic test.

REPRODUCED AT GOVERNMENT EXPENSE

Helmets After Ballistic Tests with Cal. .45 Ball Ammunition



Helmet No. G7. McCord Lot 621A. Sharon Heat 72517.
Ballistically tested in as-received condition.



Helmet No. G6. McCord Lot 621A. Sharon Heat 72517.
Entire exterior surface shot blasted prior to ballistic test.

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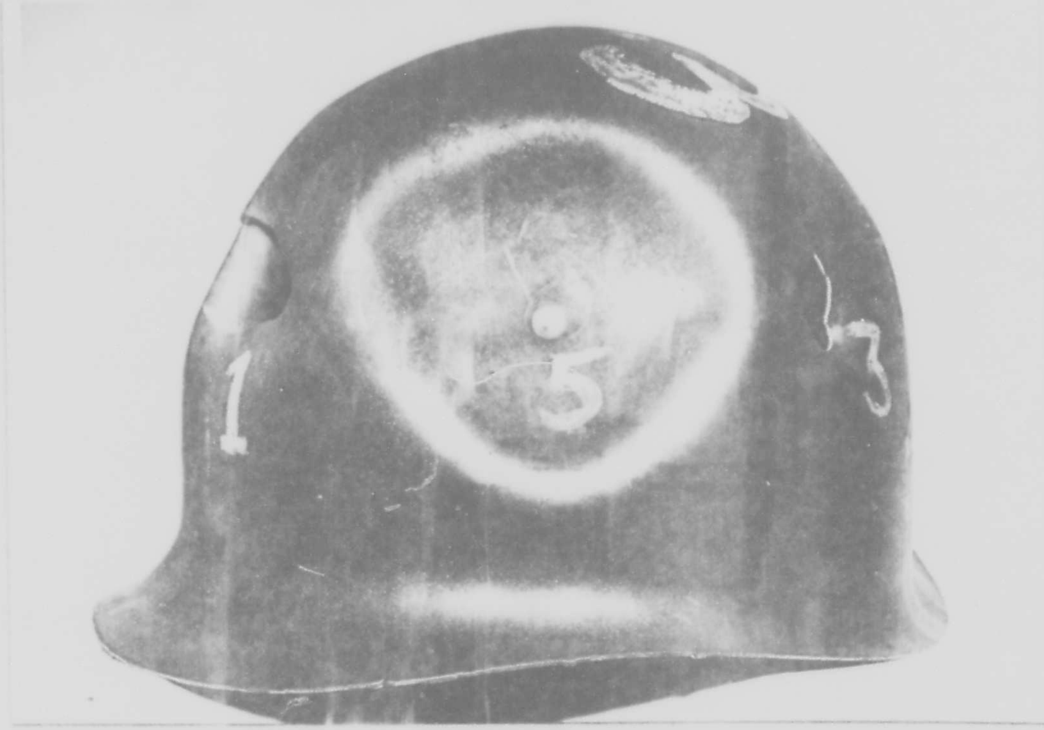
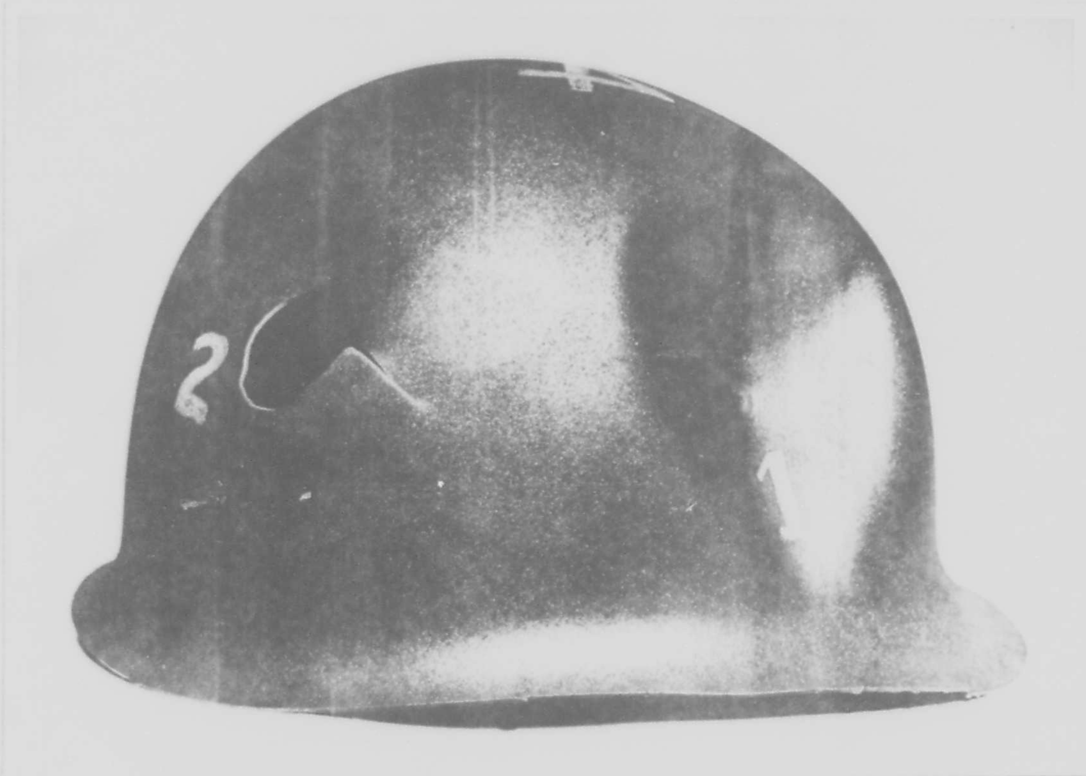
FIGURE 2.

