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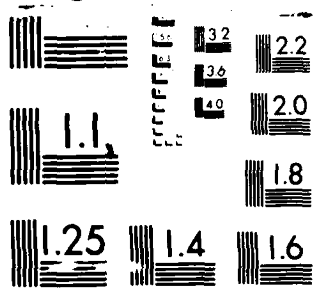

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SOME CORRELATIONS BETWEEN PLATE SHATTER AND FRACTURE TOUGHNESS

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February 1987

US ARMY
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: MTL TR 87-9

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): SOME CORRELATIONS BETWEEN PLATE SHATTER AND FRACTURE TOUGHNESS

5. TYPE OF REPORT & PERIOD COVERED: Final Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): Morris Azrin, John G. Cowie, Albert A. Anctil, and Eric B. Kula

8. CONTRACT OR GRANT NUMBER(s):
D/A Project: 1L162105AH84
AMCMS Code: 612105.H840011

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
SLCMT-TP

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS:
U.S. Army Laboratory Command
2800 Powder Mill Road
Adelphi, Maryland 20783-1145

12. REPORT DATE: February 1987

13. NUMBER OF PAGES: 14

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report):

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Cont'd

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

~~High strength steels~~	Transition temperature	Fracture toughness
Armor plate	Crack propagations,	Mechanical properties
Ballistic testing	Dynamic properties	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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ABSTRACT

Conventional ballistic evaluation of armor plate is based on a critical impact velocity for penetration. At high hardness levels and/or low temperatures, ballistic impact can give rise to extensive plate cracking whether or not penetration occurs. This report provides preliminary results on a test procedure to assess the plate cracking sensitivity of high strength steel armor plate. The procedure involves the introduction of a large flaw or crack starter at the center of a plate and then impacting the center of the opposite face with a soft, blunt-nosed projectile. The impact tests are performed over a range of temperatures to yield a plate shatter transition temperature. The PSTT is simply the highest plate temperature at which extensive plate shatter occurs. The influence of PSTT test parameters and correlation with fracture toughness are currently being studied.

INTRODUCTION

The penetration resistance of armor is based on the principle of a critical projectile impact velocity at which there is a 50 percent probability of penetration. This velocity, termed the "ballistic limit," is a function of the properties of the projectile, angle of incidence, as well as the properties of the target, including its thickness and test temperature. During the actual impact process, one or several armor defeat mechanisms may be operative; e.g., petalling, plugging, back spall, and piercing. The criterion for a "complete penetration," in terms of armor evaluation, is the existence of a hole created by either the penetrator or target material on an "aluminum witness plate" placed 15 cm behind the target. Thus, the ballistic limit does not distinguish between the various armor defeat mechanisms and, in fact, in the case of back spall, a penetration can be recorded without any penetrator material actually passing through or embedding the target.

At high hardness levels, and, particularly, at low test temperatures, ballistic impact can give rise to another phenomenon, namely, plate cracking or shattering. Plate cracking can occur whether or not there is a ballistic penetration (i.e., above or below the ballistic limit), and could render the plate useless as a structural element. In certain acceptance tests, for armor plate which is designed to stop small arms fire, the plate is in addition required to withstand impact by a heavier projectile without an extensive cracking (although penetration occurs). Examples where armor plate is satisfactory ballistically, but fails the acceptance test, particularly at low temperatures, are not uncommon.

Since the conventional test for ballistic limit does not adequately consider plate cracking or plate shattering, a program was designed to develop a test which could directly assess the plate cracking phenomenon. The test was based on the observation that when cracking or shattering occurs during a conventional test, it frequently does so in an erratic fashion. For example, in a target impacted sequentially by three projectiles in three separate areas, cracking could occur during the third impact, with the crack passing through the first impact area only. Examination of the cracked plate may show that the origin of cracking occurred not at the impact point, but at the edge of the plate which had been flame cut. Obviously, crack initiation at some defect or crack starter would be important in this instance and that once a crack is initiated, propagation could occur more easily. An additional important factor is the test temperature, since experience has shown that plate cracking occurs more readily at low temperatures. In this manner, any test for plate cracking should be akin to a Charpy test, where a series of notched test bars are broken over a temperature range to determine a ductile to brittle transition temperature.

