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WATERTOWN ARSENAL
LABORATORY

EXPERIMENTAL REPORT

NO. WAL. 710/792

ARMOR

Development of Notched Bar Impact Requirements for Heavy

Coast Armor 4" to 12" in Thickness

Spec. AXS-1013, Rev. 1

BY
A. Hurlich
Metallurgist

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DATE 19 November 1945

WATERTOWN ARSENAL
WATERTOWN, MASS.

710/792

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Watertown Arsenal Laboratory
Report No. WAL 710/792
Problems B-9.1 and B-9.4

19 November 1945

ARMOR

Development of Notched Bar Impact Requirements for Heavy

Cast Armor 4" to 12" in Thickness

Spec. AXS-1013, Rev. 1

OBJECT

To investigate the impact properties of heavy cast armor sections to obtain data to provide a basis for the development of notched bar impact requirements for specification purposes.

SUMMARY

1. Cross-sectional hardness surveys and notched bar impact tests were performed upon 4" to 13" thick sections of cast armor provided by seven manufacturers (See Tables IV and VIII). Tests were performed upon experimental cast armor blocks heat treated in full section by the manufacturers and upon insert bars welded into and heat treated in low carbon steel blocks at this arsenal to simulate the heat treatment of large sections.
2. It is concluded that the proposed notched bar impact test requirements contained in Table III of Specification AXS-1013, Rev. 1 should be incorporated into the specification without change.
3. Relatively limited testing indicates satisfactory reproducibility and agreement of notched bar impact test results obtained at this laboratory and at two industrial laboratories. More extensive investigation of the duplicability of notched bar impact testing at the plants of the seven manufacturers involved may be desirable to insure accuracy of results.

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INTRODUCTION

During the latter half of 1944 extensive development work was conducted on heavy armor which was required to defeat undermatching high velocity projectiles such as the German 88 mm. Flak 41. Experimental armor made for this purpose could not be subjected to adequate ballistic testing at American proving grounds due to the inability of the available anti-tank guns of desired caliber to fire projectiles at sufficient velocity to penetrate armor in excess of 6" in thickness. U. S. Army Specification AXS-1013 covered the procurement of the heaviest cast armor then being produced (4" to 6" in thickness), but new vehicles were being designed to carry even heavier armor.

The Watertown Arsenal was requested by the Office, Chief of Ordnance-Detroit¹ to formulate sufficient non-ballistic test requirements for cast armor 6" to 12" in thickness to insure the acceptance of armor of satisfactory quality. This Laboratory recommended the performance of fracture tests, cross-sectional Brinell hardness tests, and notched bar impact tests from both the surface and the center of the armor sections at temperatures of +70°F. and -40°F. Minimum notched bar impact values for a series of hardness ranges were suggested.

In the beginning of January 1945 this Laboratory was requested to prepare a draft of a specification to supersede AXS-1013 and to cover the procurement of cast armor 4" to 12" in thickness on the basis of non-ballistic tests. It was initially proposed to heat treat fracture test blocks with the castings and to conduct fracture tests and hardness surveys. Notched bar impact test specimens were to be prepared from the fracture blocks whenever the fractures were not completely fibrous. Tables of minimum impact test values as a function both of hardness and casting thickness were established, the first of which is contained in Table I. These values were arrived at through the compromise between the impact properties which members of the Laboratory staff considered desirable and those which could be consistently attained by the more successful manufacturers of heavy armor castings.

The proposed specification was submitted for consideration by the manufacturers of heavy cast armor, who objected, with considerable justification, to specifying minimum notched bar impact values for the center of heavy armor sections. The unavoidable occurrence of temper brittleness in heavy sections of alloy steel² combined with the inability to obtain completely martensitic structures at the centers of thick sections generally results in considerably reduced impact properties at the centers of thick steel sections. Objections to the fracture tests were also voiced because of the large amount of steel which would be consumed in fracture blocks and because of the tie-up of heavy machinery which would result when fracture blocks are sawed to produce sections for hardness surveys and impact tests.