Helmets After Ballistic Tests with Cal. .45 Ball Ammunition



Helmet No. G3. McCord Lot 620A. Sharon Heat 72516.
Entire interior surface shot blasted prior to ballistic test.



Helmet No. G4. McCord Lot 620A. Sharon Heat 72516.
Both interior and exterior surfaces shot blasted prior to ballistic test.

FIGURE 3.

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to put a few thousandths of an inch below the exterior surface into compression to radically alter the service cracking situation. Consequently, experiments involving less severe degrees of shot blasting should be performed. In this connection, the optimum size of the shot blasting particles should receive some consideration.

13. It is also possible that shot blasting the local areas most susceptable to service cracking, i. e., the visor and the two regions to the left and right of the rear of the helmet, may prove to be advantageous. It appears that the same stress distribution responsible for service cracking is also partly responsible for the superior ballistic characteristics of the present M1 helmet. If this is so, it may be necessary to adopt some sort of compromise treatment to preserve the optimum balance between the two factors.

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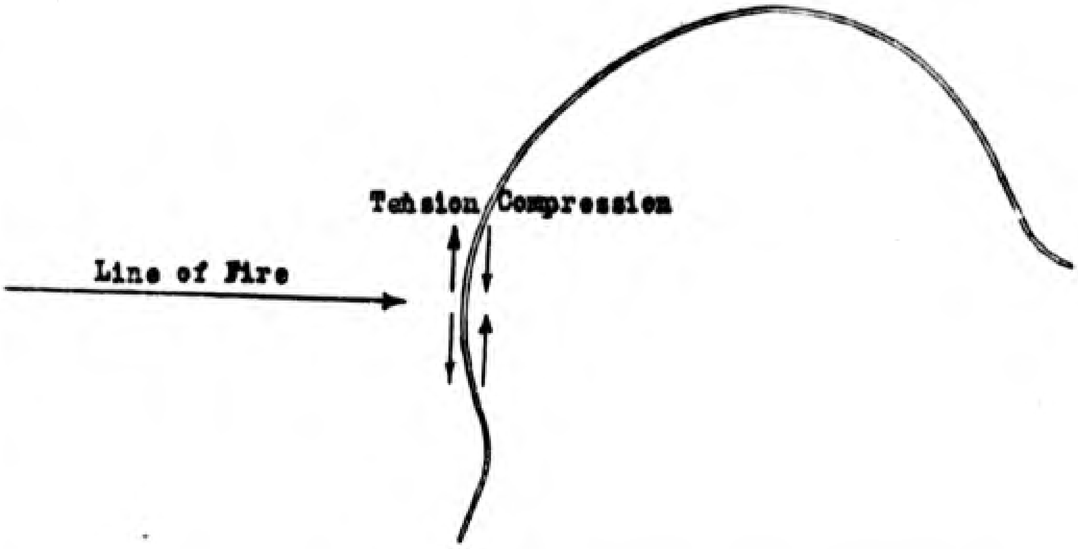
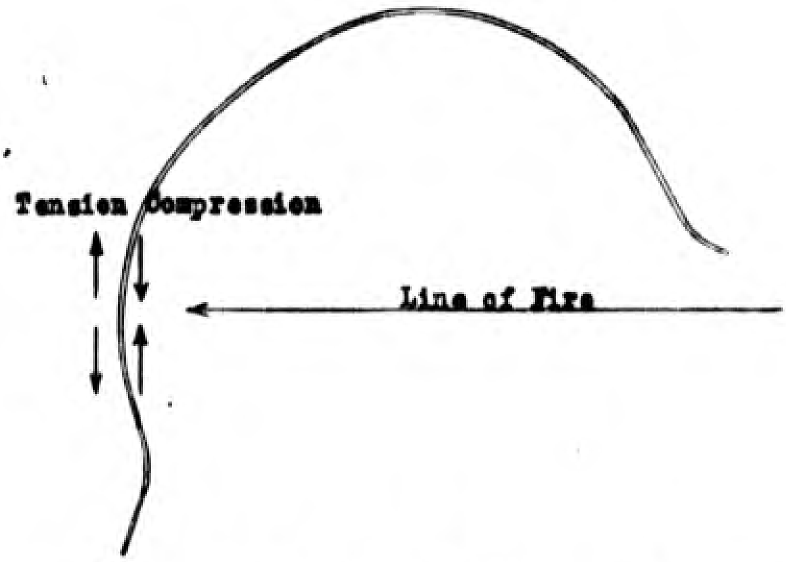
Associate Metallurgist