The test selected involved impact of the target plate with a relatively soft, blunt-nosed projectile 20 mm in diameter, at a velocity just below the ballistic limit. Under these conditions, there is a considerable transfer of momentum to the plate, without the complicating effects of penetration. To control the location of the crack, and to minimize the influence of random flaws, a "crack starter" is placed on the rear surface of the plate at a location corresponding to the point of impact on the front face. This crack starter could take various forms. One type investigated consists of two intersecting welds, with a length of 5 cm, more than double the diameter of the projectile. Tests carried out on separate plates over a temperature range would give some indication of the cracking tendency of a given heat of steel in a given heat treatment. Using the same thickness plate and velocity of projectile, comparisons can be made of propensity to cracking of different steels.

Further steps would include attempting to relate the material's shatter resistance to other mechanical properties, such as some measure of fracture toughness. This could provide a more readily measurable parameter for prediction of cracking tendency. In addition, by the use of computer calculations, stress distributions could be determined so as to more adequately consider the variables of plate thickness, projectile size, and velocity.

EXPERIMENTAL PROCEDURES

Plate Shatter Tests

The plate shatter test consists of impacting a hardened steel target, containing a large preexisting flaw, with a relatively soft projectile. The flaw, acting as a "crack starter," is provided by two 5-cm long electron beam (EB) welds in the form of a cross at the center of a 300-mm square plate (Figures 1 and 2). These welds are located on the rear surface of the target (i.e., opposite the impact face).

Square plates (300 mm x 300 mm) with the thicknesses of 25, 13, and 6.4 mm were tested to determine the effect of thickness. A relatively soft projectile (HRB 78, 1018 steel) of 20-mm diameter and of 64-mm length was fired at a velocity just below that required for penetration of the target. The use of a soft projectile produced extensive mushrooming that decreased the possibility of penetration, but increased the momentum transfer to the plates. This subjected the plate to some bulging of the back surface, inducing a tensile stress across the EB weld.

A series of plates of the same material and thickness was tested over a range of temperatures so that the maximum temperature could be estimated below which extensive cracking occurs. This temperature, henceforth referred to as the plate shatter transition temperature (PSTT), can be considered a relative measure of resistance to cracking under ballistic impact. The PSTT test is analogous to the transition temperature in a Charpy impact test, or to the nil ductility transition (NDT) temperature test.[1,2] Both the PSTT and NDT tests measure a ductile-to-brittle transition temperature under dynamic loading while employing a weld bead as a crack initiator. The two tests differ in method and rate of loading, specimen geometry, and weld bead orientation and geometry. The most important distinction is that the PSTT test more closely simulates full-scale testing of armor plate.

A metallographic examination of several EB welds was necessary to determine the precise weld geometry and also the extent to which these welds act as crack starters. A cross section of a typical weld is presented in Figure 3. By averaging the measurements of the various welds, it was found that the melted region at the center of the weld extends approximately 2.0 mm into the thickness, whereas the heat affected zone extends approximately 3.0 mm into the thickness. The hardness profile, also shown in Figure 3, indicates that the white etched band of hard untempered martensite lies adjacent to a soft layer of overtempered martensite. A similar analysis was performed on a welded plate that had been ballistically tested but which exhibited no visible external cracks at the welds. However, metallographic examination revealed a hairline crack which propagated along the interface between the untempered martensite and the overtempered martensite, arresting within the

1. PELLINI, W. S. *Principles of Structural Integrity Technology.* Office of Naval Research, Arlington, VA, 1976, p. 96-102.
2. American Welding Society. *Standard Methods for Mechanical Testing of Welds.* ANSI/AWS B4.0-77, Miami, FL, 1979, p. 58.

heat affected zone at the base of the weld 2.5 mm from the back surface. This indicated that the weld bead did indeed function as an effective crack starter with a depth of 2.5 mm ± 0.5 mm.

Dynamic Toughness Tests

Mode I dynamic fracture toughness tests were performed for each material as a function of test temperature over the range 21°C to -73°C. Standard Charpy specimens were machined from the plates and subsequently precracked in fatigue to about 2.5 mm and dynamically tested in the manner described by Server and Tetelman.[3] They developed a method for determining the dynamic fracture toughness using precracked Charpy V notch specimens impacted with an instrumented hammer. Test results include the peak load and total fracture energy. The dynamic fracture toughness was calculated using the fracture mechanics equation for three-point bending of Charpy sized specimens.[4,5]

$$K_{Id} = \frac{1.5\, Ps(a)^{1/2}}{Bw^2}\left[1.93 - 3.12(a/w) + 14.68(a/w)^3 + 25.90(a/w)^4\right]$$

where
P = maximum load,
a = effective crack length (approximately 4.6 mm),
w = specimen width,
s = support span = 3.33w, and
B = specimen thickness.

