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FRACTURE TOUGHNESS OF HIGH-STRENGTH
STEELS FOR MILITARY APPLICATIONS

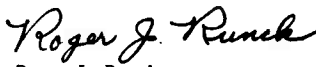
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FRACTURE TOUGHNESS OF HIGH-STRENGTH STEELS FOR MILITARY APPLICATIONS

J. E. Campbell*

SUMMARY

This Memorandum reviews the testing procedures for evaluating the toughness of alloy steels used for military applications in the United States, Canada, and the United Kingdom.

In the United States, at the present time, testing methods are being developed for plane-strain fracture-toughness testing of high-strength metals. Fracture toughness, as determined by plane-strain testing methods, has been used only to a limited extent as a criterion in qualifying steels for military applications. Because of the newness of the tests, only a limited amount of design data is available on the plane-strain fracture toughness of the high-strength steels. Also, there is only limited background experience to indicate what the minimum fracture toughness limit should be for a given component and how to interpret the data that are available. Consequently, the minimum toughness requirements for alloy steels for many military applications are often based on less sophisticated Charpy V-notch impact tests or on reduction-in-area-transverse (RAT) tests.

Steels for thick-wall motor cases in large rocket and missile boosters have been evaluated by plane-strain fracture-toughness tests, but the standard test methods available for sheet steel used in thin-wall motor cases for relatively small missiles provide only empirical data. Lacking standard plane-strain fracture-toughness tests, hydrostatic tests may be made on small prototype pressure vessels containing small cracks to determine the critical crack size at proof stress.

The present requirement in evaluating steels for landing gear is that transverse tensile specimens from the forging billets have values for reduction in area (RAT values) equal to or higher than a specified value when heat treated as for the landing gear. Steel forgings and weldments for other parts of military aircraft may or may not have minimum toughness requirements. However, for the F-111 airframe, advanced methods of plane-strain fracture-toughness testing are being used to qualify both the steel and the type of heat treatment used for the carry-through fittings of the wing pivots, for the outboard-pivot fittings and for other components.

Qualification of forgings for gun tubes is based on data obtained from transverse tensile and transverse Charpy V-notch specimens. More discriminating testing methods are being considered, but there is considerable variation in the fracture toughness of gun tubes at the present time.

Selection of alloy steel and heat treatment for recoilless-rifle tubes has been based on plane-stress fracture-toughness data.

In Canada, there is a growing interest in fracture-toughness requirements for military

applications. The applications for which high-strength steels have been evaluated by fracture-toughness tests include armor plate and hydrofoils.

The United Kingdom has extensive programs for evaluating fracture toughness for a wide range of steels from structural steels for naval applications to high-strength martensitic steels and maraging steels. Emphasis has been placed on familiarizing laboratory personnel with methods of plane-strain fracture-toughness testing rather than on establishing specifications for military applications. There is considerable interest in developing advanced testing methods and in cooperation with ASTM Committee E24 in establishing standard methods for plane-strain and plane-stress fracture testing.

This report does not consider the application of notched and precracked specimens for stress-corrosion testing at certain stress intensity levels in aqueous media, although this is an outgrowth of fracture-toughness testing and is applicable in evaluating steels for many military applications.

INTRODUCTION

This Memorandum was prepared at the request of the Working Panel on Metals of Subgroup P on Materials of The Technical Cooperation Program (TTCP). The Memorandum is intended to clarify fracture-toughness testing requirements and procedures for high-strength steels used in military applications, and is based on data subsequent to the Panel's October, 1964, symposium on ultrahigh-strength steels (see DMIC Report 210). Information in this Memorandum is based on reports in DMIC files and on interviews with a number of people concerned with materials used in military applications.

Many of those concerned with the application of high-strength steels for military hardware are aware of the need for minimum fracture-toughness specifications for the alloy steels used in these applications. However, the development of new standardized testing procedures has not kept up with the needs of those who are responsible for writing hardware specifications involving high-strength alloys. Many laboratories, using recently developed methods, have made fracture-toughness tests on specimens of high-strength steels over the past 8 years, and a large volume of data has been generated. Much of this work was done in order to determine what variables must be controlled in developing one or more standard testing specifications. Because of the many variables associated with the newer methods of fracture-toughness testing, considerable variation has been observed in the reported data. This has been confusing to those who wish to use the data.

