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WATERTOWN ARSENAL LABORATORIES

CORRELATION OF TOUGHNESS BETWEEN H-PLATE AND CHARPY IMPACT TESTS

TECHNICAL REPORT NO. WAL TR 112/98

BY
W. P. HATCH, JR.

SEPTEMBER 1959

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O.G. PROJECT: TB4-002, METALS AND NONMETALLIC
MATERIALS FOR ORDNANCE CONSTRUCTION
D/A PROJECT: 5893-32-002

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Impact testing
Welded joints, testing
Armor welds, testing

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CORRELATION OF TOUGHNESS BETWEEN H-PLATE
AND CHARPY IMPACT TESTS

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O.O. Project: TB4-002, Metals and Nonmetallic
Materials for Ordnance Construction
D/A Project: 5B93-32-002

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TITLE

CORRELATION OF TOUGHNESS BETWEEN H-PLATE
AND CHARPY IMPACT TESTS

ABSTRACT

The report presents the results of a laboratory study, recommended by the Ordnance Advisory Committee on Welding of Armor, of toughness in ballistic H-plates of high and low hardness armors as fabricated by Detroit Arsenal and Philadelphia Naval Shipyard.

Ballistic testing at Aberdeen Proving Ground indicated certain consistent differences between plates of three armor compositions when welded with a given electrode. The most notable behavior was the marked tendency for plate cracking in a high-hardness Mn-Mo steel base plate using either ferritic or austenitic electrode. In the case of a high hardness Ni-Cr-Mo base metal there was no plate cracking; however, all five rounds fired caused excessive weld-joint cracking. Likewise, in the case of a low hardness Ni-Cr steel base metal when failure occurred it was in the weld joint.

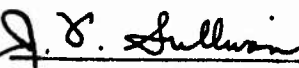
Post-ballistic laboratory examination included chemical analyses, macro and microexamination, hardness, and Charpy impact tests together with welded Charpy impact tests to determine the effects of welding on toughness of the base metals.

The relative performance of the high hardness Mn-Mo and the low-hardness Ni-Cr test plates could have been predicted from V notch Charpy impact transition curves. The Mn-Mo armor failed to meet minimum specification impact requirements for unwelded plate, while the impact transition occurred entirely below -40° in the Ni-Cr plate. In the case of the high-hardness Ni-Cr-Mo plates, the correlation between Charpy transition data and H-plate performance was not so definite, although the Ni-Cr-Mo base metal was observed to have slightly lower transition temperatures than the Mn-Mo armor.



W. P. HATCH, Jr.
Welding Engineer

APPROVED:



J. F. SULLIVAN
Director
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INTRODUCTION

Background

The economical and mechanical advantages in welded military structures have not been gained without introducing new problems in engineering technology. The question of weldability testing has been a particular enigma in welding research.

With application of welding to the fabrication of armored vehicles during World War II, the Ordnance Corps together with its industrial contractors became keenly aware of the problems involved in weldability testing. Armor, being a heat-treatable high-strength low-alloy steel composition, possessed inherent metallurgical characteristics which present difficulties in fabrication by welding. Hence, development of a test for evaluating weldability (a term which includes both ease of producing sound welds and service performance requirements) has been a prime objective in Ordnance welding research. However, despite extensive efforts by numerous researchers both in and outside the Government, no universally acceptable weldability test for armor plate has yet been developed.

For lack of a more suitable test, the H-plate, which was instituted in 1942 and is still used as a qualification test of welding procedures, has been utilized in some instances for research and development programs on weldability of armor. One such program carried out by Detroit Arsenal with the concurrence of the Ordnance Advisory Committee on Welding of Armor was a cooperative venture with the Navy Department Industrial Test Laboratory for comparison of performance in one-inch-thick welded H-plates from Army and Navy armor compositions. After fabrication, the completed H-plates were forwarded to Aberdeen Proving Ground for ballistic shock testing at -40°F .

It is important for the reader to recognize that there were actually two different types of armor involved in the test program. To avoid misunderstanding, further explanation at this point might be in order.

Armor, in general, can be classified in two categories according to the type of ballistic protection which it is designed to provide. One type of armor is heat-treated to high hardness levels with the primary objective of providing maximum resistance to projectile penetration. Although maximum toughness is also desired in this type of armor, some compromise must be made in order to obtain an optimum combination of protection against ballistic penetration and shock resistance. The second type of armor is produced to lower hardness levels with the primary objective of providing maximum resistance to failure under shock loading. In this type of armor, heat-treatments can be devised for maximum toughness without much, if any, compromise.

The fact that armors of two types were compared in one program made direct comparison between test results difficult. However, if the reader is aware that the Army armor base metals, subsequently identified as Mn-Mo and Ni-Cr-Mo, were heat-treated to high hardness for maximum penetration resistance

whereas the Navy armor base metal, subsequently identified as Ni-Cr, was heat treated to lower hardness for maximum resistance to shock, the comparative evaluation presented in this report should not be misconstrued. The weld-metal base-metal combinations investigated together with the results of the ballistic testing at Aberdeen Proving Ground are presented in Figures 1,* 2, and 3 and summarized below (see also Tables IA and IIA appended; reference Aberdeen Proving Ground Firing Records AR-19953 and AR-20512).

The following summary observations, based on the above tables and figures, provide the basis for possible correlation with post mortem laboratory tests:†

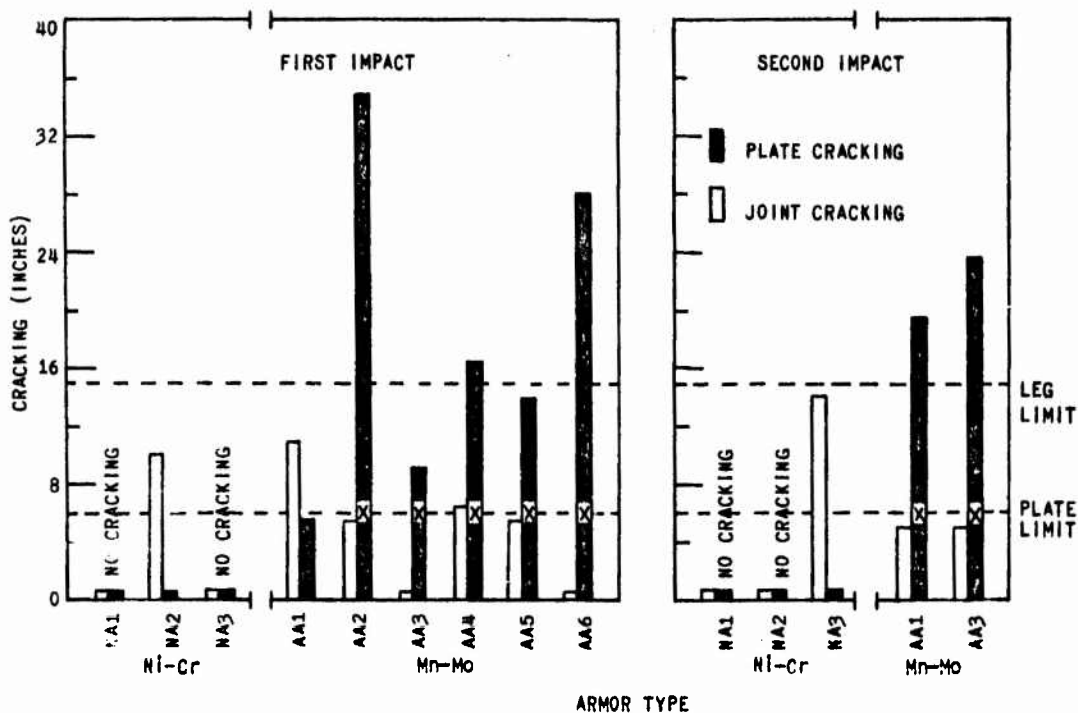


FIGURE 1: CRACKING IN AUSTENITIC EL307 WELDED ARMOR H-PLATES FROM BALLISTIC TESTS AT -40°F .

*The U.S. standard inch is the basis of measure for this report.

†Only back cracking, occurring with the first and second rounds, which were placed on opposite legs of the H-plates, were considered in this summary.

