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RESEARCH AND DEVELOPMENT ON ARMOR

NATIONAL DEFENSE AND RESEARCH COMMITTEE

WATERTOWN ARSENAL LABORATORY - ARMOR SECTION

1942-1945

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WATERTOWN ARSENAL
WATERTOWN, MASS.

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RESEARCH AND DEVELOPMENT

ON ARMOR

Watertown Arsenal Laboratory

Armor Section

1942 - 1945

Comparative Costs of NDRC and Watertown Arsenal Laboratory Research and Development on Armor Plate

Comparative Costs - April 1942 to 1 Jan. 1944		
NDRC Projects (from Rpt. of Div. 18 - 1 Jan. '44)	-	$398,350.00
Watertown Arsenal Laboratory*	-	$171,010.00
Difference	-	$227,340.00
Comparative Estimated Costs - April 1942 to 31 Aug. '45	-	
NDRC Projects (on basis of estimates in Rpt. of Div. 18 - 1 Jan. '44)	-	$726,375.00
Watertown Arsenal Laboratory*	-	$350,226.00
Difference	-	$376,149.00

*Note: Watertown Arsenal Laboratory Costs are the sum of actual and/or estimated expenditures on Armor Expenditure Orders (45, 51, 1260, 1242), plus 50% to cover cost of work on other Expenditure Orders directly or indirectly performed to augment Armor Plate research and development.

1. Alloy Conservation Program

2. Brittle Fracture in Ballistic Tests at Low Temperature

3. Nonballistic Tests

    a. Fibre Fracture Test

    b. Fracture Test for Steel Soundness

    c. Notched Bar Tensile Impact Test

    d. Notched Bar Tensile Test and Static Tensile Test

    e. Notched Bar Impact Test

4. Cast Armor Development Program

5. Temper Brittleness in Armor

6. Aircraft Armor

7. Examination of Domestic Armor

8. Helmet Programs

9. Body Armor Programs

Alloy Conservation Program

When, in February 1942 the WPB notified the cast and rolled armor industries of expected scarcities of Ni, Cr, Mo, and V, meetings of the armor subcommittees were immediately called and plans made for the development of low alloy compositions capable of meeting the ballistic specifications. Data presented by Watertown Arsenal and by the individual producers were used as the basis for selection of the compositions. During the months of March and April several hundred cast and rolled ballistic test plates 1", 1½", and 2" thick were produced, heat treated and ballistically tested. Numerous samples were forwarded to Watertown Arsenal where the compositions were evaluated with respect to hardenability, weldability, and microstructure. In addition, the results of the ballistic tests were analyzed. Eight reports covering the metallurgical and ballistic analyses were distributed to the industry through the Ferrous Metallurgical Advisory Board between the months of April 1942 and January 1943. From the examinations made at Watertown Arsenal it was concluded that drastic water quenching treatments were necessary to harden the low alloy steel compositions employed, that vanadium could be entirely eliminated from armor steels, that chromium could be reduced from a maximum of 3% to a maximum of 0.60%, that nickel could be reduced from a maximum of 2.5% to a maximum of 0.60%, that molybdenum could be reduced by approximately one third, and that manganese, which was not a critical element, could be increased to provide adequate hardenability in the low alloy steels.

Ballistic failure of low alloy armor plates examined at Watertown Arsenal were traced to -

1. Inadequate hardenability.

2. Poor quenching practice, resulting in rejection of ferrite and pearlite.

3. Poor steel quality; excessive laminations in rolled armor and interdendritic inclusion networks in cast armor.

Brittle Failure Under Ballistic Attack at Low Temperatures

During the months of January and February 1943 ballistic tests were conducted upon cast and rolled armor plates, armor structures, and armor weldments at the Ordnance Department Winter Detachment, Ordnance Proving Center, at Camp Shilo, Manitoba, Canada. The temperatures of the armor varied between -15 and -35°F. during the period of testing. A very large proportion of the cast armor failed in a brittle fashion when subjected to the 75 MM slug shock test specified under AXS-492, Revision 2; numerous plates breaking into several pieces. Rolled armor behaved, in general, more satisfactorily than cast armor at low temperatures. An increased tendency to backspall was, however, noted in several rolled plates at low temperature as compared to mate plates tested at room temperature.

In March 1943, all pertinent data regarding the plates tested at Camp Shilo were analyzed at Watertown Arsenal and the results were distributed to Ordnance and industrial agencies in the form of cast and rolled armor subcommittee reports. It was concluded that in many cases the poor shock resistance at reduced temperatures was traceable to inadequate hardenability resulting in the precipitation of ferrite during hardening. Sections from thirty (30) cast and seventeen (17) rolled plates from the Shilo Cold Test Program were examined at Watertown Arsenal. The results of the experimental work conducted at this arsenal were published in two reports, one covering cast armor and the other rolled armor. Good correlations between the ballistic and metallurgical properties of cast armor were obtained by employing the Fibre Fracture Test, V-notch Charpy impact tests, and microscopic examination. Likewise, good correlations between the ballistic and metallurgical properties of rolled armor were obtained by employing the Fibre Fracture Test, the Fracture Test for Steel Soundness, V-notch Charpy impact tests, and microscopic examination.

The primary causes for poor low temperature shock resistance were traced to either inadequate hardenability or poor quenching practice, both of which resulted in the formation of nonmartensitic products which are characteristically brittle at low temperatures. Backspalling of rolled armor was associated with stringers of nonmetallic inclusions which provide planes of weakness.

