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STRUCTURAL DEGRADATION OF HIGH PERFORMANCE ARMOR

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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, resulting in structural degradation 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 (PSTT). The PSTT is simply the highest plate temperature at which extensive plate cracking occurs. The influence of PSTT test parameters and correlation with crack arrest fracture toughness over the same temperature range are currently being studied. (SDW)

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INTRODUCTION

The standard method for assessing the projectile penetration resistance of armor is the V_{50} test. The test consists of a series of projectile impacts at slightly different velocities resulting in both partial and complete penetrations. The statistically determined velocity at which there is a fifty percent probability of penetration is termed the "ballistic limit," or V_{50}.

The ballistic limit is a function of both the mechanical properties of the target and projectile at test temperature, as well as such geometric considerations as the angle of incidence and the thickness of the plate. However, the V_{50} test results do not report the failure mechanism responsible for armor penetration. The failure mechanism can be one of many; e.g., plugging, shattering, petalling, back spall, and piercing. The U.S. Army criterion for a "complete penetration" during the V_{50} test is the existence of a hole created by either the fragments of the target material, or the projectile on a thin aluminum "witness plate" located 15 cm behind, and parallel to, the target. Should back spall be the operative armor failure mechanism, a complete penetration can be recorded with only partial penetration of the plate by the projectile.

The U.S. Army is steadily increasing its reliance on high strength steel armor. Consequently, severe plate cracking or shattering has become one of the primary armor defeat mechanisms during the armor acceptance testing. Plate cracking occurs particularly at arctic temperatures, and can appear irrespective of the ballistic limit. This failure mode results in structural degradation of the armor material, and can render the plate completely useless as a structural member. Armor acceptance testing is performed on armor plate intended to stop small-caliber projectiles. The candidate armor plate is required to exceed a certain ballistic limit. Additionally, a large-caliber projectile is shot through a full-sized section of the armor plate at arctic temperature. The armor is required to remain structurally intact even though the heavy projectile passed clean through. There are cases where the armor plate failed the large-caliber projectile test, but provided an adequate ballistic limit for small-caliber projectiles.

Because the standard V_{50} test does not adequately assess the plate cracking sensitivity, a research program was initiated to develop a new test procedure that would directly address the plate cracking phenomenon. A simple ballistic test was developed which is based on laboratory observations of fractured plates. It was observed that cracks propagated from pre-existing flaws such as a flame-cut edge or a bullet hole from a previous ballistic event. Additionally, it was observed that cracking generally occurred at colder test temperatures. Consequently, this newly developed plate shatter test is performed over a temperature range to determine a ductile-to-brittle transition temperature for a particular armor material having a "standard flaw" as a crack starter.

The test that was selected involves the 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 maximized transfer of momentum to the plate without the complicating effects of penetration. In order to minimize data scatter due to random flaws, a "crack starter" is placed on the center of the rear surface of the plate directly opposite the point of impact on the front face. This crack starter could conceivably take various forms. Initially, the crack starter was in the form of two intersecting electron beam welds, with lengths of 5 cm, more than twice the projectile diameter. More recently, two intersecting vee notches, with lengths of 5 cm, were used which proved to be a more intense crack starter than the weld beads. Tests performed on separate plates over a range of temperatures would give some indication of the cracking sensitivity of a particular armor material. In this manner, using the same plate thickness and projectile velocity, direct comparison can be made of the propensity to cracking of different materials.

Further steps would include an attempt to relate the shatter resistance of a particular material to other mechanical properties, such as some measure of fracture toughness. This could provide a more readily measurable parameter for prediction of cracking tendency and for screening of candidate armor materials. Additionally, finite element calculations of the stress distributions could be performed in order to quantify the test variables such as plate thickness, projectile size, and impact velocity.

EXPERIMENTAL PROCEDURES

Plate Shatter Tests

The plate shatter test consists of impacting a hardened target, containing a large preexisting flaw, with a relatively soft projectile. The flaw acts as a crack starter, and was initially provided by two 5-cm long electron beam welds in the form of a cross at the center of a 30-cm square plate. The welds have since been replaced by two 5-cm long vee notches, 2.5 mm in depth with as sharp a root radius as possible, using the same cross configuration as the welds. These notches are located on the rear surface of the target; i.e., directly opposite the impact face. Figure 1 illustrates plates impacted at two different temperatures.