1. OOM 400,114/Wtn. Ars. (20 Oct. 44), Wtn. 400.114/18. see Appendix A.
2. Watertown Arsenal Laboratory Report No. WAL 710/678, "The Development of Combinations of Compositions and Heat Treatments to Yield Optimum Shock Properties in Cast Armor 1 to 6 Inches Thick." 1 September 1944.

The proposed specification was accordingly revised in March 1945. Fracture tests and notched bar impact tests from the center of the armor sections were eliminated. Notched bar impact test specimens were to be machined from the ends of a 1-1/4" diameter rod of armor steel which was to be welded into the middle of a block of steel of the same thickness as the armor casting represented. After heat treatment, the rod is removed from the block and ground for a hardness survey, which is to be made before impact test specimens are taken from the rod. Details of the procedure are shown in Figure 1 and the required minimum notched bar impact properties are contained in Table II.

The seven producers of heavy cast armor agreed to prepare and heat treat sections of 6", 8", 10", and 12" thick cast armor and ship these sections to the Watertown Arsenal where hardness surveys and impact tests would be conducted for the purpose of obtaining data to be used as the basis for the establishment of reasonable impact test requirements. Data collected during the months of April and May 1945 were presented at a meeting of Ordnance and industry representatives held in June 1945. It was generally conceded that the impact properties of the initial experimental samples were unsatisfactory and not representative of the best that the companies could do. In view of the revision of the method of obtaining impact test specimens, it was agreed that the armor manufacturers would supply Watertown Arsenal with 1-1/4" diameter rods of cast armor steel 4", 6", 8", 10", and 12" in length and with carbon steel blocks in which the rods could be heat treated. The impact properties after optimum heat treatment at the Watertown Arsenal would then be used for establishing the specification requirements.

Specification AXS-1013, Rev. 1 "Armor: Steel, Cast Homogeneous (4 to 12 Inches, Inclusive) was in the meantime published on 1 October 1945 but is not to be released until the notched bar impact requirements are definitely established. The tentative impact requirements of Specification AXS-1013, Rev. 1 are contained in Table III. Table III differs from Table II only in the slight lowering of the hardness range for 4" to 6 1/2" thick armor.

The report which follows contains all the data on the impact properties of heavy cast armor which have been accumulated at this arsenal in reference to the non-ballistic specification of such armor.

MATERIALS AND TEST PROCEDURE

Heat treated cast steel blocks 6", 8", 10", and 12" in thickness were submitted by the Continental Foundry & Machine Co., the Ordnance Steel Foundry, the General Steel Castings Corp., and the American Steel Foundries. The Pittsburgh Steel Foundry supplied 4", 6 1/2", and 8 1/2" thick castings. The sizes, chemical analyses, and details of the heat treatments of the blocks are contained in Table IV. A 5/8" thick section was sawed from the middle of each block and ground on both sides to a final thickness of 1/2". Cross-sectional Brinell hardness surveys were made on the ground surfaces; the first impression being made 1" below the surface of the casting and the remaining impressions spaced 2" apart as illustrated in the upper

diagrams of Figure 2. Eight V-notch Charpy impact test specimens were machined from each $\frac{1}{2}$ " thick section; half from the surface and half from the center of the section as shown in Figure 2. Duplicate specimens from each location were tested at +70°F. and at -40°F. One half of the majority of the submitted blocks were notched and fractured for information only.

In accordance with the decision made at the meeting held in Detroit on 1 June 1945, the manufacturers of heavy armor castings forwarded to this arsenal ten 1-1/8" diameter bars including two bars of each of the following lengths; 4", 6", 8", 10", and 12". The bars were machined from castings of the standard compositions employed for heavy armor by the various companies. The analyses and the prior thermal treatments of the insert bars are contained in Table V.