The Shilo Cold Test Program and the subsequent reports by Watertown Arsenal had an important effect upon the armor industry. Brittle failures at reduced temperatures and severe degrees of backspalling emphasized the necessity of establishing some sort of control over the heat treatment of cast and rolled armor and over the quality of rolled armor and provided the necessary impetus leading to the general acceptance by the Ordnance Department and by the armor industry of the Fibre Fracture Test and the Fracture Test for Steel Soundness. The incorporation of these two tests into armor specifications was the logical consequence of the program.

DEVELOPMENT OF NON-BALLISTIC TESTS

1. Fibre Fracture Test

As the result of the metallurgical examination initiated in January 1943 on the fracture test developed at the Union Steel Castings Co. for the purpose of determining the best tempering cycles for cast armor, work was started in February 1943 at Watertown Arsenal to establish possible correlations between the appearance of the fractured surface of steel and its metallurgical and physical properties. Blocks of steel were quench hardened with various degrees of efficiency, tempered, notched, and fractured. Metallurgical tests conducted upon the blocks were the determination of their hardnesses after quenching and after tempering, V-notch Charpy impact tests over the temperature range of +70°F. to approximately -100°F., and metallographic examination.

It was established that fibrous fractures are associated with complete transformation to martensite upon quenching and with the optimum impact properties consistent with hardness over the entire range of temperature investigated. Wholly or partially crystalline fractures are associated with incomplete transformation to martensite and with reduced impact properties, particularly at the lower testing temperatures.

The value of such a simple test capable of indicating the response of steel to heat treatment and its tendency toward ductile or brittle fracture was immediately recognized. As early as April 1943 steps were undertaken to incorporate the test, known as the Fibre Fracture Test, in armor specifications, and Specification AXS-492 (Rev. 3) Amendment 1 was finally accepted in August 1943, on a tentative non-rejection basis and was made mandatory in October 1943. This specification covered the application of the Fibre Fracture Test to cast armor. The test was incorporated in rolled armor Specification AXS-488, Revision 2 in November 1943. In may 1943 special courses were given at Watertown Arsenal to the ordnance inspectors of cast armor for the purpose of explaining to them the philosophy of the test, familiarize them with the rating of fractured samples, and to provide them with sufficient technical background to give them a proper appreciation of the functions and the limitations of the test. A similar course was presented to the ordnance inspecters of rolled armor in September 1943.

It has been conceded by all companies and agencies involved with the Fibre Fracture Test that the test introduced a control over the heat treatment and shock resistance of armor which was seriously lacking prior to the development of the test. The quality of the armor produced under specifications in which the Fibre Fracture Test is incorporated is recognized as superior to that previously accepted by the Ordnance Department.

2. Fracture Test for Steel Soundness

Work on the problem of the quality of rolled armor was initiated at Watertown Arsenal in February 1943 following the visit to the plants of various rolled armor manufacturers by a member of this laboratory. Numerous samples of armor which failed and passed the PTP ballistic test which is designed to reveal spalling tendencies were forwarded to this arsenal for examination. The examination consisted of fracture tests, metallographic examination, macroetch tests and magnaflux tests, whereby it was revealed that laminations were traceable to segregation of elongated nonmetallic inclusions. As a result of the tests performed it was decided that the fracture test provided the most useful and interpretable gage of the back spalling tendencies of rolled armor. Fracture standards were developed at this arsenal upon the basis of the ballistic behavior of the samples investigated. The incorporation of the Fracture Test for Steel Soundness in rolled armor specification AXS-488, Revision 2 was proposed in August 1943 and made mandatory in November 1943. A course in the application, philosophy, and interpretation of this fracture test was conducted at Watertown Arsenal in September 1943 for the benefit of the ordnance inspectors of rolled armor.

The Fracture Test for Steel Soundness has produced an awareness of the importance of steel cleanliness in armor and has resulted in a general increase in the level of quality of rolled armor. Several manufacturers have, as a result of this fracture test, changed their deoxidation and ingot practice to improve their product sufficiently to meet the requirements of the test.

3. Tensile Impact Test

At the request of Mr. G. S. Mikhalapov, Supervisor of Welding Research, National Research Council, this arsenal investigated the application of the unnotched tensile impact test as an indicator of the ballistic quality of rolled homogeneous armor. Tests performed upon armor sections of various ballistic characteristics indicated that no correlation exists between the tensile impact properties of armor at room temperature and its ballistic properties. Neither was a correlation observed between tensile impact properties and hardness. The results of this investigation were reported in July 1943.

4. Notched Bar Tensile Tests and Static Tensile Tests Across the Gage of Rolled Armor

Tests conducted at Carnegie Institute of Technology under NRC-6 showed a good correlation between the back spalling and cracking tendencies of rolled armor and the ductility as measured by a static tensile test across the gage. Tests were undertaken at Watertown Arsenal to determine if static tensile tests in the longitudinal and transverse directions and notched bar tensile tests in the longitudinal and transverse tests also correlate with back spalling and cracking tendencies. It was concluded that physical tests of the types described show evidence of correlation with the ballistic behavior of rolled armor, but that these tests are so expensive and time-consuming as compared to easily performed fracture tests that the physical tests are useful only as academic research tools whereas the fracture test is ideally applicable for inspection and specification purposes. The results of this investigation were reported in February 1944.