Square plates, 30 cm x 30 cm, with thicknesses of 12 mm, were used as the standard specimen. A relatively soft projectile (HRB 78, AISI 1018 steel) of 20-mm diameter and 64-mm length, was fired at a velocity just below the ballistic limit of the target; in this case, 490 m/sec with a standard deviation of 40 m/sec. The use of a soft projectile allowed for extensive mushrooming of the projectile, which decreased the possibility of penetration while maximizing the energy transfer to the target. This subjected the plate to some deformation in the form of bulging of the back surface which produced a tensile stress within the crack starter.

A series of plates of the same material and processing conditions were tested over a temperature range to estimate the maximum temperature below which extensive cracking occurs. This temperature, henceforth referred to as the plate shatter transition temperature (PSTT), can be considered a relative measure of cracking sensitivity during 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 flaw as a crack initiator. The two tests differ in loading rate, specimen geometry, and crack starter type and geometry. The most important distinction is that the PSTT test approximates the full-scale testing of armor plate.

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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.

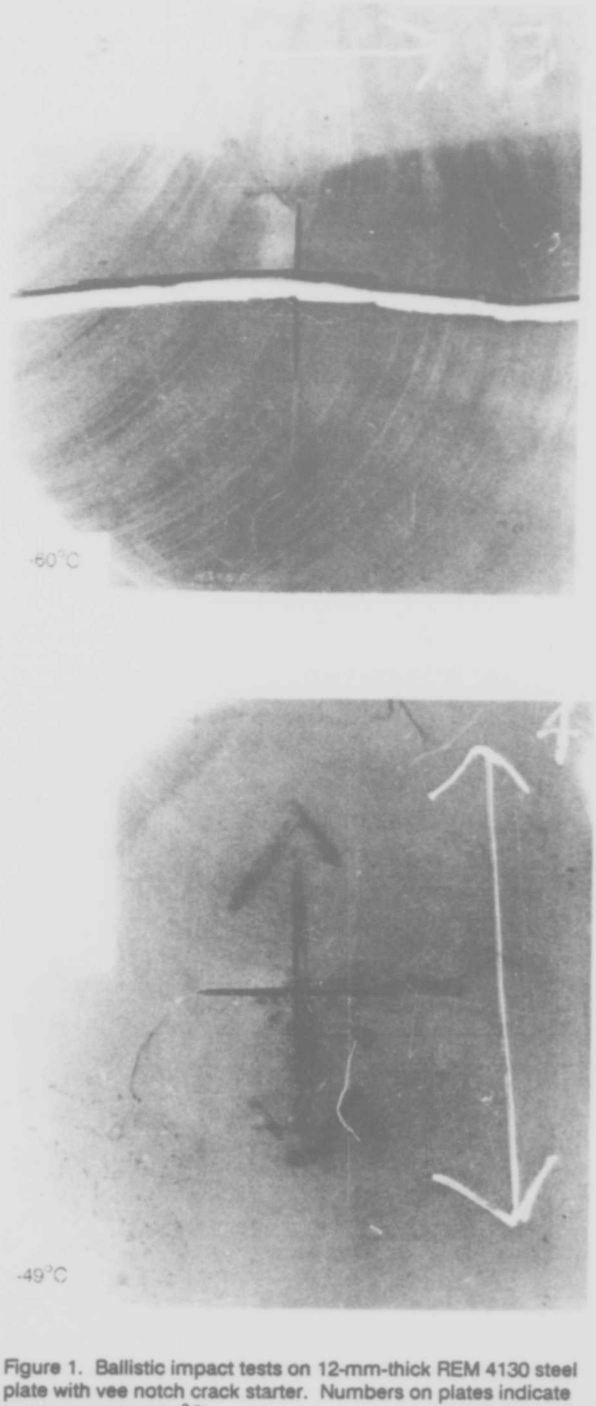

Figure 1. Ballistic impact tests on 12-mm-thick REM 4130 steel plate with vee notch crack starter. Numbers on plates indicate test temperature in °C.