MATERIALS

Two different electroslag remelted alloys were employed in the study; a conventional 4340 steel and a 3% nickel modification of 4340. Chemical compositions are presented in Table 1. Four slightly different heats of the 3% nickel modified 4340 steel, all with the same heat treatment, were tested to determine the effect of heat variation (Table 2). Mechanical property data (Table 3) indicated that of the four heats, two (54A and 53A) had generally superior properties to the other two (51B and 35). The conventional 4340 steel plates were all made from the same heat. The austenitizing and tempering temperatures were varied in order to determine the effect of heat treatment on the PSTT (see Table 2). The selection of heat treatments allows a distinction between the sharp crack fracture toughness (K_{Id}) and Charpy energy. It has been reported that increasing the austenitizing temperature can markedly increase the sharp crack fracture toughness with only a slight decrease in the Charpy energy.[6] The mechanical property data substantiate this phenomenon (Table 3). The tempering temperature was also varied at constant austenitizing temperature. The higher tempering temperature (above the tempered martensite embrittlement range) improves the fracture toughness while lowering the hardness (Table 3).

3. SERVER, W. L., and TETELMAN, A. S. *The Use of Pre-Cracked Charpy Specimens to Determine Dynamic Fracture Toughness* in Engineering Fracture Mechanics, v. 4, 1972, p. 367-375.
4. STRAWLEY, J., and BROWN, W. *Plane Strain Fracture Toughness Testing.* ASTM STP 410, 1966.
5. MADISON, R. B., and IRWIN, G. R. *Dynamic K_c Testing of Structural Steel* in Journal of the Structural Division, ASCE, 100, No. ST 7, Proc. Paper 10653, July 1974, p. 1331-1349.
6. RITCHIE, R. O., FRANCIS, B., and SERVER, W. L. *Evaluation of Toughness in AISI 4340 Alloy Steel Austenitized at Low and High Temperatures.* Met. Trans. A, v. 7A, 1976, p. 831-838.

RESULTS

Plate Shatter Tests

Each series of ballistic tests resulted in a transition temperature below which extensive cracking occurred and above which little or no cracking was observed. Extensive cracking is defined as fracturing the plate into two or more separate pieces, whereas little cracking is specified as fracture confined to within the weld area. The error for each PSTT estimate was determined from the temperature spread between the warmest plate fractured and the coldest undamaged plate. The average temperature of these two plates becomes the PSTT. The PSTT results, along with the number of ballistic tests performed for each series of plates, are presented in Table 4. In two instances (845/175 treatment and heat number 35), the plate shattered at room temperature resulting in a PSTT greater than 21°C. In a single instance (heat number 53A), no shattering was observed at its lowest ballistic test temperature for that series resulting in a PSTT less than -51°C. Two tests were performed at the same temperature, -34°C, for heat number 51B. One plate shattered while the other remained intact indicating a PSTT at that temperature. Extensive additional testing would be required before the normal "spread" or "error" associated with the PSTT can be determined.

Fractographic analysis was performed on one plate of each heat treatment of the 2.5-cm thick ESR 4340 steel series of fractured plates (see Figure 4). It was verified that the EB weld extended 2.5 mm ± 0.5 mm into the plate. The plates exhibited multiple fracture origins along the length of the weld bead, proving that the weld effectively functioned as a preexisting flaw. The crack then propagated rapidly from the weld to complete failure. The two plates austenitized at 845°C fractured in a transgranular mode, while the plate austenitized at 1205°C exhibited an intergranular fracture mode probably due to the larger prior austenite grains. Examination of the harder plates in Figure 4 (175°C temper) reveal the early stages of ballistic plugging failure mechanism due to adiabatic shear.[7,8] This band of localized shear lies beneath the area of impact. A shear band is often observed in high hardness alloys of low strain-hardening capacity.

Dynamic Toughness Tests

Dynamic fracture toughness as a function of test temperature is presented in Figures 5 and 6 for each of the conditions in Table 2. For those cases where sufficient tests were performed, there is a linear relationship between K_{Id} and test temperature. The PSTT (vertical arrow) is also plotted on the graphs. At this temperature, a value of the dynamic fracture toughness can be determined, which is associated with the conditions of the plate shatter test for each of the different materials (K_{Id} in Table 4).

A comparison of results given in Tables 3 and 4 shows that, in general, the PSTT varied inversely with both static and dynamic fracture toughness but showed no

7. ROGERS, H. C. *Adiabatic Shearing: A Review.* Drexel University Report prepared for the U.S. Army Research Office, 1974.
8. OLSON, G. B, MESCALL, J. F., and AZRIN, M. *Adiabatic Deformation and Strain Localization.* U.S. Army Materials Technology Laboratory, AMMRC TR 82-48, 1982.