5. Notched Bar Impact Test

The first demonstration at Watertown Arsenal of a good correlation between ballistic behavior and V-notch Charpy impact properties was observed in an investigation of 4" to 6" thick gun shield armor which was published in May 1943. Subsequent investigations concerned with the development of the Fibre Fracture Test, the Shilo Cold Test Program, and numerous samples of production armor forwarded to this arsenal from the Ordnance Research Center and by various producers of cast armor have provided a large amount of data which demonstrate the excellent correlation between the behavior of armor under ballistic shock tests and its notched bar impact properties.

Since a good correlation exists between the results of the Fibre Fracture Test when applied to armor up to approximately 4" in thickness and the notched bar impact properties of armor, the Fibre Fracture Test is preferred for the routine inspection of production armor since it is simpler, less costly, and more rapidly performed than are impact tests. Hence V-notch Charpy tests were never advocated as a specification test for light armor.

In October 1944 this arsenal was requested by the Office, Chief of Ordnance-Detroit to formulate a non-ballistic specification for the procurement of armor in thicknesses in excess of 6". A non-ballistic specification was made necessary by the lack of suitable armor-piercing projectiles of sufficient caliber to provide a good ballistic test of very heavy armor. The Fibre Fracture Test could not be applied to these heavy sections because the hardenability and temper brittleness problems become so extreme in heavy sections that it becomes virtually impossible to produce fibrous fractures throughout the cross section of heavy armor at the hardnesses considered desirable. Since the Fibre Fracture Test is inapplicable when completely fibrous fractures cannot be obtained, the specification of minimum V-notch Charpy impact requirements was considered the most satisfactory means of controlling shock properties.

A specification for 4"-12" thick cast armor was proposed in March 1945 and one for 4"-12" thick wrought armor in April 1945. A comprehensive program of notched bar impact testing of 4", 6", 8", 10" and 12" thick cast armor produced by the various manufacturers of heavy cast armor was initiated at Watertown Arsenal. Preliminary results were reported to the Office, Chief of Ordnance-Detroit and to the cast armor producers in a meeting held in Detroit on 1 June 1945.

CAST ARMOR DEVELOPMENT PROGRAM

With the application of the Fibre Fracture Test in October 1944, manufacturers of cast armor sections in excess of 2" thick increased the hardenability of their steels by increasing the alloy contents. Unexpected and, at that time, unexplainable ballistic failures, poor shock properties, and unsatisfactory fractures resulted, necessitating the waiver of the Fibre Fracture Test requirements for cast armor above 2" in thickness. Manufacturers returned to their former low alloy steels which were, in most cases, of insufficient hardenability to permit through hardening.

Watertown Arsenal was requested by the Office, Chief of Ordnance-Detroit to undertake an investigation of the problem of designing compositions and heat treatments to produce the desired properties in heavy cast armor. A program was accordingly initiated in February 1944 involving the casting of 22 heats into 1½", 3" and 6" thick sections. The steels were heat treated in small section size as well as in full section. Causes of reduced properties of various steels when heat treated in full section were determined. This investigation established that temper brittleness is the factor limiting the maximum hardness of armor in sections above 4" in thickness. It was determined that many compositions may be employed to provide adequate hardenability in 6" thick sections to permit complete transformation to martensite, but some of these compositions cannot be employed because of excessive susceptibility to temper brittleness. The importance of water quenching after tempering to avoid temper embrittlement was re-established. A report embodying the results obtained and the metallurgical principles involved in the alloying and heat treatment of heavy armor sections was published in September 1944.

As the result of the program conducted at Watertown, contracts were let to the Continental Foundry & Machine Co. and the General Steel Castings Corp. for the pouring and heat treatment of experimental heats of 3" and 6" thick armor castings respectively. Preliminary work both at the plants and at Watertown Arsenal indicate that satisfactory properties can be obtained with proper heat treatment. A report covering the preliminary work conducted on the Continental heats was published in July 1945.

TEMPER BRITTLENESS IN ARMOR

In September 1942 the Watertown Arsenal outlined a program for the investigation of temper brittleness in cast and rolled armor which, with the approval of the Ferrous Metallurgical Advisory Board, was conducted in cooperation with the Ordnance Research Center and the various armor manufacturers. The manufacturers submitted ballistic test plates and coupons from the same heats, some of which had been slowly cooled and others rapidly cooled from the tempering temperature. Ballistic tests and metallurgical examination revealed that the slowly cooled plates were in general temper embrittled. Shock failures, poor fractures, and low V-notch Charpy impact properties were found to occur in numerous cases, sometimes associated with temper brittleness and sometimes associated with inadequate quench hardening. A report covering these investigations was published in December 1943.

The Physical Metallurgy Section of the Watertown Arsenal Laboratory became interested in the problem of temper brittleness because of its rediscovery in armor and gun steels. This section of the laboratory conducted an extensive survey into the literature of the temper brittleness phenomenon, and in January 1945 published a report presenting, probably for the first time, an integrated picture of the nature of the phenomenon. A subsequent report largely based upon the forementioned report and containing in addition a description of the various means of eliminating or minimizing temper brittleness in ordnance steels was widely distributed in July 1945 through the Ferrous Metallurgical Advisory Board to the membership of the Subcommittees on Cast and Rolled Armor and to various Ordnance agencies.