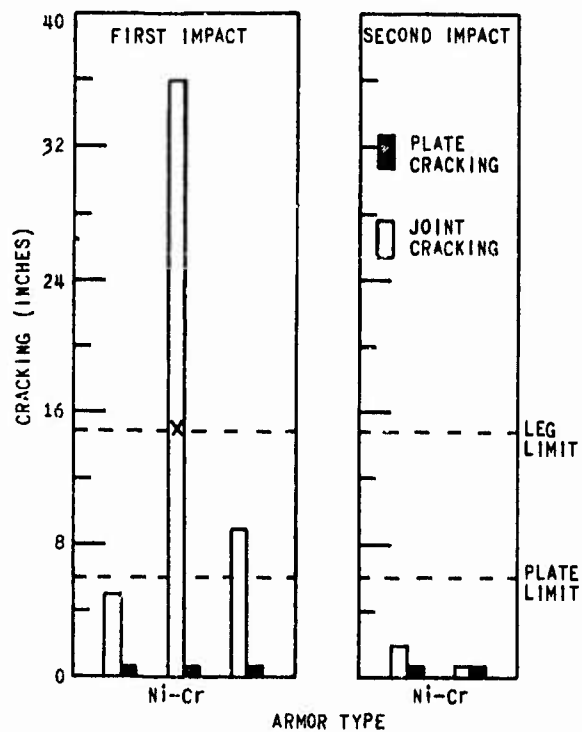


FIGURE 2: CRACKING IN FERRITIC GRADE 260 WELDED ARMOR H-PLATES FROM BALLISTIC TESTS AT -40°F.

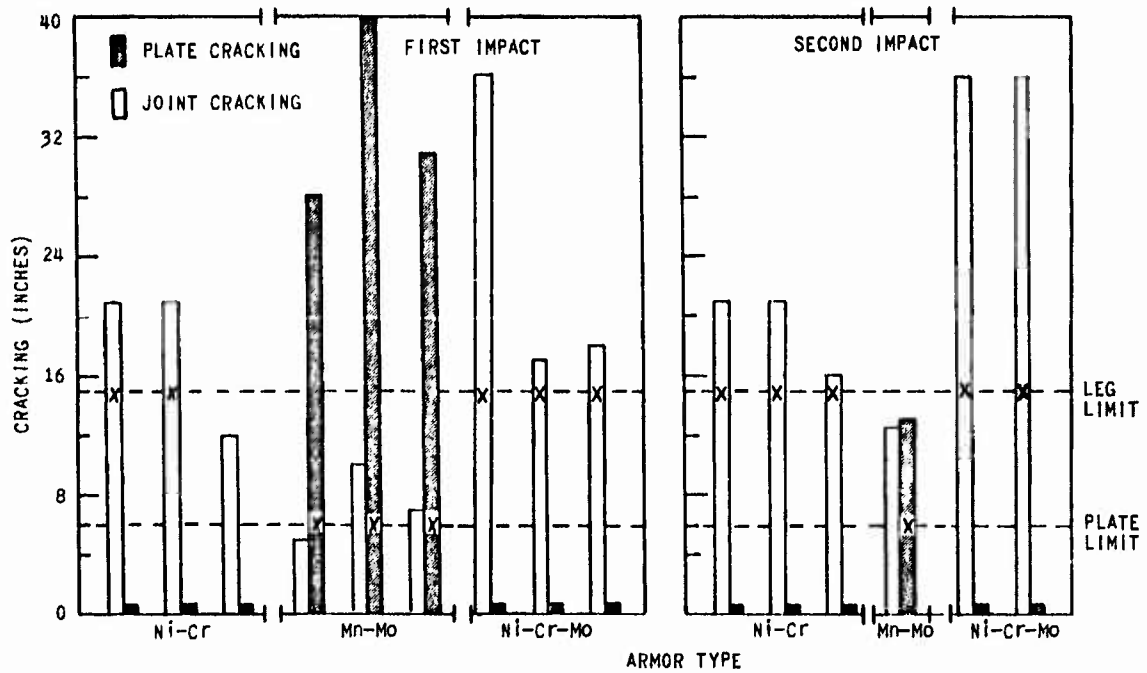


FIGURE 3: CRACKING IN FERRITIC GRADE 230 WELDED ARMOR H-PLATES FROM BALLISTIC TESTS AT -40°F.

Ni-Cr Armor

1. Welded with Austenitic E307 Electrode (see Figure 1)

Satisfactory performance, with 4 out of 6 rounds fired producing no cracking. The cracking that did occur was "fusion-zone" cracking.*

2. Welded with Ferritic Grade 260 Electrode (see Figure 2)

Satisfactory performance, with only 1 out of 5 rounds fired producing failure. One of the rounds caused complete (36") weld metal fracture, one round caused no cracking, and 3 of the 5 rounds fired produced "fusion-zone" cracking.

3. Welded with Ferritic Grade 230 Electrode (see Figure 3 & Table IIA)

Unsatisfactory performance with 5 out of 6 rounds producing excessive leg cracking. One of the rounds caused extensive weld-metal cracking, and 4 out of 6 failed as a result of extensive "fusion-zone" cracking.

Mn-Mo Armor

1. Welded with Austenitic E307 Electrode (see Figure 1)

Unsatisfactory performance with 7 out of 8 rounds producing "excessive" plate (base-metal) cracking. Six of the 8 rounds fired also caused "fusion-zone" cracking.

2. Welded with Ferritic Grade 230 Electrode (see Figure 3 & Table IIA)

Unsatisfactory performance with all rounds (4) producing "excessive" plate cracking. Three out of 4 rounds also caused "fusion-zone" cracking. Only one round produced weld-metal cracking.

Ni-Cr-Mo Armor

1. Welded with Ferritic Grade 230 Electrode (see Figure 3 & Table IIA)

Unsatisfactory performance with all rounds (5) producing excessive "leg" (weld) cracking. All five rounds caused "fusion-zone" cracking. Moreover, 4 out of 5 rounds caused excessive weld-metal cracking.

*Fusion-zone cracking is a term used by Aberdeen Proving Ground which designates that cracking occurred at the bond between the deposited weld metal and the base plate. Often the cracking is visible only on the surface of the plate in which case fusion-zone cracking occurs at the toe of the welds. However, because the contour of a weld joint is not perpendicular to the plate surface, it is difficult, if not impossible, to determine microstructures corresponding to the site of first separation and path of propagation unless a special study is made (such as that made by Battelle Memorial Institute under Contract No. DA-33-019-ORD-1132, WAL Report 642/160-12). Therefore, failures designated as "fusion zone" could be either weld-metal or heat-affected base metal failures.

Certain trends are evident from the above summary of H-plate test results. At -40°F the Mn-Mo was deficient in toughness as shown by excessive plate cracking regardless of whether austenitic or ferritic electrode was used in fabrication of the H-plates (11 out of 12 rounds fired produced excessive plate cracking and, therefore, resulted in "disqualification" of the H-plates).

The weld metal deposited with the Grade 230 ferritic electrodes also lacked sufficient toughness for testing at -40°F since excessive leg cracking occurred in both the Ni-Cr-Mo and the Ni-Cr armor steels. No plate cracking occurred in either the Ni-Cr-Mo or the Ni-Cr, although "fusion-zone" cracking was observed in both materials. In the case of the Ni-Cr armor "fusion-zone" cracking was predominant, whereas in the Ni-Cr-Mo armor extensive weld metal cracking occurred.

Objective

The objective of the laboratory tests was (1) to evaluate the differences which exist between the three armor composition types with regard to hardness, soundness, and toughness of the unwelded base metals and, (2) to determine whether effects of the differences as indicated by H-plate performance could be predicted on the basis of composite Charpy tests.

Scope

Laboratory examination was intended to determine those base metal properties most closely associated with armor specification requirements. Historically, Army armor specifications are based on certain mechanical property requirements but without direct stipulation of chemical compositions. This approach does not ignore the dependence of mechanical properties on chemistry and processing factors; provisions for control of these factors are included in the specification. The specifications also provide for certain laboratory tests to determine that the material possesses adequate soundness, hardness, and toughness for satisfactory ballistic performance. Thus the laboratory tests of the base metals included: (a) chemical analyses, (b) macro and microexamination (soundness), (c) hardness tests (resistance to penetration), and (d) Charpy impact tests (toughness).

Because the ballistic performance of H-plates depends primarily on the performance of welded joints, the scope of the laboratory examination was extended beyond the base metal evaluation recommended by the Ordnance Advisory Committee, to include an evaluation of the effects of welding on base metal toughness. The composite Charpy impact test has shown considerable promise as a method for studying simultaneously the relative notch toughness of weld and heat-affected base metal.^{1,2} Therefore, the composite test was

¹HATCH, W. P. and HARTBOWER, C. E., "V Notch Charpy Impact Testing of Weld Metal and Heat-Affected Zone Simultaneously," WAL Report 401/220, 30 December 1955.

²HATCH, W. P. and HARTBOWER, C. E., "Toughness of Welds Evaluated Separately and in Composite," WAL Report 401/220-2, May 1958.

utilized in this part of the investigation to obtain transition curves for the two major components of welds, together with low-blow impact testing to determine the location of crack initiation and mode of fracture propagation in the composite structures of welded specimens. Because of funding limitations, only one weld-metal type was investigated, viz., ferritic Grade 230.

BASE METAL EXAMINATION

Chemical Analyses

Chips for wet chemical analyses of the three armor base metals were machined from test pieces sectioned from H-plates.