Crack Arrest Fracture Toughness Tests

The crack arrest fracture toughness test evaluates the stress intensity factor at which a fast propagating crack will arrest. This is accomplished by forcing a wedge into a split pin, which, in turn, develops an opening force across the crack face of a compact type specimen, resulting in a run-arrest segment of crack extension.

Certain specimen size requirements must be maintained; the in-plane dimensions must be large enough to allow the specimen to be analyzed using linear elastic methods. Testing is performed on full-thickness plates in order to eliminate, or at least minimize, plane stress conditions. Side grooves on the specimens assure plane-strain cracking across the full specimen thickness. The minimum in-plane specimen dimensions are a function of the crack arrest toughness and the yield strength.

During the earlier portion of the run-arrest event, dynamic inertial effects are large because of the abrupt acceleration for the initially stationary crack tip. During the later portions of the event, while the crack velocity decreases toward arrest, these dynamic inertial effects become negligible so that the value of stress intensity K, at the moment of arrest, can be calculated by equations that have been established on the basis of a static-elastic stress analysis of the compact specimen.[3] Since only the arrest toughness is being evaluated, the method is independent of the manner in which the crack is initiated. Hence, the cracks may be initiated from relatively blunt-machined notches, eliminating the necessity of fatigue precracking. Calculation of the arrest toughness is based on the measurements of the crack length and displacement at arrest.

The significance of the test with respect to armor behavior is first presented here. It will be shown that crack arrest fracture toughness values can assist in selecting armor materials so as to maximize structural integrity and minimize the amount of cracking. The parameter K_{Ia} may also be useful as a material parameter for computer modeling of armor behavior.

The equation used to determine crack arrest fracture toughness is as follows:

$$K = [VE\, f(a/w) / W^{1/2}]\, (B/B_N)^{1/2}$$

where

$$f(a/w) = \frac{2.24\,[1.72 - 0.9\,(a/w) + (a/w)^2]\,[1 - (a/w)]^{1/2}}{[9.85 - 0.17\,(a/w) + 11.0\,(a/w)^2]}$$

where

V = arrest displacement
E = Young's modulus
a = final crack length
W = specimen width
B = specimen thickness
B_N = specimen width at crack plane.

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[3] RIPLING, E. J. *Crack Arrest Fracture Toughness of Armor Steels.* Materials Research Laboratory, Inc., Contract DAAG29-81-0100, Final Report, MTL TR 87-56, October 1987.

In order for K to be a valid measure of K_{Ia}, the following requirements must be met: (1) the unbroken ligament, W-a, must exceed 0.1W, and (2) the unbroken ligament, W-a, must exceed 1.25 $[K(T_{ys} + T_o)]$, where T_{ys} is the 0.2-percent offset yield strength of the test material at the test temperature, and T_o is a strain rate correction equal to 205 MPa for steels.

For more detailed information on crack arrest fracture toughness testing of armor steels, refer to the work by Ripling.[3]

MATERIALS

Two different alloys were employed in the study; a rare earth modified (REM) AISI 4130 steel, and a vacuum arc remelted (VAR) AISI 4340 steel. Chemical compositions are presented in Table 1. The austenitizing temperatures used were different, but consistent with, the conventional industrial heat treatments as shown in Table 2. The two steels were both water quenched from the austenitizing temperature. In the case of the 4340 steel, this is not the recommended practice. However, it was of interest to compare the cracking sensitivities of the water-quenched material presented in this study to the oil-quenched material presented by Azrin et al.[4] The differences in the resulting hardnesses were primarily due to the difference in the carbon contents. Obviously, higher strengths can be achieved in martensitic steels with higher carbon contents. The VAR 4340 steel exhibited a slightly finer martensitic structure than the REM 4130 steel (Figure 2).

Table 1. CHEMICAL COMPOSITION

	Weight Percent									
	C	Mn	Si	Ni	Cr	Mo	Cu	Ti	B	P	S
REM 4130	0.30	0.62	0.29	-	1.05	0.20	-	0.051	0.002	0.007	0.008
VAR 4340	0.42	0.46	0.28	1.74	0.89	0.21	0.19	-	-	0.009	0.001

Table 2. TEST MATERIALS

	Austenitize (°C)	Quench	Temperature (°C)	Hardness (HRC)
REM 4130	900	Water	200	48
VAR 4340	845	Water	200	51

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4. AZRIN, M., COWIE, J. G., ANCTIL, A. A., and KULA, E. B. *Some Correlations Between Plate Shatter and Fracture Toughness.* U.S. Army Materials Technology Laboratory, MTL TR 87-9, February 1987.