Because of the work being done at Watertown Arsenal upon the development of suitable compositions and heat treatments for heavy armor sections, considerable attention has been devoted to the problem of temper brittleness because this phenomenon is one of the chief factors controlling the maximum hardness which can be achieved with accompanying satisfactory shock properties. A total of ten (10) reports were published covering investigations of heavy armor sections in which temper brittleness played a prominent role.

As a result of the distribution to armor manufacturers during 1944 of the information which was accumulated at this arsenal (regarding temper brittleness) the manufacturers were guided in their selection of armor compositions and heat treatment cycles. Water quenching after tempering was universally adopted by the manufacturers of the more highly alloyed and thicker armor steels.

AIRCRAFT ARMOR

Cooperative programs were carried on with industry during 1942 to develop non-magnetic steels for use in aircraft armor installations. The maximum consistent resistance to penetration developed in such steels is only about 80% of that characteristic of ferritic steels. As a result a special specification for the procurement of non-magnetic armor (WXS-165) had to be devised.

A comprehensive survey and analysis of all extant data on the resistance of aircraft armor materials, conducted during 1943, disclosed that aluminum alloys, 24ST and 75ST and Dowmetal, a magnesium alloy, might afford better resistance to penetration than any equivalent weight of non-magnetic steel.

Accordingly, in September 1943, when the comments of this arsenal were requested concerning a proposed joint Army-Navy specification for non-magnetic (steel) armor (ANOS-3) it was suggested that such non-ferrous alloys would probably afford better resistance than any material procurable under the proposed specification. The response to this suggestion has not been rapid but recent indications are that such a substitution will eventually be made.

The same comprehensive survey disclosed conditions of attack under which 24ST Duralumin would afford resistance superior to that offered by the best face-hardened steel armor. The findings were presented in a manner calculated to be of great assistance to the designer of aircraft armor.

Study of the resistance of Dowmetal to attack with various armor-piercing projectiles and under angles of attack up to 70° showed that it followed a well ordered pattern best expressed by the formula:

$$Vn = \frac{1535\ (e'/d)\ 0.5}{\cos \theta}$$

where Vn is the Navy ballistic limit, e' is the thickness of steel equivalent in weight per-unit-area to the subject material, d is the diameter of the attacking projectile and θ the angle of obliquity of attack.

A comprehensive firing program, completed in September of 1942, investigating the comparative resistance of face hardened and homogeneous armor to penetration by caliber .50 APM2 projectiles indicated that the time, money and manpower expended in the production of face hardened armor might not be balanced by an increase in over-all resistance over that of homogeneous armor. Subsequent studies have shown that only under those conditions wherein the higher face hardness of this armor succeeds in fracturing the attacking projectile is it superior to homogeneous armor.

Since it may reasonably be assumed that projectiles resisting fracture may be developed the efforts of this laboratory have more recently been directed toward the development and adoption of armor which does not base its validity solely upon its ability to fracture the projectile.

Considerable thought has been devoted to the development of philosophies of ballistic testing. A statistical analysis of firings conducted under specification ANOS-1 disclosed several discrepancies, and suggestions were made in October 1943 for improvements and equalization in the specification requirements. The modifications suggested have been adopted in a majority of cases and a satisfactory specification (57-115-3, April 1945) guaranteeing the procurement of high quality aircraft armor has resulted.

Work has recently been concentrated on the development of Joint Army-Navy specifications. While there is recognized some reason for the traditional divergence between Army and Navy philosophies of testing heavy armor, the efforts of this arsenal have been expended rather successfully as regards aircraft armor.

A comprehensive investigation of metallurgical and room temperature ballistic properties of several low alloy face hardened armor steels was conducted at this arsenal in 1942 to find out whether the aircraft industry could substitute low alloy steels for the 5% nickel compositions. It was found that the Cr-Mo-V type and a 3% Ni-Cr-Mo type were satisfactory, but that lower alloy steels which were not quenched out exhibited inferior shock resistance. This investigation indicated to the aircraft armor industry the danger of reducing the alloy contents in face hardened armor to the point when incomplete quench hardening occurs upon heat treatment.

In 1944 another metallurgical investigation was conducted on an NE type face hardened armor made under NRC 30. It was shown that the shock properties of the low alloy steel were unsatisfactory at low testing temperature because non-martensitic transformation structures were formed upon quenching.

Eight (8) laboratory reports on this phase of armor have been issued.

Examination of Domestic Armor

One of the most important functions of the Armor Section of the Watertown Arsenal Laboratory involves cooperation with the manufacturers of armor and with the Ordnance Research Center in its ballistic testing programs involving domestic armor. This arsenal was instrumental in assisting new manufacturers to qualify as armor producers by providing them with all available information regarding alloys, heat treatments, and special processes involved in the production of armor. Armor manufacturers shipped many defective armor sections to Watertown Arsenal for metallurgical investigation to discover the cause of the difficulty. Time and again this laboratory stressed the importance of adequate hardenability, through quench hardening, quenching from the temper when necessary to avoid temper brittleness, and the necessity for good steel quality.

Courses were given at Watertown Arsenal to assist Ordnance inspectors of armor in understanding the nature of the various armor inspection tests developed at this arsenal and incorporated in armor specifications. Manuals describing various tests and armor manufacturing techniques were prepared at this laboratory and distributed to industry.

This laboratory conducted numerous investigations covering the metallurgical and physical properties of armor used at the Ordnance Research Center for determination of the ballistic properties of American armor. The results of these ballistic tests were used as the basis for modifying existing specifications and for the purpose of developing new ones.