Composition (Weight %)									
Type	C	Mn	Si	S	P	Ni	Cr	Mo	V
Ni-Cr	.30	0.19	.11	.020	.006	2.73	1.43	.08	Trace
Ni-Cr-Mo	.28	1.25	.27	.020	.017	0.76	0.68	.34	Trace
Mn-Mo	.28	1.56	.18	.017	.014	Trace	0.02	.47	Nil

As can readily be seen from the above data, three widely different armor base metal compositions were involved. The armor chemistries were considered representative of composition types and no unusual variations in element amounts were noted.

Macro and Microexamination

Specimens for macroexamination were machined from test sections of the armor base metals in both the longitudinal and transverse directions. Orientation with plate rolling direction was accomplished by machining specimens parallel or perpendicular to the H-plate leg welds.

The macrospecimens were etched in a hot 38% HCl -12% H_2SO_4 -50% H_2O acid solution at 170°F. Photographs showing the macrostructure in cross sections through thickness of the armor plates are presented in Figure 4. All three materials were apparently cross-rolled in the reduction to 1" plate. The macrostructure of the Mn-Mo and the Ni-Cr plates was considered typical of good quality rolled armor whereas centerline nonmetallics in the Ni-Cr-Mo plate were considered excessive for an average degree of cleanliness desired in quality armor. However, there did not appear to be any detrimental effect from this condition in the H-plate tests.

Specimens from all three armor steels were examined microscopically at X100 and X1000 magnification after polishing and etching with a 4% picral reagent. Reproductions of photographs of typical microstructures are included in Figure 5. At 100X magnification both the Mn-Mo and Ni-Cr-Mo appeared quite similar with a scattered distribution of fine elongated nonmetallics in what is seen as a uniformly dark-etching two-constituent field of microstructures. The uniformity of etching indicated an economical

PARALLEL TO WELD

PERPENDICULAR TO WELD



Mn-Mo



Ni-Cr-Mo



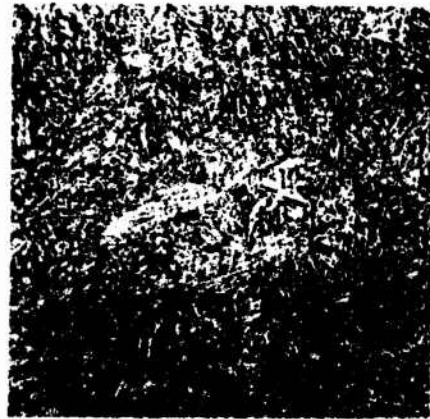
Ni-Cr



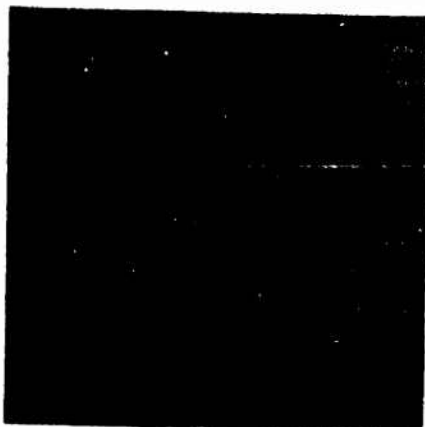
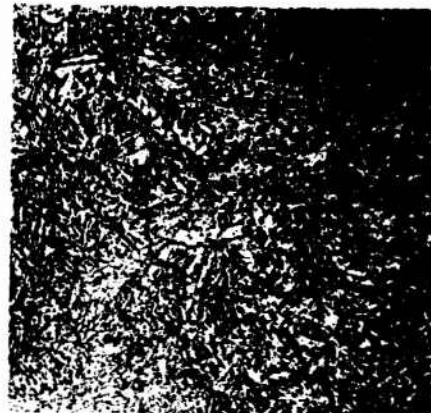
FIGURE 4: MACROSTRUCTURES THROUGH THE THICKNESS OF THE H-PLATE ARMOR BASE METALS
(X1 Magnification)



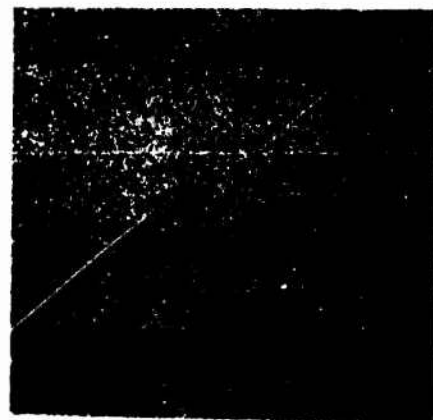
Mn-Mo



Ni-Cr-Mo



Ni-Cr



X100

X1000

FIGURE 5: MICROSTRUCTURES OF THE H-PLATE ARMOR BASE METALS (Picraml Etch).

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homogeneous distribution of the alloying elements. At higher magnification both microstructures were seen to consist of tempered martensite and tempered bainite with somewhat larger amounts of bainite in the Mn-Mo composition.

Unlike the other armors, the Ni-Cr armor etched irregularly in a banded structure as seen at 100X magnification in Figure 5. Some banding was also evident at 1000X in the microstructure of tempered martensite. The presence of discrete rounded carbides evident at the higher magnification were indicative of tempering cycles involving higher temperatures and/or longer times than those for the Mn-Mo and Ni-Cr-Mo armors.

Hardness Tests

Brinell and Rockwell hardness traverses were taken across a section through the thickness of each of the armor steels. The Rockwell results obtained are presented in Figure 6 and Table IIIA (appended). No evidence of excessive variations between hardnesses from surface to center which might result from improper heat treating procedures were noted. Test results indicated average hardnesses for the Mn-Mo and Ni-Cr-Mo armors at 355 to 360 BHN (39.8 to 39.9 R_c) against 255 BHN (25.7 R_c) for the Ni-Cr armor. The characteristic hardness levels which are evident were one of the major differences known to exist between the two types of armor. The reasons for the wide difference in hardness are directly associated with different service requirements for protection against ballistic penetration. Nevertheless, the wide separation in hardness level of armor types complicated direct comparison of performance in this investigation.

Charpy Impact Transition Tests

V notch Charpy impact specimens were machined from plate samples in both longitudinal and transverse directions. The specimens were taken from midthickness of the one-inch plates and were notched perpendicular to the plane of plate surface. Transition curves obtained from testing the specimens over a range of temperatures are presented in Figure 7. From comparison of the two curves for each material it can readily be seen that only the Ni-Cr armor exhibits marked directionality properties. No attempt was made to determine cause of the directionality which is usually associated with mill practices.

Because of the wide separation between hardnesses of the two types of armor, comparison based on a given impact-energy level favors the lower hardness material. Nevertheless, comparisons based on the relative positions of the transition curves with respect to temperature indicate the Ni-Cr armor to be superior in toughness since its entire transition occurred below -40° . The impact requirement of Specification MIL-A-12560 for transverse specimens from armor at 361 Brinell hardness is 15 ft-lb at -40° . Figure 7 shows that the Mn-Mo armor with an impact level of 11 ft-lb at -40° failed to meet minimum impact requirements while the Ni-Cr-Mo armor just met the minimum requirements with 16 ft-lb average impact energy. An energy requirement applicable to the low hardness Ni-Cr armor is indeterminate. However, it is evident that impact-wise neither the Mn-Mo nor the Ni-Cr-Mo armor approached the toughness of the Ni-Cr armor.