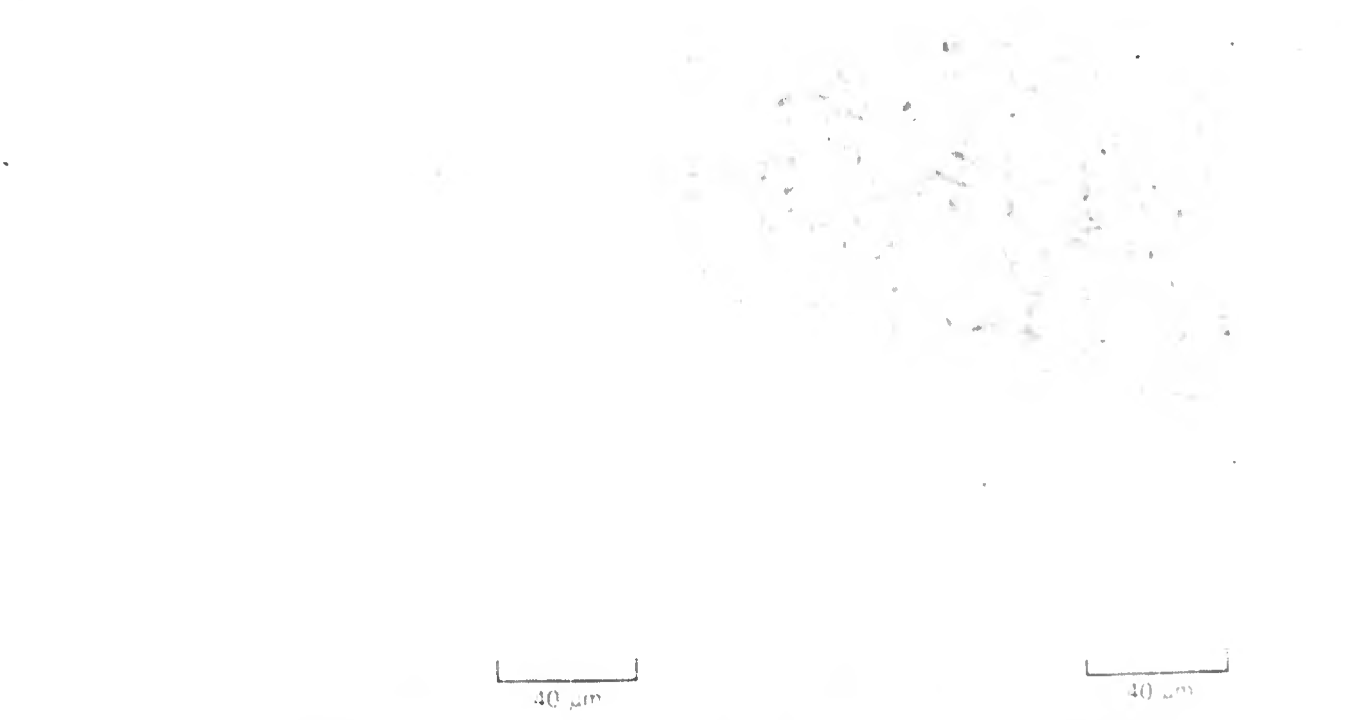

Figure 2. Photomicrographs of 4130 (left) and 4340 (right) steels as tested, showing martensitic structures.

RESULTS

Plate Shatter Test

Each series of ballistic tests resulted in a transition temperature below that 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 vee notch area. The PSTT results, along with the number of ballistic tests performed for each series of plates, are presented in Figures 3 and 4, and in Table 3. The REM 4130 steel shattered below -55°C, which was far superior to the PSTT of +18°C for VAR 4340 steel. Upon comparing the PSTT of water-quenched 4340 to that of oil-quenched 4340,[4] it is observed that these materials exhibited approximately equivalent cracking sensitivities.