A total of 103 reports covering the examination of domestic armor production were distributed by Watertown Arsenal during 1942-1945.

HELMET PROGRAMS

In April 1943 the Office, Chief of Ordnance requested that Watertown Arsenal initiate the examination of a group of M1 helmets which had cracked in service. This arsenal was notified that examination of a quarter of a million helmets in the North African theatre of operations disclosed that 2.5% of the helmets were defective due to cracking which occurred after the helmets were issued. During the course of the investigations the plants manufacturing the helmet and the helmet steel were visited by a member of the laboratory staff.

The helmet shell is formed by a very severe deep drawing operation that leaves the shell in a highly stressed condition often sufficiently severe to cause cracking. Steel defects traceable to inadequately controlled processing techniques greatly aggravate the cracking tendency. The need for a specification to control the quality of the austenitic manganese steel employed for helmets was recognized and this laboratory suggested the preparation for such a specification. With the approval of the Office, Chief of Ordnance a tentative specification was drafted by Watertown Arsenal in September 1943 and finally made mandatory in March 1944. A notable improvement in steel quality has occurred since the inception of Specification AXS-1170, Steel, Non-Magnetic; Sheet and Strip (For Helmets and Body Armor).

The helmet manufacturing processes were next subjected to scrutiny and steps were undertaken to reduce the high residual stresses of the helmet shell. In cooperation with personnel of the St. Louis Ordnance District, Watertown Arsenal helped develop the edge-annealing process which has greatly reduced the service cracking tendency. This process has now been made mandatory at the plants of the helmet manufacturers. This laboratory has received a letter of commendation from Brig. Gen. Kirk for its part in the development of the edge-annealing process.

In March 1944 the Helmet Industry Integration Committee was formed with a member of the laboratory staff as a member ex-officio of the committee. Numerous meetings were held at which data collected at Watertown Arsenal were distributed to the helmet steel and helmet producers and to the interested Ordnance personnel. Several investigations covering each of the following subjects were conducted at Watertown Arsenal:

1. Cracking of M1 helmets in service.
2. Metallurgical defects associated with Hadfield manganese steel.
3. Ballistic properties of manganese steel sheet and helmets.
4. Types of projectiles employed to test helmets.
5. Effect of variations in helmet thickness upon its ballistic properties.
6. Investigation of manganese steel modified with 3½% nickel.
7. Investigation of edge-annealing processes.

A total of eighteen (18) reports covering the various phases of the helmet program were distributed by Watertown Arsenal.

BODY ARMOR

In the spring of 1943 a program of development of Flyer's Protective Armor was undertaken by the Ordnance Department. The opinion of this laboratory was asked concerning factors to be controlled in the procurement of steel for armor components of body armor assemblies.

On 10 July 1943 it was recommended by this laboratory that Hadfield manganese steel be used if its chemistry, gauge, surface condition and heat treatment as well as its mechanical, ballistic and non-magnetic characteristics were carefully controlled.

Metallurgical and ballistic investigation of samples of the steel being used in body armor assemblies indicated that much of it was probably of poor quality and on 17 December 1943 it was urged that unless an adequate specification for the steel to be used was immediately set up and rigidly adhered to, proper protection of personnel could not be guaranteed.

On 17 September 1943 the first draft of such a specification (AXS-1170) was prepared at this laboratory and after several conferences with representatives of Ordnance and industry it was adopted officially on 10 January 1944. An amendment incorporating later knowledge was adopted on 24 February 1944.

In the communication of 10 July 1943 it was also recommended that immediate steps be undertaken to determine the comparative resistance of Hadfield manganese steel and certain non-ferrous alloys to perforation by actual fragments of high-explosive shell, since other work being done at the laboratory indicated that certain aluminum alloys and even Dowmetal should afford resistance superior to non-magnetic steel. The latest results of actual fragmentation tests indicate that several non-ferrous alloys have higher resistance to such attack than Hadfield manganese steel.

Projectiles were developed here between December 1943 and February 1944 to simulate in a simple, reproducible and measurable manner the impact of actual fragments of high-explosive shell. One such projectile, the caliber .22 T37, has been adopted as an official proof projectile and is being used to determine the control of quality of material submitted under Specification AXS-1346. At the suggestion of this laboratory a new application of the quality control technique was made to the ballistic testing of body armor material, and is included in the latest version of that specification, dated 18 April 1945.

Scores of materials - steels, non-ferrous alloys, laminates and fabrics - have been tested for their resistance to fragment-simulating projectiles and caliber .45 ball projectiles. While, as yet, no satisfactory correlation between ballistic limit tests and actual fragmentation tests obtains, invaluable information regarding the resistance of various materials to various types of perforation has been made available.

Studies of the original designs of body armor vests undertaken here indicated that the size of the armor plates used was too small and the method of integration unwieldy. It was recommended on 1 July 1944 and on 12 October 1944 that larger components be utilized even if this necessitated introducing a different system of integrating the components. The latest designs incorporate the use of larger components of an aluminum alloy with a new system of integration.

Fifty-nine (59) laboratory reports have been written on the various phases of this project.