Other considerations, such as the so-called plane-strain and plane-stress conditions for fracturing, have added to the uncertainties in using the data. The original effort of the ASTM Committee on Fracture Testing of High-Strength Metallic

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Materials was to establish a testing procedure for high-strength alloys in relatively thin sections (plane-stress condition). However, before they had made much progress, the thick-section problem for large solid-propellant booster cases became more urgent. Since that time, the plane-strain condition has received most attention from those associated with the ASTM Committee (now the ASTM Committee E24).

As noted later, one recommended practice for plane-strain fracture-toughness testing has been evaluated in a round-robin program of nine laboratories. A second recommended practice is being developed for a different type of specimen, the compact K_{Ic} specimen. Procedures for the plane-stress condition also are being considered. The value of these procedures is that the information can be used in estimating critical flaw sizes in high-strength structures when the structures are being designed, if the service stresses can be calculated. Empirical data obtained on other types of toughness tests are not applicable to design calculations.

The following categories represent the major military applications for steels having yield strengths over 150,000 psi:

- Solid-propellant motor cases (including boosters and tactical missiles)
- Pressure vessels (other than motor cases)
- Aircraft landing gear
- Structural components for aircraft (other than landing gear)
- Gun tubes and recoilless-rifle tubes.

Steels for other applications include the high-strength stainless steels, steels for armor plate and projectiles (such as armor-piercing shot), steels for small arms components and fasteners, and hydrofoils. Fracture toughness studies on armor plate and steel for hydrofoils are discussed briefly in the section on Canadian military applications.

The yield-strength range of the steels considered in this review is from 150,000 to 300,000 psi. The principal reason for using steels in this strength range for military applications is to minimize the overall weight of the structure. Service stresses usually are high for these components and, in certain instances, may even approach the yield strength.

Correlation of yield strength versus fracture toughness for alloy steels shows that the toughness decreases as the strength increases, as seen in Figure 1. Therefore, when using steels at the higher strength levels, it is important to appreciate the significance of the limited toughness of the steel and the critical flaw size at the maximum service stress. These factors will be discussed in more detail later.

U. S. MILITARY APPLICATIONS

The following alloy steels often are used when high strength levels are required for U. S. military applications:

Motor cases and other steel pressure vessels

- AISI 4340 (AMS 6414 and AMS 6415)
- AMS 6434
- D6ac
- 18Ni maraging steel (200 to 300 grades)

Landing gear

- AISI 4340 (AMS 6414 and AMS 6415)
- 300 M (0.40-0.45C and 0.38-0.43C)
- AMS 6427 (4330 V Mod.)
- AMS 6407
- AMS 6423 (98BV40)

Airframe components other than landing gear

- AMS 6427 (4330 V Mod.)
- AMS 6407
- AISI 4340
- D6ac

Gun tubes

- Gun steel

Recoilless-rifle tubes

- 4330 V (Mod. + Si)
- AISI 4337

Compositions of these steels are given in Table 1.

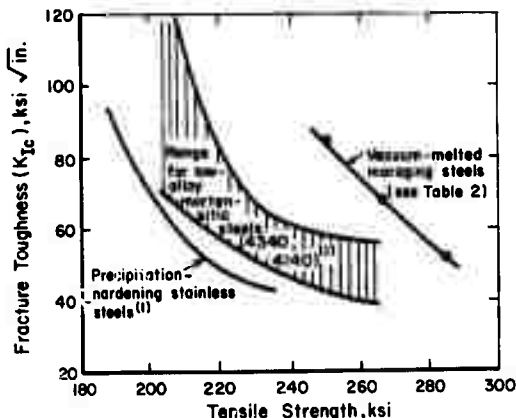


FIGURE 1. VARIATION OF PLANE-STRAIN FRACTURE TOUGHNESS WITH STRENGTH LEVEL FOR SEVERAL TYPES OF STEELS

Type H-11 steel also has been used for some of these applications, including pressure vessels, landing gear, and airframe components. At the present time, however, its use is usually limited to applications where high strength is needed at elevated temperatures.