The Pacific Car and Foundry Co. had sent to this arsenal some time ago a $2\frac{1}{2}$ "x $4\frac{1}{2}$ "x12" section cut from a heavy armor casting. Insert bars machined from the same casting were heat treated in a 12" thick plate at the Pacific Car and Foundry Co. and sections tested both at the plant and at this arsenal were found to exhibit excellent impact properties. 10" and 12" long insert bars were prepared from the $2\frac{1}{2}$ "x $4\frac{1}{2}$ "x12" section and were included in the present investigation.

Duplicate blocks of plain carbon cast steel of all thicknesses involved were supplied by the manufacturers. Table VI contains information regarding the sizes, analyses, and prior thermal treatments of the blocks. Three 1-3/8" diameter holes were drilled in each block to take the insert bars, see Figure 2. Discs of low carbon steel, 2" in diameter and 1/8" thick, were welded over one end of the drilled holes, the insert bars placed in the holes and fine iron powder tamped around the inserts to hold them securely in place. Discs of low carbon steel were then welded over the opposite ends of the holes. Both ends of the insert bars were firmly in contact with the discs.

The three insert bars welded into each block represented compositions produced by three different companies, thus the two blocks of each thickness were sufficient to accommodate insert bars from all the manufacturers in a single heat treatment cycle. The blocks were heat treated in accordance with the schedules outline in Table VII. The quenching tank consisted of a cylindrical unit 12 feet deep and 5 feet in diameter having a capacity of 1700 gallons. A flow of approximately 450 gallons/minute of cold water was maintained during the quenching operations, the water entering the tank at the bottom and rising in a spiral stream to overflow into an outlet at the top of the tank. The blocks were quenched in the vertical position, suspended, except for the 12" thick blocks, in pairs from the opposite ends of a horizontal arm. The 12" thick blocks were quenched individually to insure the most favorable cooling conditions. All blocks were allowed to remain in the quenching tank until they cooled to the temperature of the water.

The insert bars were removed after the final heat treatment by means of a press. It was found that the iron powder tamped around the inserts had been sintered during the heat treatment. The sintering was considered fortunate in that the heat treatment of a homogeneous material was more

closely simulated and furthermore because, if leakage had occurred because of the cracking of the weld beads attaching the thin steel discs over the holes, no water could have penetrated into the hole to cause more rapid cooling of the insert bars. The insert bars were ground longitudinally on two sides to a final thickness of $3/4$ ". Brinell hardness surveys were made on one of the ground faces, after which four V-notch Charpy impact test specimens were machined from each bar, two from each end notched approximately 1" below the end, see Figure 2. Duplicate specimens were tested at $+70^{\circ}\text{F.}$ and at -40°F.

A check between impact test results obtained at various laboratories was made possible when the Pacific Car and Foundry Co. and the American Steel Foundries submitted specimens for impact testing at this Laboratory and retained similar specimens for testing at their plants. The question of the duplicability of notched bar impact test results has repeatedly arisen and it is extremely important to determine that such tests are sufficiently duplicable for specification usage.

DATA AND DISCUSSION

Impact Properties of Heavy Cast Armor

The hardnesses, fractures, and notched bar impact properties of the heavy armor sections heat treated by the armor manufacturers are contained in Table IV. In no case was the fracture of any section greater than 4" in thickness completely fibrous, indicating that the fracture test cannot be applied as an inspection tool for heavy armor sections. Fibrous zones were obtained, in most cases, adjacent to the surfaces of the castings. This resulted from a combination of a better microstructure at the plate surfaces and the lower strain rate and decreased restraint at the plate surfaces during fracture.

Only 2 of the 7 sections in the $4"-6\frac{1}{2}"$ thickness range met both the $+70^{\circ}\text{F.}$ and the -40°F. notched bar impact requirements of Spec. AXS-1013, Rev. 1 which are contained in Table III, see Figure 3. None of the 16 sections in the $6\frac{1}{2}"-13"$ thickness range met the impact requirements at both testing temperatures, although 13 of the sections exceeded the room temperature requirements, see Figure 4. A summary of the results obtained with the sections heat treated by the armor manufacturers follows:

Thickness Range	Total No. of Sections	No. Failing to Meet Spec. Impact Requirements	No. Failing at $+70^{\circ}\text{F.}$ Only	No. Failing at -40°F. Only	No. Failing Both at $+70^{\circ}\text{F.}$ and at -40°F.
$4"-6\frac{1}{2}"$	7	5	0	1	4
$6\frac{1}{2}"-13"$	16	16	0	13	3

It was as the result of the very poor showing of the experimental sections heat treated by the armor manufacturers that it was decided to heat treat insert bars in heavy sections at the Watertown Arsenal. The results obtained at this laboratory are presented in Table VIII and in Figures 5 and 6 and are summarized as follows:

Thickness Range	Total No. of Insert Bars	No. Failing to Meet Spec. Impact Requirements	No. Failing at +70°F. Only	No. Failing at -40°F. Only	No. Failing Both at +70°F. and at -40°F.
4"-6½"	12	6	2	2	2
6½"-12"	17	7	0	5	2

It appears, at first glance, that the proposed specification requirements for the notched bar impact properties of heavy cast armor are too severe since approximately one half of the sections subjected to optimum heat treatments at this laboratory failed to meet the requirements. Analysis of the data contained in Table VIII discloses, however, a different picture. Three of the six sections in the 4"-6½" thickness range which failed to meet the specified impact requirements (American 4" and 6", and Pittsburgh 4") failed by less than 2 ft.lbs.; in fact, one of the two duplicate tests in most cases exceeded the requirements while the second failed by a sufficient margin to pull the average below the requirements. In these cases retests, which would naturally be allowed in practice, would probably result in the final acceptance of the material.

The Mn-Ni-Mo composition employed by the Continental Foundry is known to be sufficiently susceptible to temper brittleness that water quenching of heavy sections from the tempering temperature does not provide cooling rates sufficiently rapid to prevent the temper brittleness precipitation from occurring. The insert bars supplied by the Continental Foundry and Machine Co. met the proposed impact specification requirements in 4", 6", and 8" thick sections but failed in 10" and 12" thick sections, exhibiting the lowest impact properties of all inserts tested in the latter thicknesses. This behavior is consistent with the greater susceptibility to temper brittleness of the Mn-Ni-Mo composition as compared to the Cr-Mo composition which is employed by all the other producers of heavy cast armor.

Inserts submitted by the General Steel Castings Corp. and the Union Steel Castings Division possessed, with minor exceptions, very satisfactory notched bar impact properties over the entire thickness range investigated. Inserts machined from Pacific Car and Foundry Co.'s heat 45B613 exhibited exceptionally good low temperature impact properties in 10" and 12" thick sections. These results are in good agreement with those obtained at the Pacific Car and Foundry Co. upon material from the same heat which was heat treated both in the form of a 12" thick plate and as 12" long inserts welded into a test block.

Inserts from the American Steel Foundries and the Scullin Steel Co. exhibited generally unsatisfactory impact properties over the thickness range investigated. No reason can be ascribed for the poor properties of the inserts supplied by these two companies.

From the preceding discussion it is concluded that cast armor of both the Mn-Ni-Mo and the Cr-Mo compositions can be produced in the 4"-6½" thickness range to meet the proposed notched bar impact requirements with a considerable degree of success. To meet the notched bar impact requirements proposed for cast armor in the 6½"-12" thickness range only the Cr-Mo composition is recommended. The steel must be of high quality and very carefully heat treated to consistently meet the proposed requirements.

Duplicability of Notched Bar Impact Testing Between
Different Laboratories

The Pacific Car and Foundry Co. heat treated 5 inserts bars of the Cr-Mo composition in a 12" x 24" x 24" test block as shown in the diagram of Figure 7. Notched bar impact tests were conducted on some of the insert bars at the Pacific plant and some of the remaining inserts were forwarded to this laboratory for similar testing. Diagrams of the locations of the impact test specimens and the impact data are included in Figure 7. The values obtained at the two laboratories at both the surface and center at the testing temperature of -40°F are in complete accord, although the impact properties determined at room temperature at this arsenal are somewhat lower than those obtained at the Pacific Car and Foundry Co. The impact properties obtained in this material are considered excellent.