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Research and Development on Armor

National Defense Research Committee

1942-1945

RESTRICTED

Comparative Costs of NDRC and Watertown Arsenal

Laboratory Research and Development on

Armor Plate

Comparative Costs - April 1942 to 1 Jan. 1944

NDRC Projects (from Rpt. of Div. 18 - 1 Jan. 44)		- $398,350.00
Watertown Arsenal Laboratory*		- $171,010.00
	Difference	$227,340.00

Comparative Estimated Costs - April 1942 to 31 Aug. 45

NDRC Projects (on basis of estimated in Rpt. of Div. 18 - 1 Jan 44)		- $726,375.00
Watertown Arsenal Laboratory*		- $350,226.00
	Difference	$376,149.00

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NRC PROJECTS

Watertown Arsenal Direct Liaison

NRC-4 - Effects of Hydrogen, Nitrogen and Oxygen in Armor Plate

NRC-5 - Correlation of Metallographic Structures and Hardness Limit in Armor Plate

NRC-6 - Nonballistic Test for Armor

NRC-14 - Low Alloy Steels for Armor

NRC-23 - Flame Hardening of Homogeneous Armor Plate

NRC-31 - Investigation of Boron in Armor Plate

Watertown Arsenal Not Direct Liaison

NRC-24 - Manufacture and Welding of Face Hardened Armor

NRC-29 - Manufacturing and Welding of Homogeneous Armor Plate

NRC-30 - Manufacturing and Welding of Case Carburized Armor Plate from Non-alloy Steels

NRC-4 - Battelle (Nov. 1942-Oct. 1943)

Effects of Hydrogen, Nitrogen and Oxygen in Armor Plate

Reports published under this project included (1) the study of fractional vacuum fusion analyses of armor plate samples and (2) the results of an investigation of intergranular fracture found in cast armor steels. It was shown that value of the study of gases in armor steels was slight since it was indicated that very few ballistic difficulties were associated with excessive gas contents. It is noted that an opportunity was lost by the investigators to study the effect of gases on temper brittleness susceptibility during the progress of this report. The results of the investigation on intergranular fracture in cast armor include the factors producing the intergranular fracture and steps which may be taken to eliminate this type of fracture. This information was of particular value to about two cast armor manufacturers who produced cast armor having fractures of this brittle type. On the other hand, it was the result of Watertown Arsenal research that demonstrated that intergranular fractures were related to poor physical and ballistic properties.

Six reports were published under Project NRC-4.

NRC-5 - Battelle - Nov. 1942-October 1943

Correlation of Metallographic Structures and Hardness Limit in Armor Plate

This project was covered by eight reports. The project consisted of two investigations, as follows: (1), metallurgical examination, including metallographic examination, low temperature impact testing, and Jominy end quench tests, of passing and failing (ballistically) 1", 1½", and 2" cast and rolled plates and (2), heat treatment of forty-four ½" rolled plates to various hardness levels by full quenching and tempering, intercritical quenching, and partial isothermal transformation followed by tempering to several hardness levels; ballistic testing of the plates with cal. .30 AP M2 projectiles for resistance to penetration and with cal. .50 AP M2 for PTP testing, and finally metallurgical examination of the plates.

The first phase of the project was essentially a duplication of investigations previously made by the Armor Plate Department of Watertown Arsenal on correlation between ballistic performance and metallurgical characteristics of cast and rolled armor and, although confirming work performed at Watertown, did not contribute new knowledge or concepts about the subject under investigation. The results of the Battelle Investigations were reported in reports dated 15 July 1942; 15 October 1942; 1 March 1943; 21 May 1943; and probably October, 1943. Corresponding and preceding Watertown reports, which were much more informative and pertinent than the Battelle reports (such as, for instance, by the application of the fibre fracture test in a report dated 16 August 1943), were issued on the following dates: 25 April 1942; 16 May 1942; 4 June 1942; 24 August 1942; 7 October 1942; 21 January 1943; 19 March 1943; and 16 August 1943.

The conclusions drawn for the second phase of the project did not affect production practice since it had been previously considered that tempered martensite was the optimum microstructure for armor plate. Moreover, recent investigations have contradicted the conclusions made that tempered bainite microstructures are better than tempered martensite for resistance to penetration.

NRC-6 - C.I.T. (July 1942-Nov. 1943)

Nonballistic Test for Armor

The project has resulted in the development of two tests which correlate with two characteristics, resistance to back spalling and resistance to cracking, now determined by ballistic tests. The test developed for spalling tendencies consists of a tensile test across the thickness direction wherein, for the thicknesses studied, reductions in area of over 30% are associated with satisfactory plate whereas reductions in area of less than 10% are associated with failing plate. The Charpy impact test is proposed as a substitute for the ballistic shock test. In the thicknesses investigated, impact values of greater than 25 foot pounds at -40°F. are associated with noncracking plate.

The above tests are technically sound but cumbersome. The qualities involved can more simply be determined by the fracture test for steel quality and the fibre fracture test for shock resistance, respectively. Furthermore, the tensile test across the thickness direction is restricted to comparatively thick plate, probably over 1 inch in thickness. All of these objections are overcome by the fracture tests which cover the total thickness and do not involve accurately machined specimens. The fracture tests were accepted by the manufacturers and are now incorporated in the specifications for the procurement of rolled and cast armor. The two tests described under project NRC-6 were not accepted by industry. Three reports were published under project NRC-6.

NRC-14 - Battelle (July 1942-To Date)

Improvement of Low Alloy Armor Steel

The project NRC-14 was divided into fifteen parts covering several phases of armor research undertaken, in general, to add to the metallurgical knowledge of the armor industry and the Ordnance Department.