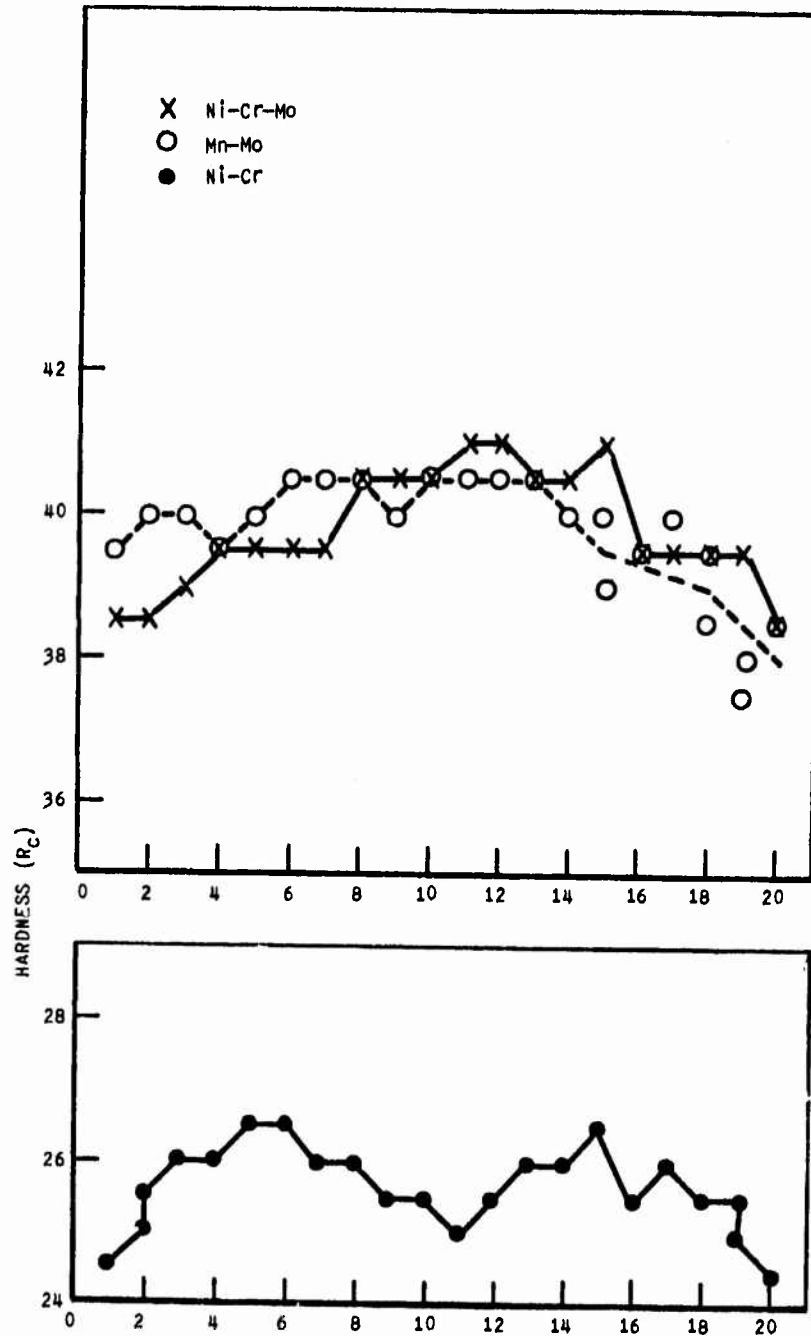


FIGURE 6: HARDNESS THROUGH CROSS-SECTION OF THE ONE-INCH THICK ARMOR BASE METALS.

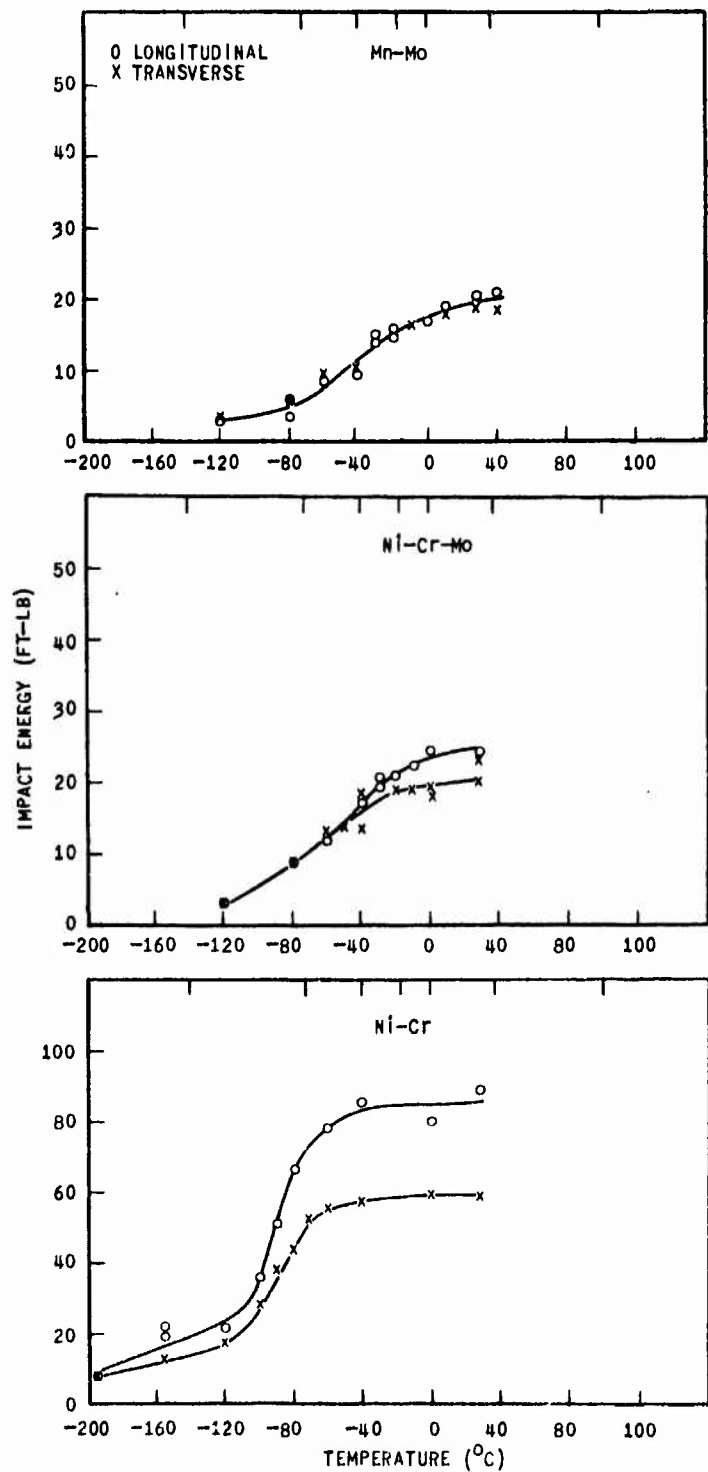


FIGURE 7: V NOTCH CHARPY IMPACT TRANSITION CURVES FOR THE H-PLATE ARMOR BASE METALS.

It should be emphasized again that in evaluating these results a direct comparison of impact properties in the two types of armor may be somewhat arbitrary because of basic differences in chemistry and hardness between the materials. The relatively inferior impact in the Mn-Mo and Ni-Cr-Mo armors is largely the result of high hardness (for greater resistance to projectile penetration) and lean chemistries (imposed as an alloy conservation measure). Nevertheless, experience indicates that for adequate armor toughness, the impact energy at the lowest anticipated service temperature must approach the maximum level attained at the upper plateau in a V notch Charpy transition curve. Therefore, it appears that the low hardness Ni-Cr armor has a distinct advantage over the high hardness Mn-Mo and Ni-Cr-Mo armors from the standpoint of toughness at -40° .

WELDING TESTS

Composite Test Procedure

Examination of the ballistic H-plate firing records* revealed that cracking in every case had originated near the point of impact either in or just adjacent to the weld metal. Since the welded joints appeared to be critical areas for origin of cracking, tests designed to yield information on the relative notch toughness of weld and heat-affected base metal were considered highly desirable.

The composite Charpy impact test developed at Watertown Arsenal Laboratories has been found to be a useful tool for studying the effects of welding (see References 1 and 2). The test consists of a weld deposited in a groove machined in the surface of a test plate (Figure 8). Charpy impact specimens are machined from the welded test plate in such a manner that the cross-section under the notch consists of approximately equal areas of weld metal and heat-affected base metal. Measurements of the lateral deformation occurring in test specimens broken over a range of temperatures yield two transition curves indicating the relative notch toughness of weld and heat-affected base metal.

An innovation was introduced in these tests in order to obtain the maximum number of specimens from a single test plate. Welds were deposited in grooves machined opposite one another in two surfaces of the 1" thick plates. Composite specimens were machined from locations at either side of midthickness in the 1" plate thus doubling the number of specimens available from one test plate. With this procedure the test plate illustrated in Figure 8 represents one of two test pieces lying at either side of the thickness centerline in 1" plate.

Each weld was deposited in two passes using Grade 230 electrodes of the low-hydrogen ferritic type covered by Specification MIL-E-986. The Grade 230 weld metal was selected in that it was the only electrode type which had

*Aberdeen Proving Ground No. AR-19953 and AR-20512.