DISCUSSION

Analysis of Tables 3 and 4 suggests several conclusions concerning the PSTT. There is no direct correlation of the PSTT with either room temperature Charpy impact energy or HRC hardness. However, the tendency is for heat treatments (ESR 4340 steel) which resulted in higher room temperature K_{Id} values to also produce lower and, hence, better PSTT's. This was expected since the metallography and fractography indicate that the EB weld acts as a sharp crack requiring very little fracture initiation energy. Therefore, fracture toughness, being a measure of resistance to crack propagation, better correlates with plate shattering than do results of Charpy tests which are also a measure of resistance to crack initiation.

Heat treatments significantly affected the PSTT. The 1205°C austenitizing treatment improved both the fracture toughness and PSTT over the 845°C austenitizing treatment given the same tempering treatment, consistent with toughness results previously reported.[6] Correspondingly, for two plates given the same austenitizing treatment, the one with a 470°C temper exhibited a lower hardness but improved fracture toughness and PSTT compared with the 175°C temper.

The above analysis is not intended as a basis for substituting fracture toughness evaluations for the direct approach of shatter sensitivity determinations using PSTT tests. However, valid correlations between PSTT tests and K_{Id} tests using slow bend precracked Charpy specimens would permit establishing shatter trends when only limited test material is available. The PSTT test is akin to that of performing hardness, strength, and toughness tests in addition to obtaining the ballistic limit of armor by actually firing projectiles to measure penetration velocity.