Other steels, such as the HP 9Ni-4Co types and the 12Ni maraging steels, have not been used for these applications, except for experimental programs. A large shear spun motor case has been made of HP 9Ni-4Co-25C steel, which was heat treated as flat plate.⁽²⁾ Other experimental pressure vessels and gun tubes have been fabricated of 9Ni-4Co steel.^(3,4) Some of these newer steels may be used for certain U. S. military applications in the future.

Fracture-Toughness Testing

Fracture-toughness testing involves testing notched or precracked specimens to determine the tendency for brittle fracturing of a specific

TABLE 1. COMPOSITIONS OF ALLOY STEELS USED AT HIGH STRENGTH LEVELS FOR U. S. MILITARY APPLICATIONS

Steel Type	Composition, percent									
	C	Mn	Si	P	S	Ni	Cr	Mo	V	Others
AISI 4340	0.38- 0.43	0.60- 0.90	0.20- 0.35	0.040 max	0.040 max	1.65- 2.00	0.70- 0.90	0.20- 0.30	-	
AMS 6434	0.31- 0.38	0.60- 0.80	0.20- 0.35	0.040 max	0.040 max	1.65- 2.00	0.65- 0.90	0.30- 0.40	0.17- 0.23	
AMS 6407	0.27- 0.33	0.60- 0.80	0.40- 0.70	0.025 max	0.025 max	1.85- 2.25	1.00- 1.35	0.35- 0.55	-	Cu 0.35 max
AMS 6427	0.28- 0.33	0.75- 1.00	0.20- 0.35	0.040 max	0.040 max	1.65- 2.00	0.75- 1.00	0.35- 0.50	0.05- 0.10	
AMS 6423 (98BV40)	0.40- 0.46	0.75- 1.00	0.50- 0.80	0.025 max	0.025 max	0.60- 0.90	0.80- 1.05	0.45- 0.60	0.01- 0.06	B 0.007 max
D6ac (Ladish, typical)	0.46	0.75	0.22	0.015 max	0.015 max	0.55	1.00	1.00	-	
300M ^(a) (AMS 6416)	0.41- 0.46	0.60- 0.90	1.45- 1.80	0.015 max	0.015 max	1.65- 2.00	0.70- 0.95	0.30- 0.50	0.05- 0.10	
Gun Steel (Typical)	0.35	0.70	0.30	0.010	0.008	2.70	1.10	0.60	0.13	
4330V (Mod + Si)	0.28- 0.33	0.65- 0.85	1.45 ^(b)	-	-	1.65- 2.00	0.70- 0.90	0.20- 0.30	0.10 ^(b)	
18Ni (200) ^(c)	0.03 max	0.10 max	0.10 max	0.010 max	0.010 max	17.0- 19.0	-	4.0- 4.5	-	Co 7.0- 8.5
18Ni (250) ^(c)	0.03 max	0.10 max	0.10 max	0.010 max	0.010 max	17.0- 19.0	-	4.6- 5.1	-	Ti 0.10- 0.25
18Ni (300) ^(c)	0.03 max	0.10 max	0.10 max	0.010 max	0.010 max	18.0- 19.0	-	4.6- 5.2	-	8.0 9.5

(a) 0.40 to 0.45 percent carbon for C-54 landing gear. There is another version of this alloy called 4340M, with 0.38 to 0.43 percent carbon and 1.50 to 1.80 percent silicon, which is also used for landing gear.

(b) Typical.

(c) In addition, these alloys contain 0.05 to 0.15 percent aluminum, and these elements shall be added: boron 0.003 percent, zirconium 0.02 percent, calcium 0.05 percent (ASTM Standards, Part 4, 1967).

material. When brittle fracturing occurs, the gross fracture stress is usually lower than the yield strength. From the historical standpoint, brittle fractures have occurred in a number of structures such as steel storage tanks, welded ships, and Polaris missile cases.