APPROVED:

N. A. MATTHEWS
Major, Ord. Dept.



Helmet No. 6. Residual Stresses Oppose Penetration.
Partial Penetration at 789 Ft. Per Sec.



Helmet No. 5. Residual Stresses Aid Penetration.
Complete Penetration at Approximately the Same
Velocity as Above.

FIGURE 4

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Helmets After Ballistic Tests with Cal. .45 Ball Ammunition

Helmet No. 6. McCord Lot 608A. As-received Condition.
Outside surface of helmet impacted at velocity of 789 ft./sec.
Partial penetration.

Helmet No. 5. McCord Lot 608A. As-received Condition.
Inside surface of helmet impacted at approximately the same velocity as above. Complete penetration, brittle behavior.

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FIGURE 5.

APPENDIX A

Ballistic Test Data

GUN: Cal. .45 Thompson Sub-machine Gun Barrel Fitted with Springfield Mod. 1903 Bolt Action #1534454

PROJECTILE: Cal. .45 M1911 Pistol Ball, F.A. Lot 1349.

POWDER: Lot 137. Aberdeen Chronograph Range - 25 feet.

Helmet No. H3 McCord Lot 618B Carnegie Heat 166839 Exterior Surface Shot Blasted

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	Service Load	lost (approx. 900)	PTP*	Hit 3" up from rim at 50°. 1.7" x 1.1" piece folded back. Bullet hit opposite side 3½" up from rim at 255°, blowing out 1.1" x 0.9" piece in brittle manner.
2	5.5	822	PTP	Hit 3½" up from rim at 10°. 1.2" x 0.7" piece blown out.
3	5.0	809	PP*	Hit 3½" up from rim at 280° at very high obliquity. Disregard.
4	5.0	lost	PTP	Hit 3½" up from rim at 180°. 1.2" x 0.5" piece blown out. Bullet hit opposite side 4" up from rim at 275°, folding back 1.3" x 1.0" piece. PTP.
5	4.7	781	PTP	Bullet hit 4½" up from rim at 115°. 1.0" x 0.5" piece blown out.
6	4.5	lost	PTP	Hit 2" up from rim at 310°. 1.0" x 0.6" piece blown out. Bullet hit opposite side ½" up from rim at 155°, causing 3" long vertical crack through impact extending to edge.
7	4.6	658	PTP	Hit 2½" up from rim at 85°. 1.0" x 0.8" piece folded back. Bullet hit opposite side 1" up from rim at 300°, causing 2" vertical crack extending to edge.

Ballistic Limit - Below 658 ft./sec.

*PTP Complete penetration, bullet passed through the plate.

*PP Partial penetration, bullet failed to pass through the plate.