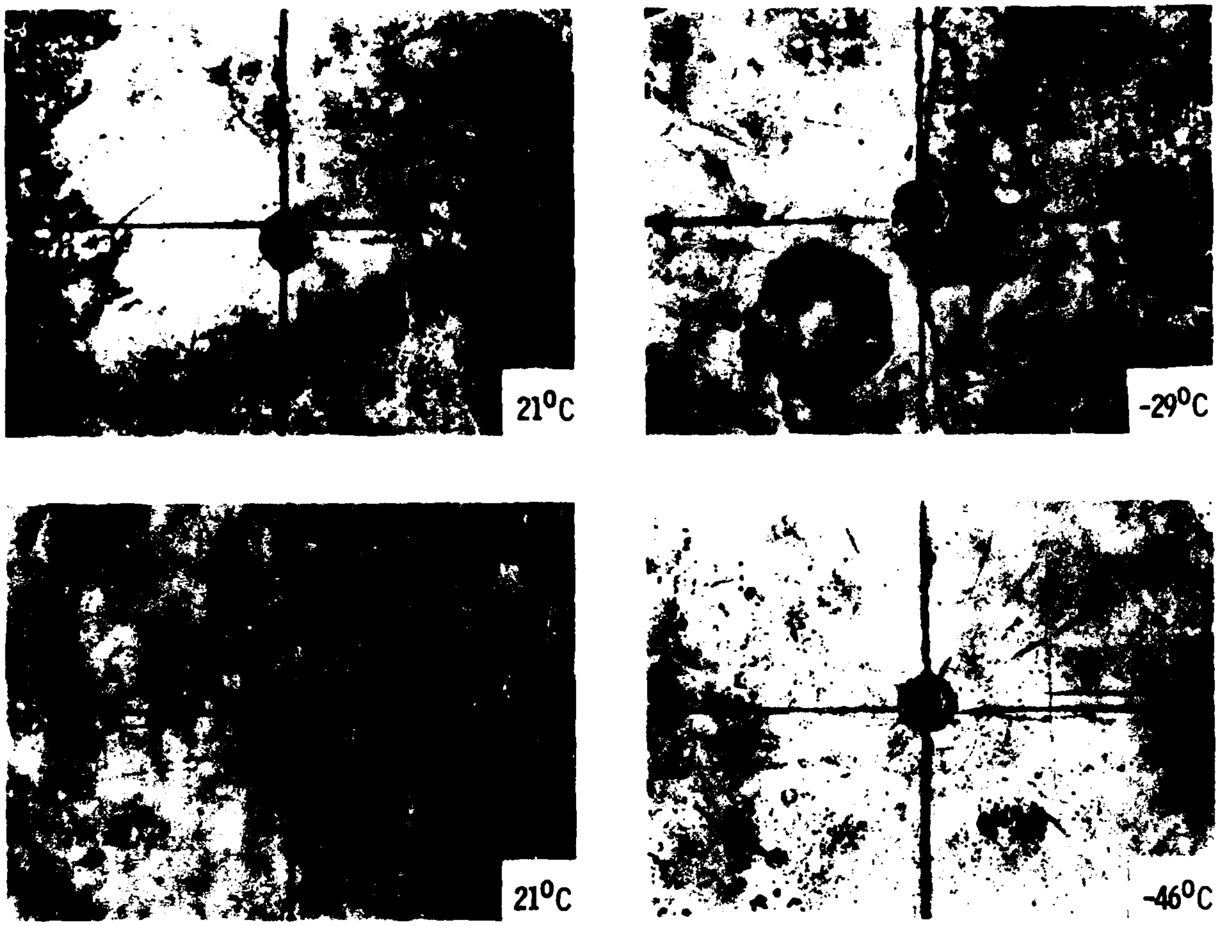
CONCLUSIONS

Metallographic and fractographic examination of ballistically impacted plates containing an electron beam weld revealed that crack propagation initiates at the EB weld. Based on these results, the EB weld is an effective crack starter and, therefore, for the purpose of the PSTT test, can be considered equivalent to a preexisting crack.

The PSTT test quantitatively determines a transition temperature below which extensive cracking occurs and above which little, if any, cracking is observed. Since the test conditions are not standardized, the test is, therefore, a relative measure of shatter sensitivity (or resistance).

Variations in heat treatment of high strength steel, even at a constant hardness level, can affect the resistance to shattering. High austenitizing temperatures significantly improve both fracture toughness and PSTT.

PSTT varied with sharp crack fracture toughness but displayed no correlation with either Charpy energy or hardness.



Front Surface

Figure 1. Ballistic impact test on 25-mm ESR 4340 steel armor plate with an E.B. weld crack starter. Plates austenitized at 1205°C, tempered at 175°C. Projectile velocity = 850 m/s.