Table 3. PLATE SHATTER TRANSITION TEMPERATURE

	No. of Firings	PSTT (°C)	K_{Ia} (MPa m$^{1/2}$)*
REM 4130	12	-55	80
VAR 4340	6	+18	55

*Determined at PSTT

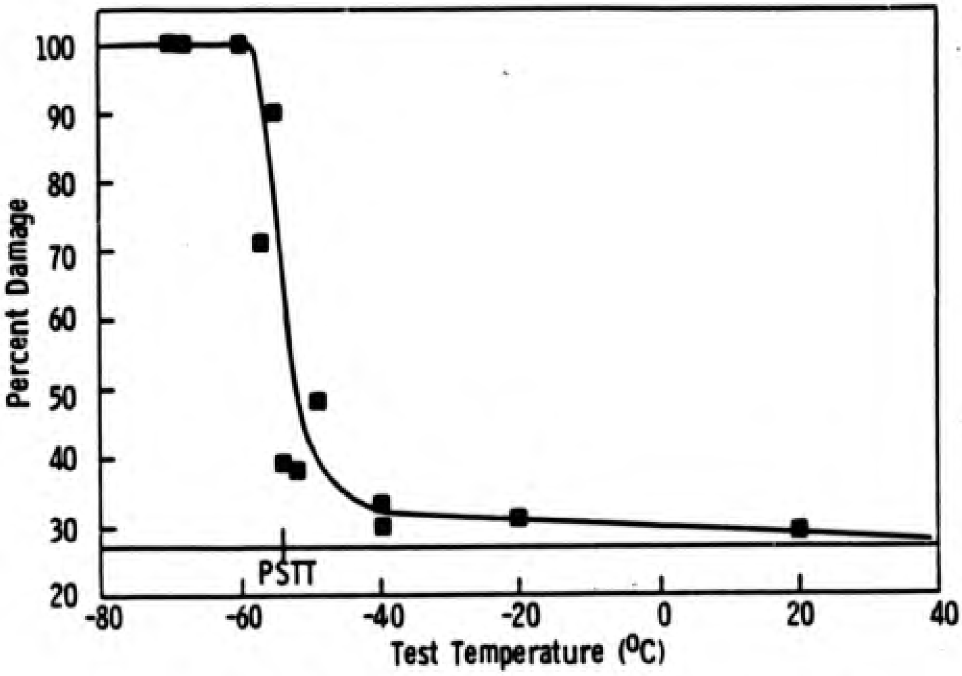

Figure 3. Plate shatter transition temperature curve for REM 4130 steel.

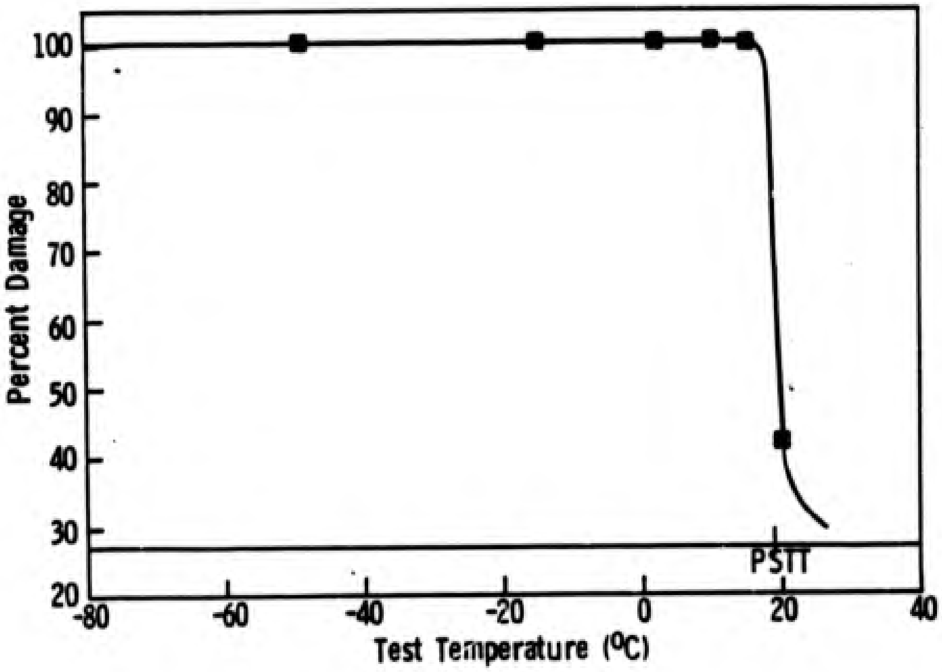

Figure 4. Plate shatter transition temperature curve for VAR 4340 steel.