A 12" x 24" x 24" test block poured from another heat of similar analysis at the Pacific Car and Foundry Co. was heat treated and then sectioned for impact testing. One section was sent to this laboratory for the purpose of checking the results obtained by the manufacturer. The results obtained at both the Pacific Car and Foundry Co. and this arsenal are listed in Figure 8. The agreement between the two laboratories is sufficiently good to permit confidence in the duplicability of notched bar impact testing, at least as conducted at the two laboratories involved.

A very interesting experiment was conducted at the American Steel Foundries. Groups of standard V-notch Charpy impact test specimens were prepared from a heat treated cast armor section using a new milling cutter, a slightly worn milling cutter, and a badly worn milling cutter to shape the V-notches of the various groups of specimens. One half of the specimens were tested at -40°F at the American Steel Foundries and the other half were forwarded to this laboratory, where the notches were checked for dimensional accuracy using a shadowgraph at a magnification of X20, the thickness under the notches measured, and the specimens finally tested at a temperature of -40°F. The results obtained at both the American Steel Foundries and the Watertown Arsenal are contained in Table IX. Almost perfect duplication of results was obtained at the two laboratories. The results further indicate that minor variations in notch dimensions may not be as critical as generally supposed, but considerably more testing with steels of different microstructures and hardnesses at a series of temperatures would be required to verify this conclusion.

To definitely investigate the duplicability of notched bar impact testing it would be necessary to provide each of the seven or eight manufacturers of heavy cast armor who would be concerned with Spec. AXS-1013, Rev. 1 with sufficient material from a number of selected steels to prepare notched bar impact specimens for testing at +70°F and -40°F. Comparison of the results with data obtained from similar tests conducted at this laboratory would establish the reliability and reproducibility of notched bar impact tests.

General Considerations

The solution to the problem of obtaining in heavy steel sections the properties associated with tempered martensite appears just as distant today as it did several years ago. The metallurgical limitations which prevent the securing of optimum properties in very thick steel sections are now, however, much more clearly understood than formerly. The role of the specific alloying elements as well as that of combinations of such elements in promoting hardenability has been the subject of intensive investigation. During the last war and, more recently, during the past few years the problem of temper brittleness has received considerable attention.

The basic problem of obtaining optimum shock resistance in thick steel components is now recognized to consist of obtaining tempered martensite free of temper embrittlement. Since the same alloying elements which are necessary to provide hardenability adequate to result in the complete transformation to martensite upon quenching are also responsible for increasing the susceptibility to temper brittleness, no martensitic composition satisfactory for heavy sections has been developed. The addition of large amounts of hardenability promoting alloys introduces further difficulties associated with increased susceptibility to quench cracking and to the retention of austenite after quenching. Retained austenite may transform during the tempering cycle to decomposition products which have inferior properties. Relatively small amounts of such transformation products are capable of seriously impairing the properties of an otherwise martensitic structure.

The best results in very thick steel sections which have been obtained to date have been achieved through the use of steels of relatively low hardenability and low susceptibility to temper brittleness. These steels possess sufficient hardenability to avoid transformation to pearlite upon quenching, transforming to essentially bainitic structures. They are then tempered to low hardnesses (200-250 Brinell), at which hardnesses bainitic steels exhibit resistance to impact which is almost comparable to that of tempered martensite down to moderately low testing temperatures and at moderately high rates of straining. The Cr-Mo composition employed by the majority of the heavy cast armor producers is probably the most successful bainitic composition developed.

To obtain the best possible results it is necessary to maintain the quality of the steel as high as possible. Freedom from excessive segregation of nonmetallic inclusions at grain boundaries, dendritic structure, excessive shrinkage porosity, and any type of heterogeneity are necessary to achieve the highest impact energy levels.