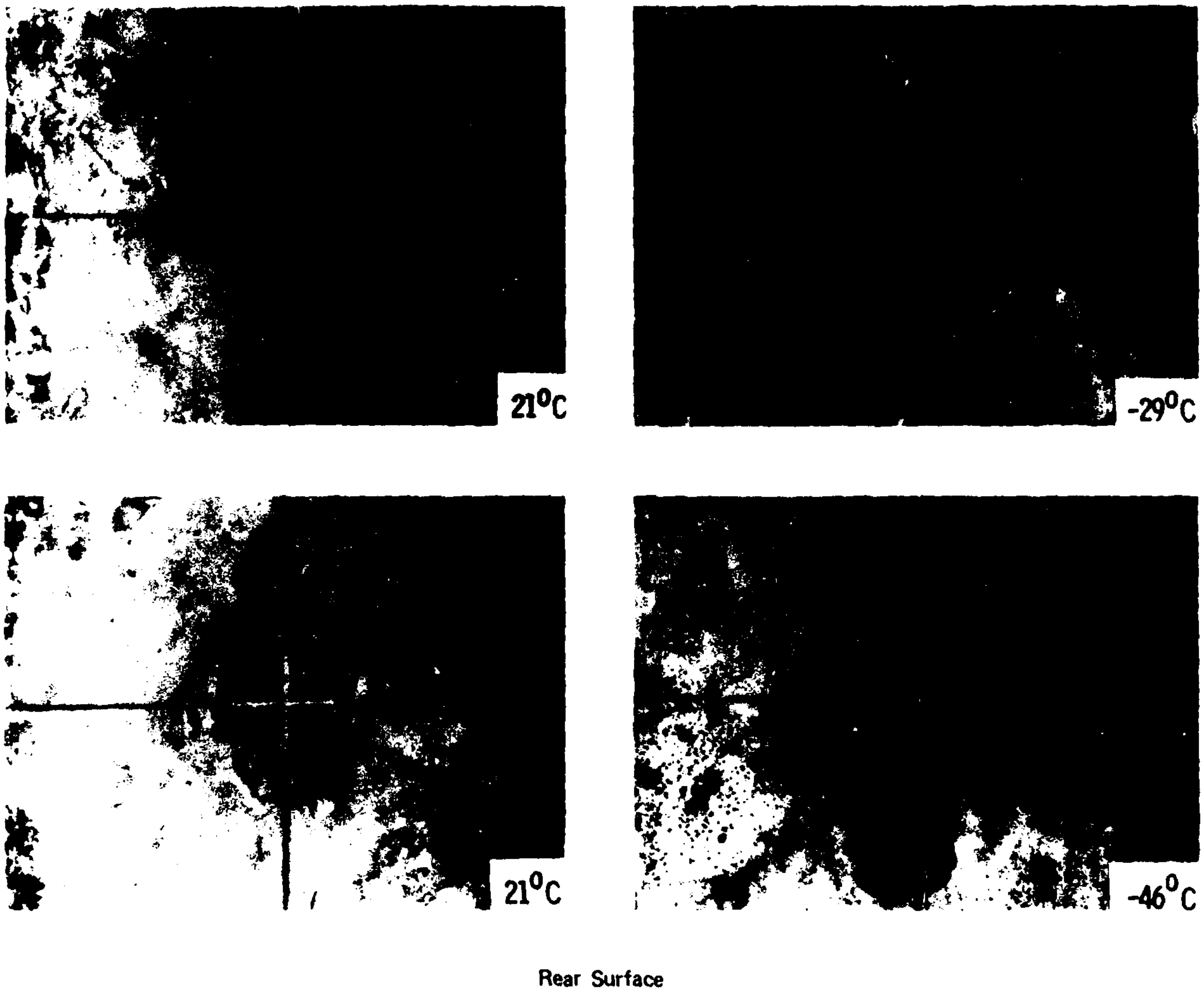


Figure 2. Ballistic impact test on 25-mm ESR 4340 steel armor plate with an E.B. weld crack starter. Plates austenitized at 1205°C, tempered at 175°C. Projectile velocity ≈ 850 m/s.

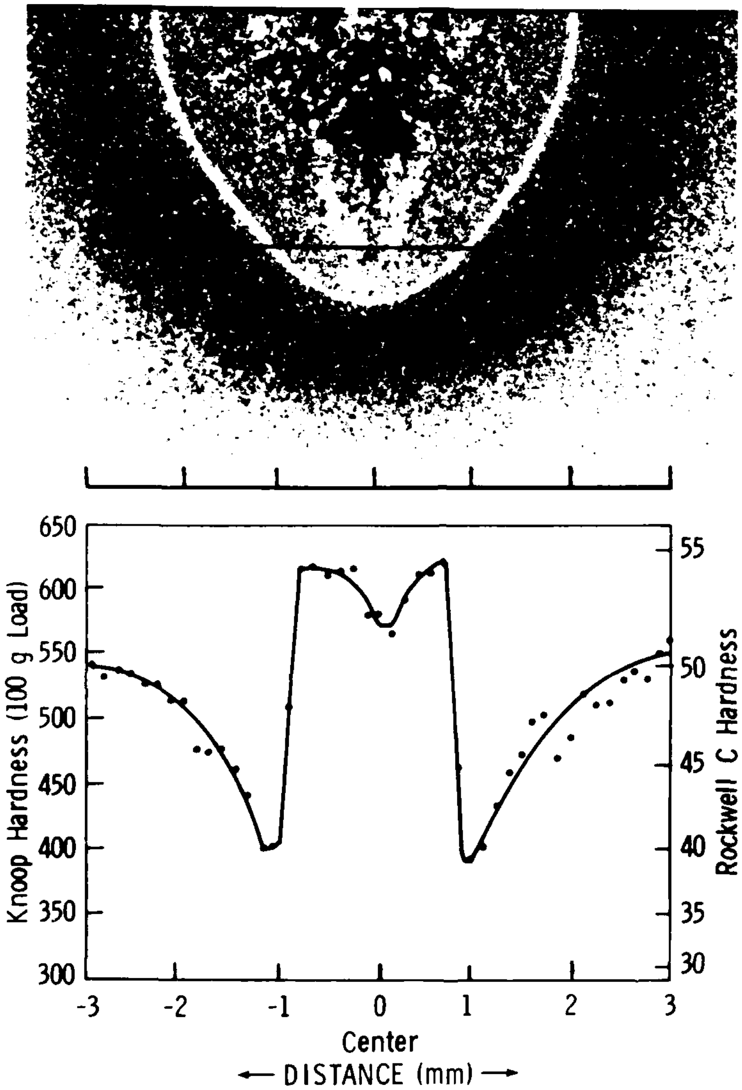


Figure 3. Photomicrograph of a typical electron beam weld cross section accompanied by its corresponding hardness traverse