Fractographic analysis was performed on a 25-mm-thick plate of ESR 4340. The plate exhibited multiple fracture origins along the length of the crack starter (Figure 5). The crack then propagated rapidly from the weld to complete failure. The fracture propagated in a transgranular mode. Closer inspection of the point of impact reveals the early stages of ballistic plugging failure mechanism due to adiabatic shear.[5] This band of localized shear lies beneath the area of impact. A shear band is often observed in high hardness alloys exhibiting low shear instability strains.

Figure 5. Fractograph of ballistically tested ESR 4340 steel plate. The crack starter is located between the arrows and extends to a depth of 2.5 mm. The point of impact was centered opposite the crack starter.

Crack Arrest Fracture Toughness Tests

Crack arrest testing was performed over a similar range of temperature as were the PSTT tests. The fracture appearances of the K_{Ia} specimens, for both elevated (38°C) and low (-73°C) temperatures, are presented in Figure 6. The crack fronts were generally straight, with no shear lips at the specimen surfaces. These specimens closely simulate the type of cracking that occurs in armor plate during projectile-induced plate shatter.

The crack arrest toughness of REM 4130 steel and VAR 4340 steel are shown in Figures 7 and 8, respectively. The scatter in both sets of data is greater than that found in earlier tests on similar steel.[6,7] In spite of the scatter, the curve representing the AISI 4130 data is shown to have a transition temperature consistent with the behavior found in the earlier studies. If the steels do, indeed, exhibit a transition temperature, the data collected on the 4340 suggest that the transition temperature would be above 38°C. The most conspicuous feature of the data, however, is that the REM 4130 is tougher than the VAR 4340 at all temperatures. The significance of this can only be ascertained by comparing these results with the plate shatter tests.

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5. ROGERS, H. C. *Adiabatic Shearing: A Review.* Drexel University Report prepared for the U.S. Army Research Office, 1974.
6. RIPLING, E. J., MULHERIN, J. H., and CROSLEY, P. B. *Crack Arrest Toughness of Two High Strength Steels (AISI 4140 and AISI 4340).* Met. Trans. A., v. 13A, April 1982, p. 657-664.
7. RIPLING, E. J., MULHERIN, J. H., and CROSLEY, P. B. *Comparison of the Plane Strain Crack Arrest Fracture Toughness of 4340, 4140, and 1340 Steel.* Met. Trans. A., v. 14A, July 1983, p. 1459-1465.