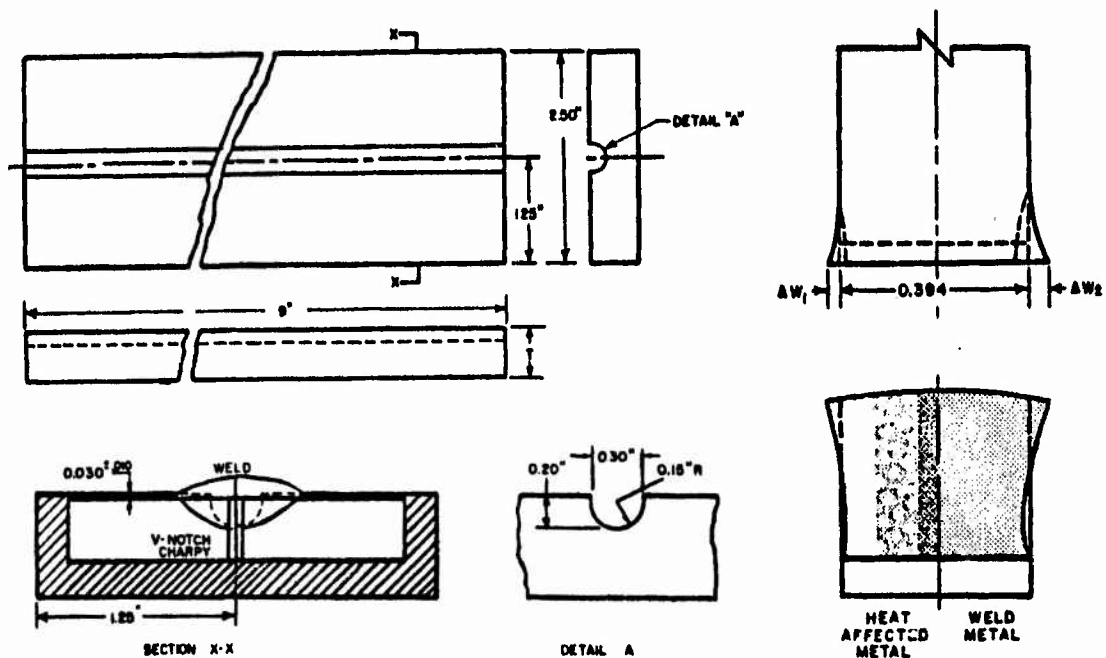


FIGURE 8: COMPOSITE CHARPY IMPACT TEST - illustration shows the test plate, orientation of test specimen, and lateral expansion in a fractured test specimen.

been used in fabricating H-plates from all three base metals. Welding conditions duplicating as closely as possible those for the first two passes in the H-plates were used in producing each test plate weld.

Composite Test Results

The lateral deformation transition curves for weld metal and heat-affected base metal in composite specimens are presented in Figure 9.* In this illustration a difference between the relative toughness of the Grade 230 weld metal and heat-affected base metals in the high and low hardness armor materials is readily evident. Heat-affected base metal in both the Mn-Mo and Ni-Cr-Mo armors, at least over the major part of the transition range, is indicated to be more notch sensitive than the weld metal. On the other hand, in composite tests with the Ni-Cr armor, the heat-affected base metal is indicated to be considerably less notch sensitive than the weld metal. By superimposing the weld-metal transition curves of Figure 9, it was noted that approximately the same transition curve was obtained irrespective of the base metal in which the weld metal was deposited. Thus, tough-

*Because impact energy values are not directly useful in determining relative notch toughness of weld and heat-affected base metal, the composite energy-temperature transition curves, obtained as a matter of course during fracture of the test specimens, have been appended for possible reference (see Figure 1A).

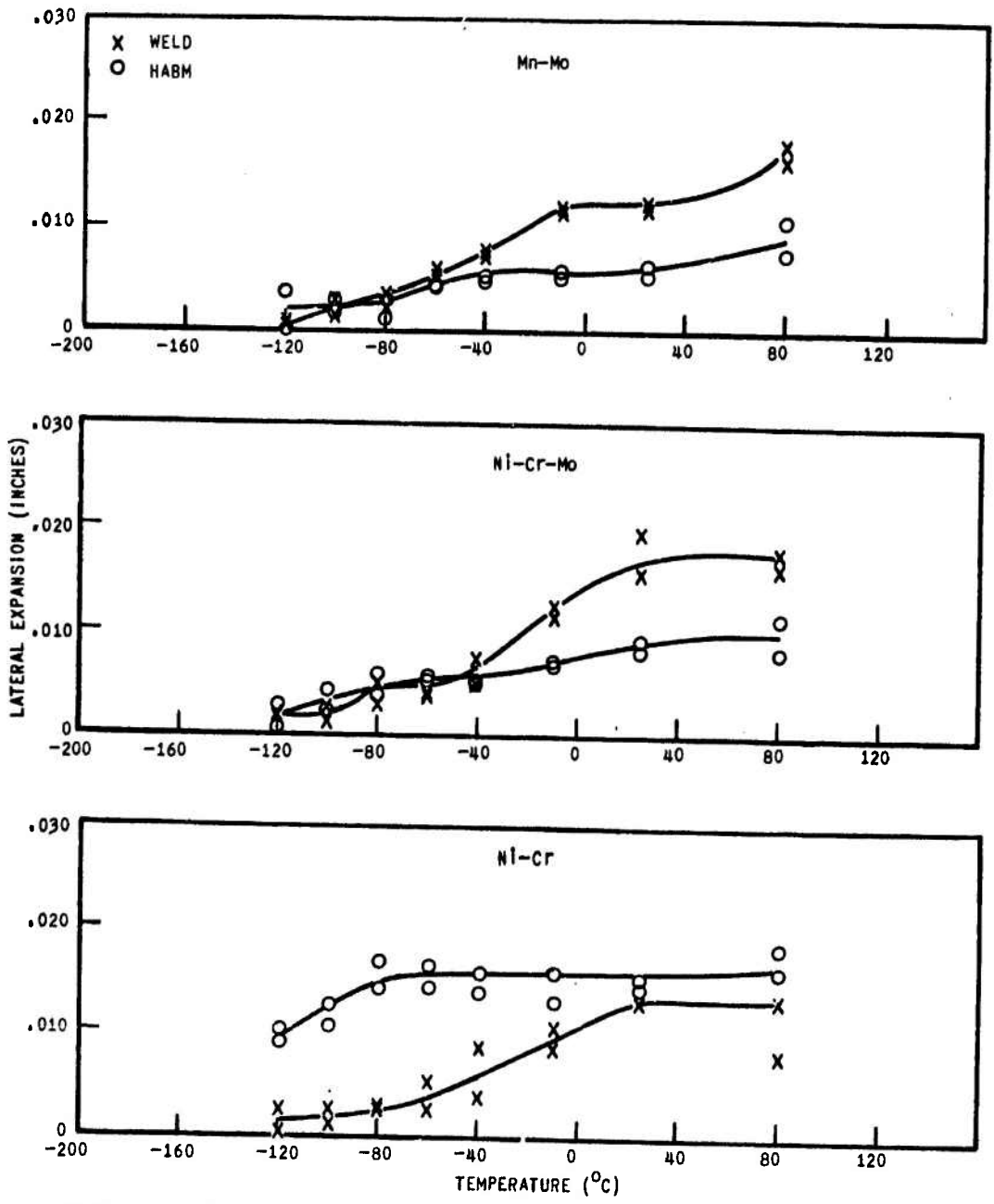


FIGURE 9: LATERAL DEFORMATION TRANSITION CURVES FOR COMPOSITE CHARPY IMPACT TESTS OF WELDS IN THE H-PLATE ARMORS.

ness of weld heat-affected zones in the low hardness armor was shown to be considerably better than in either high hardness armor.

Certain observations with regard to H-plate performance can be made from Figures 7 and 9. First, one might predict that weld-metal cracking rather than plate or heat-affected base metal cracking would occur in the Ni-Cr H-plates tested at -40°F . H-plate results were consistent with this prediction of no plate cracking; however, numerous cases of "fusion-zone" cracking were reported by Aberdeen Proving Ground. Such results are not necessarily inconsistent since "fusion-zone" cracking may indicate either heat-affected base metal or weld metal failures (see footnote on page 6).

Secondly, because of the low, rather flat, transition curves for the Ni-Cr-Mo and Mn-Mo plate and heat-affected base metals, extensive plate and heat-affected base metal cracking under ballistic shock might have been predicted. The prediction in one case appeared inconsistent with actual H-plate behavior in that no plate cracking occurred in the Ni-Cr-Mo armor; however, all rounds fired produced some fusion-zone cracking. The Mn-Mo armor performed as might have been predicted in that all rounds fired produced excessive plate cracking. In connection with these results it should be recalled from Figure 7 that the Ni-Cr-Mo steel had somewhat higher impact energy values than the Mn-Mo armor at -40° . Apparently, the greater toughness of the Ni-Cr-Mo base plate was reflected in the comparative H-plate performance.

Following from the above, a third observation might have been made; viz., that because of greater toughness of both base plate and heat-affected base metal, better over-all resistance to ballistic shock would be expected with the Ni-Cr armor than with either the Mn-Mo or Ni-Cr-Mo armor. The H-plate test results could not be used satisfactorily to determine the consistency of the latter observation because excessive leg cracking occurred in both the Ni-Cr and Ni-Cr-Mo H-plates welded with the Grade 230 electrodes. However, the observation was consistent with results in the Mn-Mo armor where excessive plate cracking occurred due to lack of toughness in the base metal.

Low-Blow Tests

In connection with the lateral deformation transition curves obtained with composite specimens, it should be noted that the curve for heat-affected base metal represents an integration of a gamut of structures of varying strength, hardness, and toughness levels. Thus, "low-blow" impact testing (see References 1 and 2 on page 7) was employed to determine which of the weld heat-affected-zone structures was the most notch sensitive.