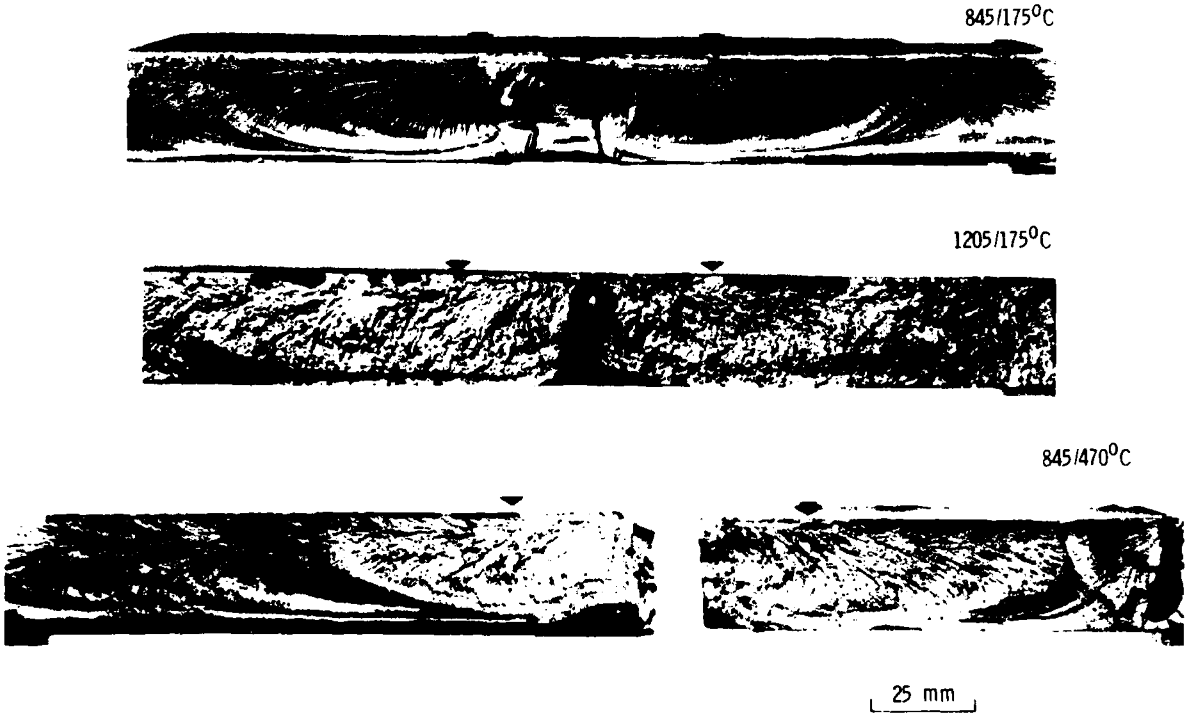


Figure 4. Photographs of three fracture surfaces of ballistically tested ESR 4340 steel plates. Prior to testing, the plates were austenitized and tempered as indicated. The electron beam welds are located between the arrows and extend to a depth of 2.5-mm. The points of impact were centered opposite the weld beads.

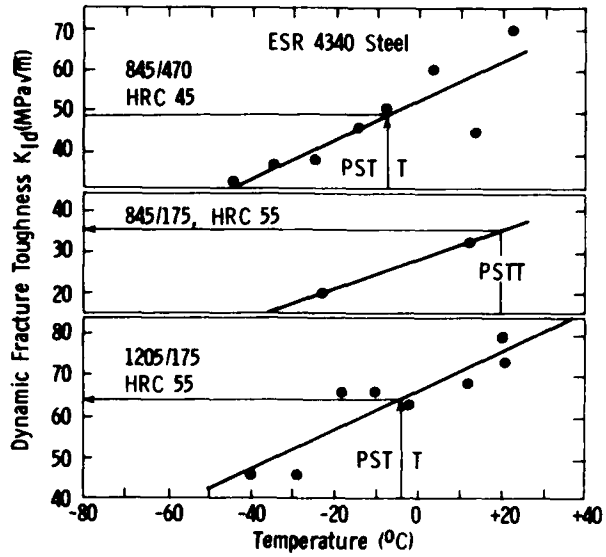


Figure 5. Dynamic fracture toughness as a function of test temperature for conventional ESR 4340 steel. Heat treatments are shown: austenitize/temper (°C).