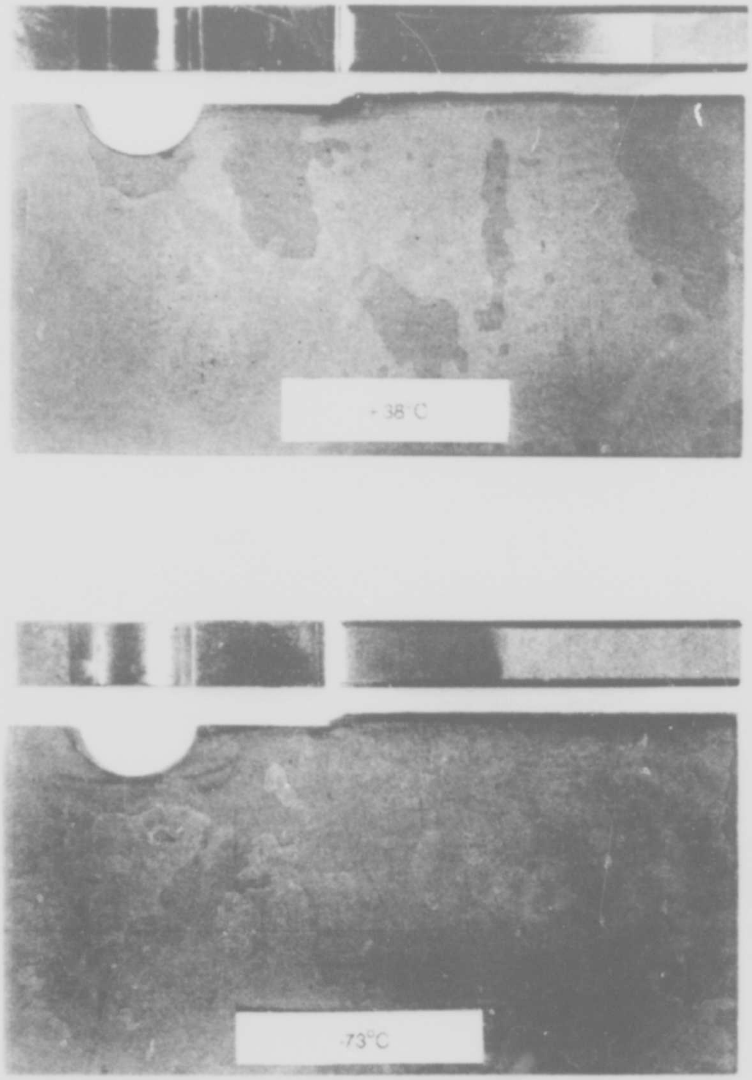

Figure 6. Fracture appearances of the crack arrest fracture toughness specimens for both 38°C (top) and -73°C (bottom).

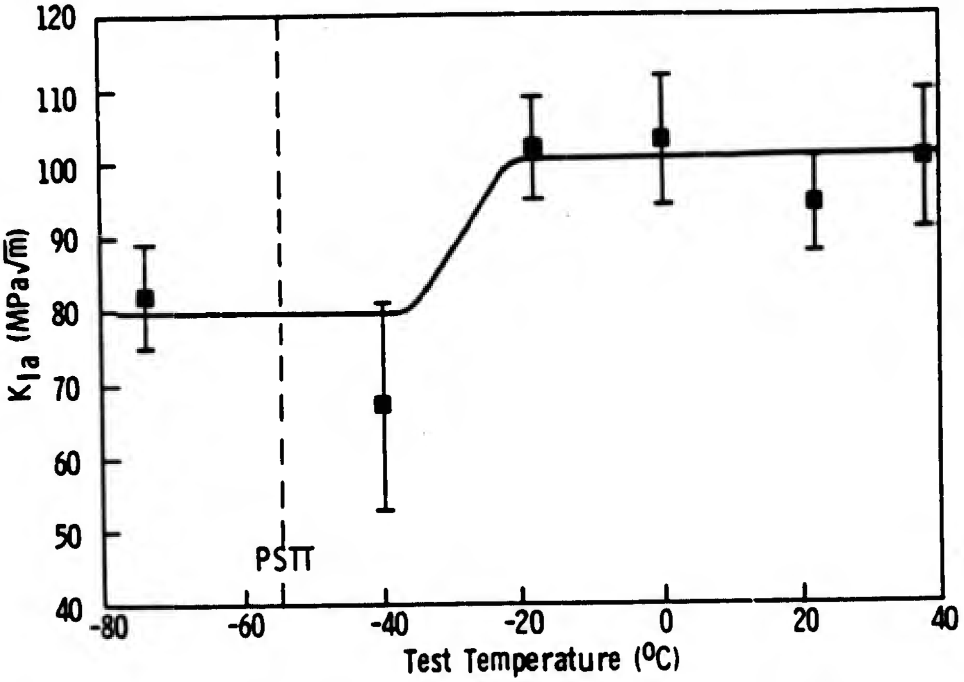

Figure 7. Crack arrest fracture toughness curve for REM 4130 steel.