The low-blow procedure consisted of striking each specimen with a low-energy impact blow so as to just initiate cracking without complete fracture of the test specimen. The desired magnitude of low blow was obtained by swinging the pendulum of a standard impact testing machine from a calculated intermediate height. Following the initial blow the specimens were stained with india ink containing a wetting agent which resulted in the liquid being drawn into the initiated crack by capillary action. After allowing time for

the ink to dry, the specimens were fractured with a single full-capacity impact blow. Ink staining on the fracture face of the specimens indicated the location and extent of cracking occurring from the initial blow.

Figure 10 shows results of tests conducted with 10 and 20 ft-lb initial blows at room temperature on composite specimens of each of the three armor materials. Absence of ink staining on specimens struck with a 10 ft-lb initial blow indicated that such a low blow was not sufficiently severe to initiate a crack. On the other hand, ink staining on specimens struck a 20 ft-lb initial blow showed not only initiated cracking but extensive propagation at certain locations.

In connection with the fracture mechanics of composite specimens it should be noted from Figure 10 that the ink staining was not symmetrical with respect to the centerline (midwidth) of the specimens. Thus, it must be concluded that the location of crack initiation and propagation was determined by the greater notch sensitivity of certain structures in the welded specimens rather than by geometrical considerations.

From Figure 10 it can be seen that the notch-sensitive structures were in the heat-affected base metal side of the test specimens in both the Mn-Mo and Ni-Cr-Mo armors; whereas, crack propagation occurred primarily in the weld-metal side of the composite specimens in the Ni-Cr armor. Thus, the ink staining on the fracture surfaces of specimens impacted with a 20 ft-lb blow was consistent with the relative notch toughness of weld and heat-affected base metals as indicated by the deformation-temperature transition curves of Figure 9.

The location of the most notch sensitive structures in which cracking initiated were indicated by the leading edge of the ink staining as shown in Figure 11. The most notch-sensitive structures in the Mn-Mo and Ni-Cr-Mo armors occurred in the heat-affected base metals between .045 and .070 inch from the fusion line in the Mn-Mo steel and between .020 and .080 inch from the fusion line in the Ni-Cr-Mo steel. In both cases ink staining occurred in heat-affected zones produced by the first weld pass. The most notch-sensitive structures in the composite specimen of the Ni-Cr armor were located in the weld metal (first pass of the two-pass weld) and in heat-affected metal just adjacent to the fusion line (within a distance of .020 inch). Moreover, ink staining in the composite specimen of the Ni-Cr armor occurred in the heat-affected zone of the second weld pass.

Note from the photomicrographs in Figure 11 that in all cases the most notch-sensitive regions occurred around the outer boundary of darkly etching heat-affected zones. The structures in these areas are the products of incomplete transformation resulting from short-time thermal cycles having peak temperatures in or near the range of critical transformation temperatures. Notch sensitivity in these regions has been noted previously in research on weld heat-affected zones in armor steels at Rensselaer Polytechnic Institute.^{3,4}

³ NIPPES and GERKEN, Rensselaer Polytechnic Institute Contract No. DA-30-115-ORD-490, WAL 112/86, Interim Reports Nos. 1 and 3.

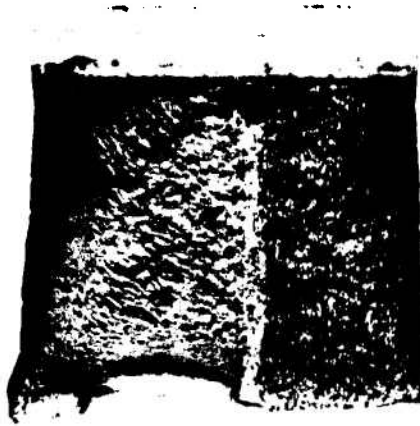
⁴ Rensselaer Polytechnic Institute Contract DA-30-115-505-ORD-782, Final Report, WAL 310/208-2.

WELD METAL

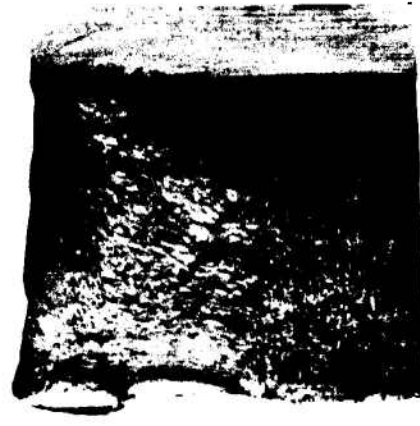
BASE METAL

WELD METAL

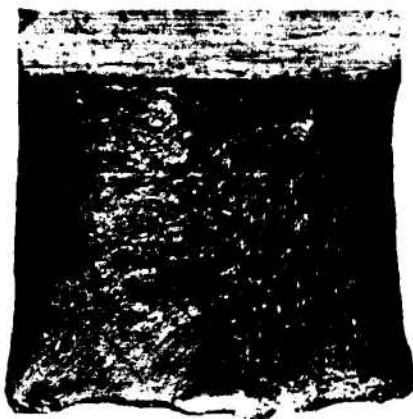
BASE METAL



Mn-Mo



Ni-Cr-Mo



Ni-Cr



10 FT-LBS

TESTS AT ROOM TEMPERATURE

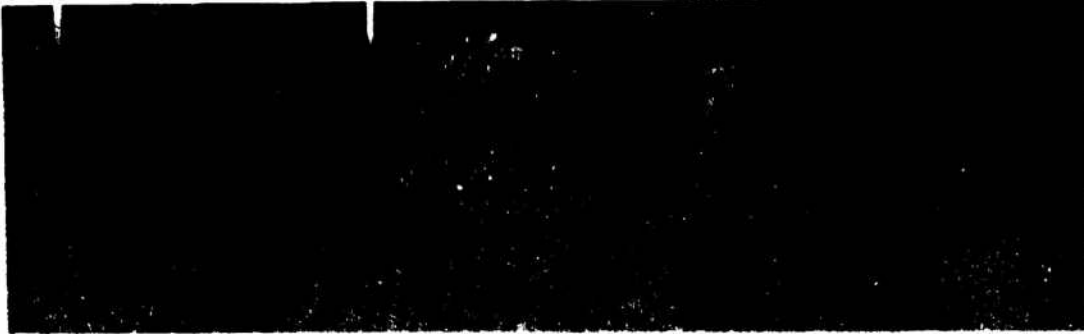
20 FT-LBS

FIGURE 10: LOW-BLOW TESTS OF COMPOSITE SPECIMENS OF WELDS IN THE H-PLATE ARMORS - ink stain pattern shows cracking initiated by low-blow. Location of most sensitive structures is indicated by the leading edge of the ink stain.

BASE METAL



WELD METAL



Mn-Mo

BASE METAL



WELD METAL



Ni-Cr-Mo

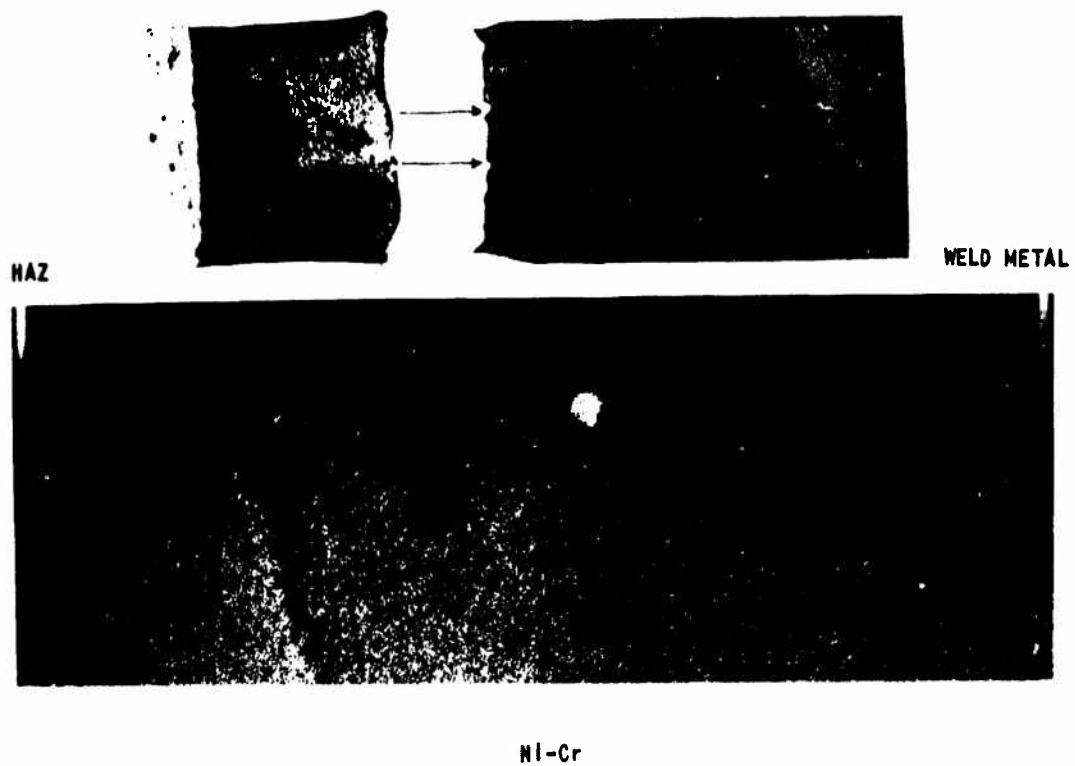


FIGURE 11: LOCATION OF MOST NOTCH-SENSITIVE MICROSTRUCTURES IN COMPOSITE SPECIMENS -
Arrows indicate the metallurgical structures at locations corresponding with the
point of deepest penetration of cracking in low-blow tests.