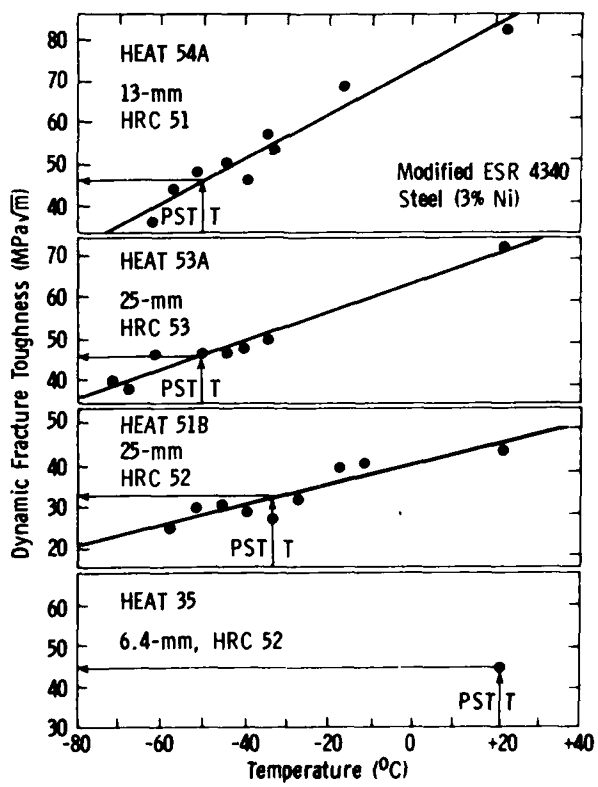


Figure 6. Dynamic fracture toughness as a function of test temperature for modified ESR 4340 steel (3% Ni), austenitized at 845°C and tempered at 175°C.

Table 1. CHEMICAL COMPOSITION

	Weight Percent							
	C	Mn	Si	Cr	Mo	Ni	P	S
ESR 4340	0.41	0.71	0.29	0.79	0.28	1.78	0.007	0.003
Heat #54A (3% Ni)	0.31	0.86	0.37	0.84	0.27	3.32	0.011	0.002
Heat #53A (3% Ni)	0.31	0.88	0.36	0.85	0.27	3.37	0.010	0.002
Heat #51B (3% Ni)	0.30	0.88	0.33	0.84	0.27	3.04	0.009	0.002
Heat #35 (3% Ni)	0.34	0.89	0.39	0.85	0.24	2.87	0.009	0.003

Table 2. TEST MATERIALS

ESR 4340 Steel (25 mm Thick)

Austenitize/Temper* (°C)	Hardness (HRC)
845/470	45
845/175	55
1205/175	55

Modified ESR 4340 Steel (3% Nickel)

Austenitize 845°C, Temper 175°C*

Heat No.	Hardness (HRC)	Thickness (mm)
54A	51	13
53A	53	25
51B	52	25
35	52	6.4

*Austenitize 1 hour at temperature, oil quench, temper 2 hours at temperature.

Table 3. ROOM TEMPERATURE PROPERTIES

ESR 4340 Steel

Austenitize/Temper (°C)	Hardness (HRC)	K_{Ic} (MPa$\sqrt{m}$)	K_{Id} (MPa$\sqrt{m}$)	Charpy Energy (J)
845/470	45	86	72	22
845/175	55	43	33	20
1205/175	55	99	78	15

Modified ESR 4340 Steel (3% Nickel)

Heat No.	Hardness (HRC)	K_{Ic} (MPa$\sqrt{m}$)	K_{Id} (MPa$\sqrt{m}$)	Charpy Energy (J)
54A	51	81	76	38
53A	53	77	69	34
51B	52	53	41	24
35	52	47	46	24*

*Corrected values from subsize specimens.

Table 4. PLATE SHATTER TRANSITION TEMPERATURE

ESR 4340 Steel

Austenitize/Temper (°C)	PSTT (°C)	Projectile Velocity (M/S)	No. of Firings	K_{Ic} (MPa$\sqrt{m}$)
845/470	-7±28	760-855	4	48±18
845/175	>21	760-855	2	>35
1205/175	-4±25	760-855	4	64±15

Modified ESR 4340 Steel (3% Nickel)

Heat No.	PSTT (°C)	Projectile Velocity (M/S)	No. of Firings	K_{Id}* (MPa$\sqrt{m}$)
54A	-51±5	490-640	8	46±2
53A	<-51	820	2	<45
51B	-34	820	3	32
35	>21	215-335	8	>45

*K_{Id} determined at PSTT.

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U.S. Army Materials Technology Laboratory,
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SOME CORRELATIONS BETWEEN PLATE SHATTER AND FRACTURE TOUGHNESS -
Morris Azrin, John G. Cowie, Albert A. Anctil, and Eric B. Kula

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Key Words

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Armor plate
Ballistic testing

Technical Report MTL TR 87-9, February 1987, 14 pp - illus-tables, D/A Project 1L162105AH84 AMCMS Code 612105.H840011

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