A literature survey and subsequent investigation revealed that boron is effective in increasing hardenability without impairing the mechanical properties. Since the results of these experiments in small sections showed promise in tests completed in March 1943 a more complete investigation was set up under NRC-31.

The effects of a wide variety of homogenization treatments were determined on two-inch thick commercial cast armor. Five plates were investigated and the results published in March and May 1943. It was found that there was no significant effect upon the hardenability or mechanical properties as a result of the homogenizing treatments employed. This information confirmed the fact that short homogenizing treatments were satisfactory for low alloy armor steels. However, the cast armor industry had already reduced their homogenization cycles when they changed to low alloy steels in 1942, and the cycles were not changed as a result of this investigation.

In September 1943, an investigation was completed on a method of controlling the maximum carbon content in the carburized case of face hardened armor by the addition of a chloride and a silicon bearing material to the carburizing compound.

An investigation on the effect of 1% nickel upon the low temperature notched bar toughness of low alloy armor steels was conducted between September and November 1943 and completed in February 1944. Although there was a widespread opinion that nickel improved the low temperature impact properties, this investigation showed that in heat treated steels no improvement in toughness results from the addition of 1% nickel other than that resulting from an increase in hardenability. This work corroborated the results of the metallurgical investigation conducted earlier in the year 1943 on the plates subjected to low temperature ballistic tests at Camp Shilo, Canada. In this latter investigation by Watertown Arsenal, it was shown that chemical composition per se caused a relatively minor effect upon toughness as compared to hardenability and heat treatment efficiency.

A statistical study of the mechanical properties of various low alloy armor compositions was undertaken and the results published in March 1944. This investigation was conducted at several hardness levels on steels heat treated in small sections. This study revealed that short draw times yielded the best properties in steels susceptible to temper brittleness and that there is a gradual drop in impact properties as the testing temperature is reduced.

This information increased our basic knowledge of the low temperature impact properties of low alloy steels, but at this time difficulties were encountered in the manufacture of thicker armor which required higher alloys. Preliminary information regarding the temper brittleness of these higher alloy steels was obtained from the literature by Watertown Arsenal and suggestions were made to Battelle to investigate the use of higher alloy steels heat treated in heavy sections.

In April 1944, an investigation was completed in which the effect of variations in melting practice in cast and rolled armor was determined. The results increased the basic knowledge of steel making although no direct application to production armor steel manufacture occurred.

A study of the cause of intergranular fractures was undertaken under this project, but it was completed under NRC-4 and will be discussed more fully under that project.

A study of the effect of heat treating variables on the mechanical properties of two low alloy steels was completed in May 1944. In this report it was concluded that incomplete austenitization caused the formation of microstructural constituents exhibiting inferior toughness. This study corroborated the information already available which showed that the toughness of tempered intermediate and high temperature transformation constituents, especially ferrite, was inferior to that of tempered martensite.

As a result of using the higher alloy compositions for heavy gage armor plate, research was initiated under this project to study various phases of the problem, and the results were published in reports having the following titles:

1. "Heating and Cooling Rates in Heavy Armor Plate and Calibration of Air Cooled Hardenability Specimens." June 1944.

2. "Hardenability and Isothermal Transformation Curves of Several Proposed Heavy Armor Plate Analyses." June 1944.

3. "Mechanical Properties of Various Isothermally Developed Structures Compared with Those of Martensite Tempered to the Same Hardness." October 1944.

4. "The Evaluation of Constant Temperature Transformation." December 1944.

5. "The Cause of Quench Cracking in Cast Armor Steel." February 1945.

6. "Determination of Martensite Transformation Points." April 1945.

This group of six investigations has added considerably to our basic knowledge of high alloy steels used for heavy sections. Much of this work is an adjunct to the information obtained at Watertown Arsenal which has been undertaken to devise compositions and heat treatments capable of yielding satisfactory toughness in armor over 4 inches in thickness at a higher hardness than that employed for production armor at present. The results of these studies have helped make the heavy armor problem more amenable to investigation, and added to the Ordnance Department's knowledge on the various difficulties of making heavy armor, which requires knowledge of the following phases: quench cracking, comparison of isothermal curves with results obtained on continuous cooling, and determination of the martensite transformation points. However, the results obtained to date have not solved the heavy armor problem. Further research will be necessary for its solution.

A total of twenty-four reports were made under this project which constitutes an important contribution to the metallurgical aspects of armor. The direction of the studies was closely coordinated with work conducted at Watertown Arsenal. Part of the studies were undertaken to confirm through more complete investigations, conclusions obtained at Watertown Arsenal as the result of limited investigations. Others, such as, the investigation of melting practice and quench crack susceptibility of high alloy steels, were original studies undertaken to overcome or clarify the armor producers' problems.

In this group of investigations one very important criticism which may be made is that there was not sufficient reference to published literature, particularly as regards the problem of temper brittleness. In this case the work done under this project to a great extent duplicates investigations conducted twenty-five years earlier by Greaves and Jones at Woolwich Arsenal, England. Had more adequate reference been made to extant information, the work done under this project could have been more efficiently organized and more effort could have been expended on problems for which no solution had been previously determined.