Because of its usefulness in evaluating steels for storage tanks, ship plate, and line pipe, the Charpy V-notch impact test has been widely accepted as a standard test method for determining transition temperatures and for indicating relative toughness at specific testing temperatures. However, for high-strength steels, tests using standard V-notch Charpy specimens do not adequately discriminate between heats that possess the desired toughness and those that do not. In spite of the limited value of the Charpy impact test, it has been recommended for qualifying steels for gun tubes and landing gear. This test method

was selected primarily because there was no other toughness test that was applicable. The precracked Charpy impact test and the precracked Charpy "slow bend test" have only limited usefulness in evaluating the toughness of high-strength steels, but they have been used to some extent for this purpose. Other toughness tests, such as the drop-weight test and the explosion-bulge test, provide useful empirical data on the toughness of low- and intermediate-strength steels, but they are not satisfactory for high-strength steels.

For determining the relative toughness of high-strength steels in sheet form (to 0.250-inch thickness), one may use notched tension test specimens described in "Proposed Recommended Practice for Sharp-Notch Tension Testing of High-Strength Sheet Materials".⁽⁵⁾ The resulting test data will provide information on the notch-strength/yield-strength ratio at a specific testing temperature.

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Notch-tensile data also may be obtained on large precracked panels. Information on the residual strength of such panels may be useful to the designer, but the panel specimens require too much material for acceptable test specimens for qualification tests.

The present phase of fracture-toughness technology originated as a result of analysis of early Polaris motor cases, which had failed at unexpectedly low stresses on proof testing. These motor cases had been fabricated by roll forming and welding alloy steel sheet. They were heat treated after fabrication. During proof testing, fractures were initiated at flaws or cracks in the cases. These flaws or cracks usually were in the longitudinal welds and had not been detected by nondestructive tests. Personnel of the Naval Research Laboratory who were assigned the task of analyzing this problem realized that the steel should have sufficient toughness to perform satisfactorily in the presence of flaws that were too small to be detected by available nondestructive methods. The fracture-mechanics concept was applied to the problem to permit an estimation of the critical flaw size in a specific alloy steel at a certain strength level when subjected to a specific stress. At the present time, the fracture-mechanics concept for estimation of critical flaw sizes is still being developed, as discussed below.

At the same time, there was some effort devoted to improving the sensitivity of nondestructive testing methods. When small flaws or cracks are detected, they can be ground out and the area rewelded. The fracture-toughness of the steel should be sufficient to preclude fracture initiation at flaws too small to be detected by whatever nondestructive testing methods are used.

Those assigned to the Polaris program were interested in developing a more fundamental fracture testing method than the empirical methods that were being used for ship plate and line-pipe steels. The fracture-mechanics approach was applicable to high-strength steels, since an elastic stress field could be assumed at the leading edge of a crack beyond a small plastic zone. Thus, the application of fracture mechanics to design for high-strength metals is based on the assumption that there are flaws or cracks in a structure fabricated from these metals. The calculations are based on the assumption that in the structure there is at least one flaw of a size just below that which can be detected by whatever nondestructive testing methods are used. It is further assumed that this flaw is at the location of highest stress and at an orientation transverse to the direction of the major stress. In a thick-wall pressure vessel of high-strength steel, for example, the critical flaw size is a function of the plane-strain fracture-toughness parameter (K_{Ic}) and the maximum stress at proof pressure. If failure occurs at stresses equal to or lower than the intended proof pressure, the fracture usually initiates as a brittle fracture with its origin at a flaw or some other form of stress concentrator. The validity of this concept has been confirmed on several Air Force programs. (3,6,7)

In addition, fracture-toughness parameters have been applied to stress-corrosion testing and fatigue testing using precracked specimens. In

either case, it is important to know the rate of crack propagation under specific conditions (for specific stress intensities, K_I) and the residual strength of components containing cracks that have been developed under these conditions. This information may be used in estimating the life of critical components having cracks when exposed to cyclic and/or corrosive environments. Certain aircraft components, gun tubes, and other structures have certain finite service lives when they contain subcritical flaws and cracks.