In their recent work the transition temperatures of heat-affected-zone structures produced by thermal cycles having peak temperatures in the intercritical range were shown to be more than 150°C (270°F) higher than those of the unwelded base metals.

The reason for the difference in location of the most notch-sensitive structures in the first-pass heat-affected base metal in the Mn-Mo and Ni-Cr-Mo armors as opposed to the second-pass heat-affected weld metal and base metal in the Ni-Cr armor was not investigated. The problem of studying metallurgical effects produced by a gradient of thermal cycles associated with welding is too complex to have been included in the scope of this report. The superior toughness of the Ni-Cr armor as compared with weld metal was undoubtedly involved. However, in the photomicrograph of the Ni-Cr armor in Figure 11 it can be seen that the darkly etching heat-affected zone produced by the first weld pass appears to have been almost obliterated by the second weld pass. In the Mn-Mo and Ni-Cr-Mo armors the darkly etching first-pass weld heat-affected zones are still visibly evident in the photomicrographs. Since the times and peak temperatures of thermal cycles produced by welds deposited with a given procedure should have been essentially the same in all materials, it appears that differences between metallurgical characteristics of the heat-affected-zone structures in the different types of armors may also have been involved.

The metallurgical structures at locations corresponding to the deepest penetration of cracking are shown in the photomicrographs in Figure 11. The photographs were taken at the edge of fracture in the specimens which had been machined to a plane just below the base of the notch and normal to the fracture face. The deep rounded depressions along the fracture edge at or between the arrows are reference impressions filed into the specimens to locate the point of crack initiation. The photomicrographs for the Mn-Mo and Ni-Cr-Mo armors include a panorama of the heat-affected zone from the weld metal at the extreme right-hand side to base metal beyond the darkly etching heat-affected-zone structures at the left. The photomicrograph for the Ni-Cr specimen includes a panorama of the weld metal deposited with the first pass and the heat-affected zone adjacent to the fusion line. The outer limit of the darkly etching heat-affected zone produced by the thermal cycles of the second weld pass is at the extreme left in the illustration.

The photomicrographs of the Mn-Mo and Ni-Cr-Mo armors in Figure 11 are indicative of the problem of evaluating weld heat-affected zones. The entire gamut of structures from the fusion line at the right to the white areas just inside the arrows at the left occurred in a band approximately 1/16" wide in the actual welds. The metallurgical structures existing in this narrow band correspond to thermal cycles having a gradient of peak temperatures between approximately 1200° and 2700°F. Thus, unless the leading edge of the ink staining crack is pointed, as in the Mn-Mo specimen, it can safely be assumed only that the most notch-sensitive structures occur somewhere within the width of the leading edge of the crack. The relatively flat leading edge of ink staining in both the Ni-Cr-Mo and Ni-Cr armor specimens illustrate this problem. However, as noted previously, one common denominator in this study was the fact that the structures produced by thermal

cycles with peak temperatures in the intercritical range occurred within the leading edge of ink staining in all three materials. Thus, at least for the Mn-Mo and Ni-Cr-Mo armors, it appears that the most notch-sensitive structures may be produced by the welding thermal cycles associated with incomplete transformations.

A number of low-blow tests of composite specimens in each material were conducted, using a 15 ft-lb initial blow, over a range of temperatures to determine the effect of temperature on the extent and location of initial cracking. Similarity of performance in composite specimens of both the Mn-Mo and Ni-Cr-Mo armors is evident in Figures 12 and 13. Note that in each case cracking was more extensive in heat-affected base metal at temperatures down to -40°C . At approximately -50°C cracking became considerably more extensive in both weld and heat-affected base metal, and at -70°C the specimens fractured under the initial low blow.

Performance of composite specimens in the Ni-Cr armor is shown in Figure 14. Ink staining indicated that the weld metal was more notch sensitive than the heat-affected base metal. At approximately -60°C an increase in stained area at the weld-metal side of the test specimen indicated a transition. Note that the ink staining extended even to the free surface at the side of the specimen indicating that the weld metal deposited in the second pass was also crack-sensitive at this temperature. A similar transition for the heat-affected base metal occurred at approximately -90°C . At -100°C the composite specimen fractured under the initial low blow.

DISCUSSION

Composite Test Results

The principle objective of the composite tests was to determine whether the test results could be used for predicting H-plate performance. Two outstanding results obtained in this investigation were significant in this respect. First, the reversal of positions in lateral deformation transition curves left little doubt as to the relative notch toughness of weld metal and heat-affected base metal in the different type armors. Secondly, the reversal about the fusion line of ink staining in the low-blow tests of composite specimens offered conclusive evidence on whether the weld metal or heat-affected zone was predominant in determining initial location of cracking.

Low-blow testing indicated crack-propagation transitions (temperature at which decisive increase in ink staining under low-blow occurred) as follows:

Base Metal	Transition Temperature ($^{\circ}\text{C}$)	
	Weld Metal	Heat-Affected Zone
Mn-Mo	-50 to -60	-50 to -80
Ni-Cr-Mo	-50 to -70	-50 to -70
Ni-Cr	-40 to -80	-80 to -90

WELD METAL

BASE METAL

WELD METAL

BASE METAL



0°C



-40°C



-20°C



-50°C



-30°C



-60°C

FIGURE 12: CRACK PROPAGATION IN LOW-BLOW TESTS OF COMPOSITE SPECIMENS WITH THE Mn-Mo ARMOR - Specimens impacted with 15 ft-lb initial blow at temperature shown.

Wtn. 689-16, 381

WELD METAL

BASE METAL

WELD METAL

BASE METAL



0°C



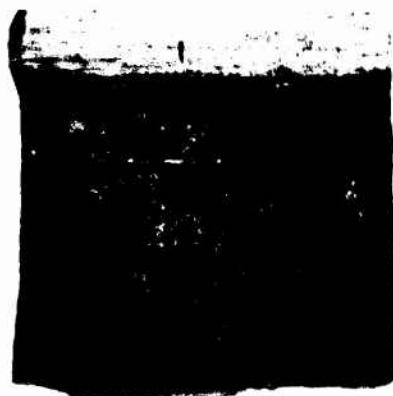
-20°C



-40°C



-60°C



-80°C



-100°C

FIGURE 13: CRACK PROPAGATION IN LOW-BLOW TESTS OF COMPOSITE SPECIMENS WITH THE NI-CR-MO ARMOR - Specimens impacted with 15 ft-lb initial blow at temperature shown.

WELD METAL

BASE METAL

WELD METAL

BASE METAL



0°C



-60°C



-20°C



-80°C



-40°C



-90°C

FIGURE 14: CRACK PROPAGATION IN LOW-BLOW TESTS OF COMPOSITE SPECIMENS WITH THE NI-Cr ARMOR - Specimens impacted with 15 ft-lb initial blow at temperature shown.

These results indicate that the temperature of -40° at which the H-plate tests were conducted was very close to the transition from ductile to brittle behavior for the weld metal as well as for heat-affected base metal in both the Mn-Mo and Ni-Cr-Mo armors. Thus, the excessive cracking occurring in the H-plates of these armors probably resulted from ballistic testing near the transition temperatures. However, unlike the Mn-Mo armor in which cracking propagated extensively in the base metal, crack propagation in the H-plates of Ni-Cr-Mo armor occurred entirely in the weld and heat-affected-zone structures. Apparently the Ni-Cr-Mo armor base metal had sufficient toughness to resist crack propagation at the H-plate testing temperature. This performance was consistent with the impact test results (see Figure 7) in which slightly lower transition temperatures were observed for the Ni-Cr-Mo armor than for the Mn-Mo armor. Thus, in the Ni-Cr-Mo armor, H-plate cracking occurred as leg cracking in weld metal or heat-affected (fusion-zone) structures which were more notch sensitive than the base plate.

The correlation between composite low-blow tests and H-plate behavior in the Ni-Cr armor was less apparent since the firing records indicated extensive "fusion-zone" cracking. The low-blow results in Figure 14 indicated notch sensitivity in weld metal at -40° to -60°C . However, in Figure 11 the most notch-sensitive structures included heat-affected base metal contiguous to the fusion line. These results appear consistent with the H-plate performance although the degree of correlation is indeterminate without extensive study of H-plate cracking to determine location of initiation and propagation.