Helmet No. H7 McCord Lot 619B Carnegie Heat 246861 **As-received Condition**

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	4.7	lost (approx. 800)	PTP	Hit 3½" up from rim at 85°. 1.0" x 0.9" piece folded back. Bullet hit opposite side at 255°, 3" up from rim causing PTP. 0.8" diameter piece folded back.
2	4.5	601	PP	Hit ½" up from rim at 30° and glanced off.
3	4.5	635	PP	Hit 1½" up from rim at 300°, 2½" diameter indent.
4	4.7	762	PP	Hit 2½" up from rim at 185°, 3" diameter indent.
5	4.7	792	PTP	Hit 5" up from rim at 350°. 1.0" x 0.5" piece folded back. Bullet hit opposite side at 185°, striking back of impact #4, causing 2" long vertical crack through impact, not extending to rim.
6	4.6	649	PP	Hit 2½" up from rim at 145°, 3½" diameter indent.

Ballistic Limit 777 ft./sec.

Helmet No. G6 McCord Lot 621A Sharon Heat 72517 **Exterior Surface Shot Blasted**

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	4.7	lost	PP	Hit 4" up from rim at 15°. 4" diameter indent.
2	5.0	847	PTP	Hit 5" up from rim at 100°. 1.2" x 1.0" piece blown out. Bullet hit opposite side 4" up from rim at 265°, blowing out 1.3" x 1.0" piece.
3	4.8	745	PTP	Bullet hit edge of round #2, enlarging the hole. Bullet hit opposite side 3" up from rim at 315°, blowing out 1.5" x 0.7" piece. Disregard.
4	4.8	709	PP	Hit 1" up from rim at 165°, bullet glanced off.
5	4.9	lost	PP	Hit 3½" up from rim at 210°. 3½" diameter indent.

Helmet No. G6 (Cont'd)

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
6	4.9	lost	PP	Hit 3" up from rim at 85°. 4" diameter indent.
7	5.0	lost	PP	Hit 3½" up from rim at 150°. 3½" diameter indent.
8	4.9	731	PP	Hit 3" up from rim at 285°. 3" diameter indent.
9	5.0	862	PTP	Hit 2½" up from rim at 335°. 1.5" x 1.1" piece folded back, 1½" vertical crack extending from edge of impact to rim.

Ballistic Limit - Below 847 ft./sec.

Helmet No. G7 McCord Lot 621A Sharon Heat 72517 As-received Condition

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	5.0	lost	PP	Hit 4" up from rim at 0°. 4" diameter indent.
2	Service Load	893	PP	Hit 3½" up from rim at 65°. 4½" diameter indent.
3	6.0	920	PTP	Hit 4" up from rim at 150°. 1.6" x 0.9" piece folded back.

Ballistic Limit 907 ft./sec.

Helmet No. G3 McCord Lot 620A Sharon Heat 72516 Interior Surface Shot Blasted

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	Service Load	922	PTP	Hit 3½" up from rim at 5°. 1.2" x 1.2" piece folded back. Bullet hit rear of helmet 1" up from rim at 175°, causing 2" vertical crack through impact extending to rim.
2	5.7	842	PP	Hit 3½" up from rim at 90°. 4" diameter indent.

Helmet No. G3 (Cont'd)

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
3	5.8	lost	PTP	Hit 3½" up from rim at 280°. 0.9" x 0.8" piece folded back.
4	5.8	lost	PP	Hit 3" up from rim at 210°. 3½" diameter indent.
5	5.8	801	PP	Hit 3½" up from rim at 305°. 4" diameter indent.
6	5.8	871	PP	Hit 3½" up from rim at 45°. 4" diameter indent.

Ballistic Limit - 897 ft./sec.

Helmet No. G4 McCord Lot 620A Sharon Heat 72516 Interior and Exterior Surfaces Shot Blasted

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	Service Load	859	PP	Hit 3½" up from rim at 25°. 4" diameter indent.
2	Service Load	lost	PTP	Hit 3" up from rim at 100°. 1.2" x 1.4" piece folded back.
3	Service Load	904	PTP	Hit 3½" up from rim at 265°. 1.4" x 1.3" piece folded back. Bullet hit opposite side at impact #2, causing 1" crack at edge of impact.

Ballistic Limit - 882 ft./sec.

Helmet No. 6 McCord Lot 608A Sharon Heat ____ As-received Condition Exterior Surface of Helmet Impacted

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	4.6	789	PP	Hit 4" up from rim at 0°. 3½" diameter indent.

Helmet No. 5 McCord Lot 608A Sharon Heat_____ **As-received Condition**
Interior Surface of Helmet Impacted

Round No.	Powder Charge Grains	Velocity Ft./Sec.		Results on Helmet
1	4.6	lost (approx. 790)	PTP	Hit 4" up from rim at 0°. 0.9" diameter fragment blown out in brittle manner.