ASTM Committee E24, with its four subcommittees and several task groups, has been actively engaged in studying and developing methods for evaluating fracture toughness of high-strength and intermediate-strength alloys. During 1967, one recommended practice for measuring plane-strain fracture toughness, using notched and precracked bend specimens, was submitted to ASTM for publication. This was the "Proposed Recommended Practice for Plane-Strain Fracture-Toughness Testing of High-Strength Metallic Materials Using a Fatigue-Cracked Bend Specimen" (ASTM Standards, Part 31, pp. 1018-1030, May 1968). This practice has been used in a round-robin program in which nine laboratories have participated. The alloys evaluated were:

2219-T851 aluminum alloy
18Ni maraging steel (250 grade)
AISI 4340 steel (500 F temper)
AISI 4340 steel (800 F temper).

The specimens were of sufficient thickness to obtain valid data for the plane-strain stress-intensity factors (K_{Ic} values). Results of this program were presented at the Annual Meeting of ASTM in June, 1968.

Plane-strain fracture-toughness testing by the above method can be used only for relatively high-strength alloys. For 1-inch-thick specimens, this practice specifies that the yield-strength/elastic-modulus ratio be equal to 0.0075 or greater to obtain valid K_{Ic} data. Thus, to permit use of 1-inch-thick specimens, the minimum-yield strength for steels is about 210,000 psi, for aluminum alloys is 75,000 psi, and for titanium alloys is 120,000 psi. The 1-inch-thick specimen is 2 inches wide and 8.5 inches long. Larger specimens are required for testing corresponding alloys at lower yield strength levels.

Many other technical committees have been interested in evaluating fracture toughness of engineering materials. These committees usually have adapted ASTM testing methods to their programs.

The amount of available plane-strain fracture-toughness data that complies with the recommended practice is very limited at the present time. The scatter in K_{Ic} data is expected to be somewhat greater than that obtained for tension-test data and other data from less complex tests. Eventually, sufficient fracture-toughness data will be available for high-strength steels, aluminum alloys, and titanium alloys to permit establishing minimum allowable values for design purposes. The designer then can apply the fracture-toughness data to the calculation of critical flaw sizes for a structure of relatively simple design, for a material of a given strength level, and for a predetermined design load. These

calculations may be made for several alternate materials, with the objective being to determine what material has the best balance of crack tolerance, strength level, fabricability, etc., for the structure.

Before reliable design data can be established, however, information on optimum mill practice is desirable. Variation in fracture toughness for 250-grade maraging steel, with variation in finishing temperature, is shown in Figure 2.(8) Effects of variations in mill processing also are presented in Reference (9).

Representative plane-strain fracture-toughness data for high-strength plate materials are presented in Table 2. An explanation of the code letters for crack-propagation direction is shown in Figure 3.

Fracture-toughness data also may be applied to failure analysis of structures of high-strength alloys. One notable example of this is the analysis of the failure of the 260-inch-diameter booster of 18Ni maraging steel that failed on proof testing.(10) This investigation provided a demonstration of the method for calculation of critical flaw sizes and correlation of calculated flaw size with the sizes of flaws observed in the fractures.

Other applications for fracture-toughness testing and uses for the stress-intensity criteria will be made as more experience is gained in applying this concept to design, material selection, material evaluation, and nondestructive testing requirements. However, because of the relatively high cost for producing the specimens and the special procedures required for obtaining the data, considerable time and expense will be required before a large backlog of data and experience is acquired.