Exact correlation of low-blow composite results with H-plate performance was not anticipated since not only was detailed macroscopic or microscopic information pinpointing crack initiation and the location of original propagation in the ballistic test plates lacking, but also because the laboratory tests involved different electrodes and welding procedures. However, from the applicable sketches in the Aberdeen Proving Ground Firing Records, excellent correlation of composite and H-plate results is indicated since H-plate cracking in every case appeared to initiate either in weld metal or heat-affected-zone structures contiguous to the fusion line. The composite test results not only indicated notch sensitivity around the fusion line but, moreover, pinpointed the location of the most notch-sensitive structures. Further studies are required to determine whether composite test results have reproducible significance correlating with the critical locations for crack initiation in actual welded joints. It is recommended that such studies be included whenever possible in future programs on evaluation of the toughness in welded joints.

CONCLUSIONS

Interpretation of H-plate test results was complicated by the unknown effects of material hardness and toughness on weldment performance. The wide differences in chemical composition and hardness which are characteristic of different types of armors were evident in this investigation. However, in the laboratory tests which were conducted, correlation was found between

toughness in V notch Charpy impact tests and H-plate ballistic performance. The relative performance of the armor base metals was consistent with toughness as determined from Charpy impact transition curves. Composite impact tests provided an indication of the relative toughness of welds in the three armor base metals. Furthermore, the composite results appeared to correlate with location of crack initiation and temperatures corresponding to start of crack propagation for the H-plate conditions investigated.

APPENDIX A

TABLE IA

SUMMARY OF H-PLATE CRACKING

Plates Tested at -40°F with 57MM M1001 Plate Proofing Projectiles

Base Metal	Electrode	No. of Plates Tested	No. of Rounds Fired	Back Cracking (inches)			
				Weld Metal	Fusion Zone	HAZ	Plate
Mn-Mo	El-307	6	8	-	42	6	142
	Gr-230	3	4	4	20	-	115
Ni-Cr-Mo	Gr-230	3	5	112	31	-	-
Ni-Cr	El-307	3	10	1	46	-	-
	Gr-230	3	7	27	111	7	-
	Gr-260	3	7	40	37	3	-

TABLE IIA

CRACKING IN H-PLATES WELDED WITH GRADE 230 ELECTRODES

Plates Tested at -40°F with 57MM M1001 Plate Proofing Projectiles

Plate No.	Base Metal	Round No.	FRONT (inches)				BACK (inches)			
			Weld Metal	Fusion Zone	HAZ	Plate	Weld Metal	Fusion Zone	HAZ	Plate
N1	Mn-Mo	1	-	2	-	10	-	5	-	8 1/2
			21	-	-	18				
N4D	Mn-Mo	1	3	-	-	19	-	-	-	5 1/2
			4 1/2	-	-	13 1/2	-	-	-	18
			7 1/2	-	-	5	-	-	-	8
N5D	Mn-Mo	2	11	-	-	4	4 1/2	8	-	5
			7	-	-	8	-	-	5	
N6D	Mn-Mo	1	6	-	-	17	-	7	-	17
			14	-	-	14	-	-	14	
Total			20	2	-	110	4 1/2	20	-	115 1/2
NA4	Ni-Cr-Mo	1	36	-	-	-	32	4	-	-
NA5		1	13	-	4	-	4	13	-	-
		2	31	5	-	-	28	8	-	-
NA6		1	4	12	-	-	15	3	-	-
	2	36	-	-	-	33	3	-	-	
Total			120	17	4	-	112	31	-	-
86H1	Ni-Cr	1	4	3 1/2	10 1/2	-	1 1/2	19 3/4	-	-
		2	6 1/2	-	2 1/2	-	-	18	-	-
86H2	Ni-Cr	1	13	-	7	-	-	14	7	-
		2	18 1/2	-	-	-	21	-	-	-
86H3	Ni-Cr	1	-	11	-	3 1/2	-	12	-	-
		2	-	13	-	2	-	16	-	-
		3	31	5	-	-	5	31	-	-
Total			73	32 1/2	20	5 1/2	27 1/2	110 3/4	7	-

TABLE IIIA
HARDNESS THROUGH THICKNESS OF ARMOR BASE METALS

	Mn-Mo			Ni-Cr-Mo			Ni-Cr		
	Rc	BHN*	BHN**	Rc	BHN*	BHN**	Rc	BHN*	BHN**
1	39.5			38.5			24.5		
2	40.0	352		38.5	341		25.5	255	
3	40.0			39.0			28.0		
4	39.5		330	39.5		342	26.0		242
5	40.0			39.5			26.5		
6	40.5	363		39.5	375		26.5		
7	40.5			39.5			26.0		
8	40.5		370	40.5		356	26.0		258
9	40.0			40.5			25.5		
10	40.5	363		40.5	375		25.5		
11	40.5			41.0			25.0		
12	40.5		370	41.0		370	25.5		258
13	40.5			40.5			26.0		
14	40.0	363		40.5	375		26.0		
15	40.0			41.0			26.5		
16	39.5		342	39.5		342	25.5		242
17	40.0			39.5			26.0		
18	39.5	341		39.5	341		25.5		
19	38.5			39.5			25.0	255	
20	38.0			38.5			24.7		
Aver.	39.9	356	352	39.8	361	353	25.7	255	250

*3000 Kg load
**2000 Kg load

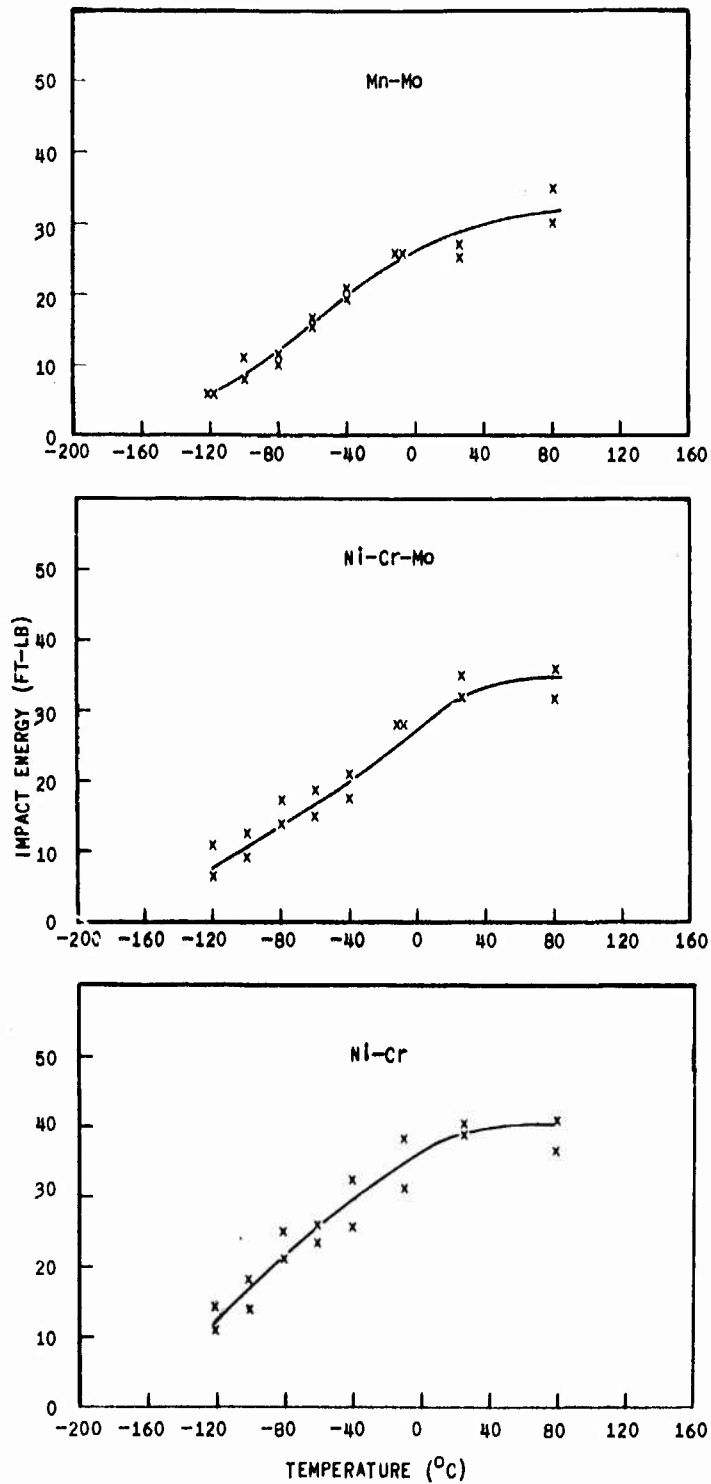


FIGURE 1A: IMPACT-ENERGY TRANSITION CURVES FOR COMPOSITE SPECIMENS OF WELDS IN THE H-PLATE ARMORS.

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