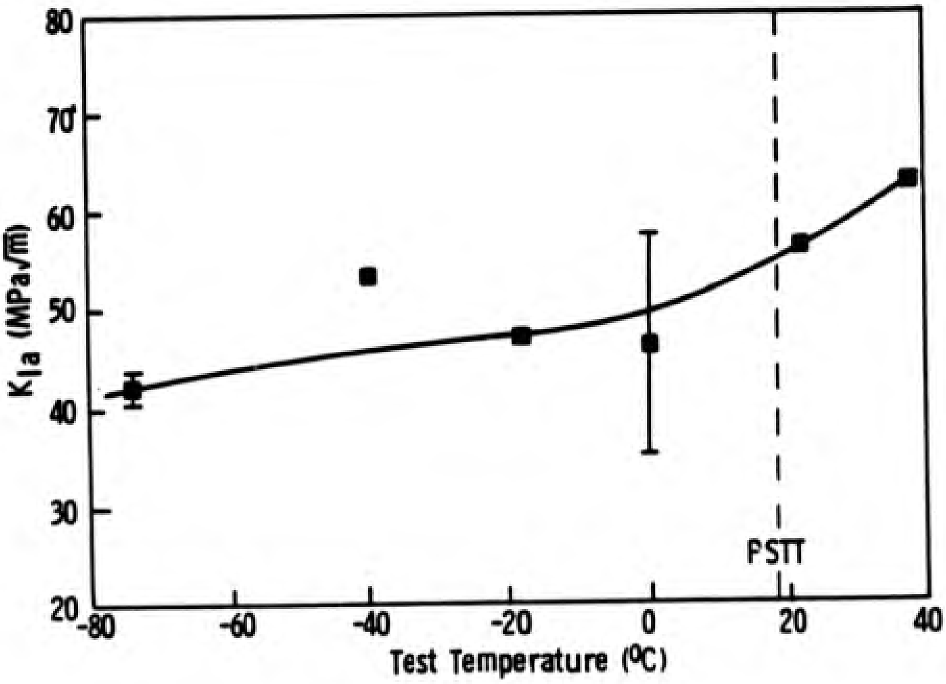

Figure 8. Crack arrest fracture toughness curve for VAR 4340 steel.

DISCUSSION

Analysis of the shatter transition curves (Figures 3 and 4), and the crack arrest curves (Figures 7 and 8), suggests an important conclusion concerning the PSTT; namely, that the crack sensitivity, as defined by the ballistic tests, scales with the crack arrest fracture toughness for the two materials studied. The steel with the higher crack arrest fracture toughness curve, REM 4130, exhibited a lower, and hence, better PSTT. A preliminary study by Azrin et al.,[4] indicated that fracture toughness, being a measure of resistance to crack propagation, better correlates with plate shattering than do the results of Charpy tests, which are more a measure of resistance to crack initiation than propagation. Additionally, the 12-mm-thick VAR 4340 steel plate, which was water quenched from the austenitizing temperature, exhibited a nearly identical PSTT as the 25-mm-thick ESR 4340 steel plate, which was oil quenched.[4] This indicates that the quenching medium has little effect on the resulting cracking sensitivity of this particular alloy.

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 fracture toughness tests would permit establishing cracking trends when only enough material is available for the fracture toughness tests. Also, the PSTT is an additional parameter, similar in value to the hardness, strength, and toughness parameters, reported when obtaining the ballistic limit of armor by the actual firing of projectiles to measure penetration velocity.

CONCLUSIONS

Fractographic examination of ballistically impacted plates containing a preexisting flaw revealed that crack propagation initiates at the flaw. Based on these results, the flaw, whether it be the electron beam weld or the vee notch, is an effective crack starter, and for the purpose of the PSTT test, can be considered equivalent to a preexisting sharp crack.

The PSTT test quantitatively determines a transition temperature below which extensive cracking occurs and above which little cracking is observed. Since the test conditions have not yet been standardized, the test is a relative measure of shatter sensitivity and/or resistance.

PSTT varied with crack arrest fracture toughness, but displayed no correlation with Charpy energy.

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STRUCTURAL DEGRADATION OF HIGH
PERFORMANCE ARMOR - John G. Cowie,
Morris Azrin, Eric B. Kula, and
Edward J. Ripling

Technical Report MTL TR 89-38, April 1989, 14 pp-
illus-tables, D/A Project: 1L162105.AH84

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Key Words

Fracture
Armor
High strength steel

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