The V-notch Charpy impact energy of tempered martensite of the hardnesses involved in heavy armor averages probably 20 ft.lbs. higher than the proposed specification values listed in Table III. Due to the inability of obtaining martensitic structures in thick sections it was necessary to compromise upon impact energies lower than those possessed by tempered martensite. Fortunately, this laboratory has in the course of the past few years had opportunities to investigate the metallurgical properties of relatively numerous samples of cast armor in the thickness range of 3" to 6" and a few samples of thicknesses greater than 6". These samples were cut from large plates or other types of castings which had been ballistically tested at Aberdeen Proving Ground. The correlation between the impact energies and the ballistic characteristics of these castings provided the basis for the selection of the values listed in Table III.

Room temperature impact energy values do not themselves provide sufficient assurance of satisfactory ballistic shock resisting qualities since slightly reduced temperatures, or equivalently, slightly increased strain rates may change the behavior of the material from ductile to brittle. Furthermore, the notched bar impact test at room temperature is much less severe than the ballistic shock tests currently employed for proofing armor. It has been determined¹ that the severity of ballistic shock tests is equivalent to that of a V-notch Charpy impact test conducted at some temperature between -10°C. (+14°F.) and -40°C. (-40°F.). It is considered desirable to conduct impact tests at both room temperature and at -40°F. since the spread between the two values so obtained is believed to be very significant. Tempered martensite exhibits the least spread between the impact energies at +70°F. and at -40°F. and as the structure and the shock resisting properties deviate more and more from the optimum, the spread between room temperature and reduced temperature impact properties becomes greater. Of course, when the material becomes so brittle that the room temperature impact energy falls off considerably, the spread between room temperature and reduced temperature values may again decrease, but only because the room temperature values begin to approach the very low values obtained at reduced temperatures.

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1. M. Bolotsky. "Correlation of Metallurgical Properties with Low Temperature Ballistic Performance of 1", 1½", and 2" Rolled Armor Tested at Camp Shilo, Canada." Watertown Arsenal Laboratory Report No. 710/662, 15 June 1944.

TABLE I

(Proposed Draft of Spec, Superseding AXS-1013)
(Prepared January 1945)

Minimum V-Notch Charpy Impact Requirements - Ft.Lbs.

Cast Armor

<u>Brinell Hardness</u>	<u>3/4"-1" Below Surface (to Centerline of Charpy Bar)</u>		<u>Center</u>	
	+70°F.	-40°F.	+70°F.	-40°F.
	<u>4-6 1/2 Inch Thick Inclusive</u>			
210-230	50	40	45	35
231-245	45	35	40	30
246-260	40	30	35	25
	<u>Over 6 1/2 to 12 Inches Thick</u>			
190-210	50	40	45	35
211-225	45	35	40	30
226-240	40	30	35	25

TABLE II

(Proposed Draft of Spec. Superseding AXS-1013)
(Prepared March 1945)

Minimum V-Notch Charpy Impact Requirements - Ft.Lbs.

Cast Armor

<u>Brinell Hardness</u>	<u>Centerline of Notch Minimum 1" from and Parallel to Ends of Bars</u>	
	<u>+70°F.</u>	<u>-40°F.</u>

4-6 $\frac{1}{2}$ Inch Thick Inclusive

220-240	50	40
241-255	45	35
256-270	40	30

Over 6 $\frac{1}{2}$ to 12 Inches Thick

190-210	50	40
211-225	45	35
226-240	40	30

TABLE III

(Draft of Spec. AXS-1013, Rev. 1)
(Issued 1 October 1945)

Minimum V-Notch Charpy Impact Values

<u>Thickness of Section Inches</u>	<u>Brinell Hardness Range</u>	<u>Impact Value</u>	
		<u>at +70°F.</u>	<u>at -40°F.</u>
4 to $6\frac{1}{2}$, incl.	210-230	50	40
4 to $6\frac{1}{2}$, incl.	231-250	45	35
4 to $6\frac{1}{2}$, incl.	251-270	40	30
more than $6\frac{1}{2}$ to 12	190-210	50	40
more than $6\frac{1}{2}$ to 12	211-225	45	35
more than $6\frac{1}{2}$ to 12	226-240	40	30