NRC-23 - M.I.T. (Oct. 1942-Sept. 1944)

Flame Hardening of Homogeneous Armor Plate

The project covers the results of flame hardening $\frac{1}{2}$, 1, and 1$\frac{1}{2}$ inch thick plates of preheat treated medium-carbon, low alloy homogeneous armor, and the results of flame softening of quenched homogeneous armor of the same thicknesses. It was determined that the improvement in ballistic properties of flame-hardened 1 inch thick rolled armor is not considered sufficient to warrant its use on combat vehicles. The flame hardening of 1$\frac{1}{2}$ inch thick plate did not improve the ballistic properties. It was found that flame softening of quenched 1 inch thick plate showed some promise. One of the serious limitations of the flame hardening process was found to be distortion, particularly in the flame hardening of $\frac{1}{2}$" thick plate. The results of this investigation indicated that flame hardening is not a practical method for face hardening medium-carbon, low alloy homogeneous armor. Seven reports were published under project NRC-23.

NRC-31 - U.S. Steel, Bureau of Standards, Battelle (Nov. 1942-Apr. 1945)

Investigation of Boron in Armor Plate

This project included two investigations, namely -

(1) Influence of boron on some properties of experimental steels containing 0.3% C and varying amounts of manganese, chromium and molybdenum.

(2) Investigation of boron in armor plate.

The object of investigation No. 1 was to determine the influence of boron additions with ferrocarbon and grainal No. 79 on the structure, grain size, hardenability and notch toughness at room and low temperatures of experimental steels of the type noted above. The hardenability due to boron varied with the base composition, the amount of boron retained and the composition of the addition agent. It was determined that, in general, additions of 0.0007 to 0.001 percent boron were more effective than 0.0015 to 0.006 percent and the additions with grainal No. 79 were more effective than with ferrocarbon. The notch toughness at room and low temperatures of fully hardened and tempered steels was not appreciably affected by relatively small additions of boron, whereas the notch toughness of many of the steels with high boron was inferior to that of the steels without boron. The results of this work increased our basic knowledge on the affect of boron on the properties of low alloy steels.

The investigation No. 2 presents the results of determinations of grain size and normality, inclusion rating, hardenability and tensile and endurance properties of several commercial boron containing carbon steels and NE9400 type steels. The results of this investigation presented very little new information and were of essentially no value to industry or to the Ordnance Department.

Fifteen reports were published under project NRC-31.

NRC-24 - Buick (Aug. 1942-July 1944)

Manufacture and Welding of Face Hardened Armor

A process for the manufacture of face hardened armor plate, from grainal treated steels containing little or no alloy without resorting to the usual carburizing process, was developed by the Buick Motor Division of General Motors Corporation. Plates by this process were heated to a uniform temperature throughout and quenched on the face only. The depth of hardening was dependent on the hardenability of the material which was regulated by the manganese content. An initial plate was made which performed satisfactorily ballistically and as a result of this test, Buick was awarded the NRC-24 project contract. However, Buick was never able thereafter to duplicate the results of the initial plate,and, therefore, the process was never tried in production.

Arc and spot welded joints made with the grainal-treated plain carbon steels were satisfactory ballistically, but since the face hardening process was a failure, the welding results were not of value.

One report was published under project NRC-24.

NRC-29 - General Motors (Sept. 1942-March 1944)

Manufacturing and Welding of Homogeneous Armor Plate

The results of this investigation were reported in Part I and Part II.

Part I deals with the manufacture of machinable and high hardness homogeneous armor from boron treated plain carbon and low alloy steels. Satisfactory prime plates up to and including ½ inch thickness were produced from plain carbon boron treated steels containing varying carbon and manganese contents. Due to low hardenability it was found that heat treating conditions must be controlled to a degree which cannot be considered commercial. Satisfactory prime machinable homogeneous armor was produced under laboratory control and commercially from NE 9400 steels (boron treated and untreated) in thicknesses up to ½". Satisfactory 1" plates were produced commercially from 9400 steel, boron treated. Satisfactory hard homogeneous plates ½" thick were produced from the NE9400 type analysis. Hard homogeneous armor, 1/4"-1/2" thick processed from plain carbon, boron treated steels were not entirely satisfactory.

Part II deals with the welding of machinable and high hardness homogeneous armor processed from plain carbon and low alloy boron treated steels. The initial work consisted of tests to determine the usability of various types of ferritic and austenitic electrodes in various sequences by means of a torture test with and without chill bars. Work on torture tests and chill bar cooling was dropped early in 1943. Ferritic welding was dropped to prevent duplication of work being carried out under NDRC projects. Program was continued, determining weldability of armor developed under this project— "H" plates were welded with austenitic electrodes. A few plates were welded with NRC-2A ferritic electrode. In general, the results of the ballistic shock tests on "H" welded plates from all categories were unsatisfactory.

The project was initiated with the purpose of determining whether it is possible to conserve alloys in high gage armor. The results showed that there is a definite limit to the extent to which hardenability could be reduced without detriment to the ballistic properties of commercially heat treated armor.

Two reports were published under project NRC-29.

NRC-30 - Buick Motor Division (Sept. 1942-Dec. 1943)

Manufacturing and Welding of Case Carburized Armor Plate from Non-alloy Steels

This investigation was undertaken to determine processes for the manufacture and welding of carburized low alloy (boron treated) and plain carbon steels. Although no outstanding armor was obtained, the study did reveal that thin face hardened armor tested at normal temperatures could be processed from the boron treated 9400 series steels using gas carburizing. The final report was published in March 1945, but as yet no armor producers have employed gas carburizing in the production of face hardened armor. The use of NE type steels has not as yet proven satisfactory under all types of ballistic attack (especially at low temperatures) and is not employed in production.

One report was published under project NRC-30.

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