Motor Cases and Large Boosters

In the examinations made on early Polaris motor cases that had failed prematurely on proof testing, various notched and precracked

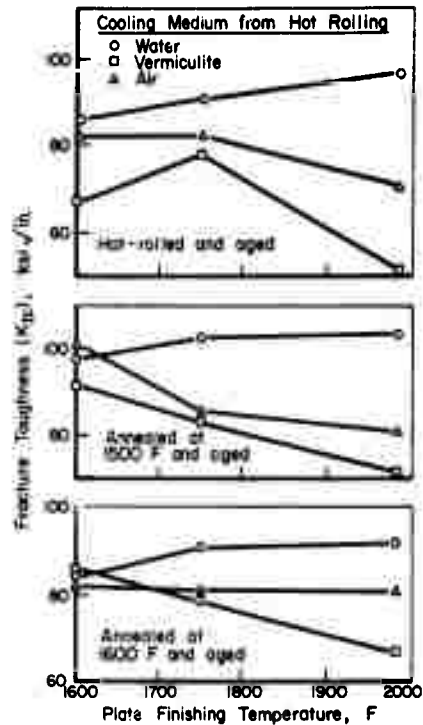


FIGURE 2. EFFECT OF FINISHING TEMPERATURE ON FRACTURE TOUGHNESS OF 18Ni MARAGING STEEL AT A YIELD STRENGTH OF 250,000 PSI(8)

TABLE 2. REPRESENTATIVE PLANE-STRAIN FRACTURE-TOUGHNESS DATA FROM NOTCHED-AND-PRECRACKED BEND SPECIMENS OF HIGH-STRENGTH ALLOY STEELS AT ROOM TEMPERATURE

Steel Type ^(a)	Yield Strength, ksi	Tensile Strength, ksi	Specimen Orientation	Specimen Dimensions,		Type of Bend Test	Best Estimate for K_{Ic} ksi√in.	Reference
				Thickness, in.	Width, in.			
18Ni Marage (VAR)	242	-	WR	0.45	1.2	4 pt.	84.5	(11)
18Ni Marage (VAR)	259	-	RW	0.50	1.2	4 pt.	68	(11)
18Ni Marage (VAR)	285	-	RW, RT	0.25-1.0	1.2	4 pt.	52	(11)
4340	213	-	RW ^(b)	0.5	-	3 pt.	70	(12)
4340	230	-	RW ^(b)	1	-	3 pt.	53	(12)
4110 (3 heats)	190	205	RW ^(b)	1	1	4 pt.	70-110	(1)
4340 (3 heats)	220	265	RW ^(b)	0.4	1	3 pt.	52-56	(1)
5Cr-Mo-V (H-11)	211	260	RW ^(b)	0.5	1	3 pt.	31-35	(1)
5Cr-Mo-V (H-11)	-	275	RW ^(b)	1	1	3 pt.	25	(1)
Doac	-	275	RW ^(b)	0.25	0.26-0.7	3,4 pt.	60-70	(15)

(a) AM = air melted, VM = vacuum melted, VAR = vacuum arc remelted.

(b) Probable orientations of specimens and notches (see Figure 3).

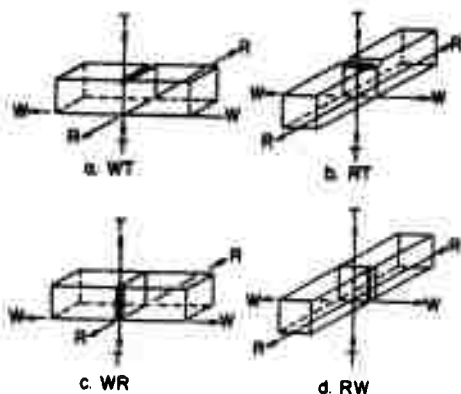


FIGURE 3. CRACK-PROPAGATION DIRECTIONS

R = Rolling Direction
W = Width Direction
T = Thickness Direction

specimens were used in attempting to obtain a quantitative parameter for evaluating the plane-stress (thin-section) properties of high-strength sheet steels and weldments. As a result of these studies, a better understanding was reached regarding the fracture-toughness requirements for high-strength steels used in thin-wall pressure vessels; however, no standard procedure is yet available for determining quantitative parameters to define the plane-stress fracture toughness of high-strength steels in sheet thicknesses.

Alloy-steel motor cases for tactical missiles usually are thin-wall cylinders that would require plane-stress analysis for determining the fracture-toughness parameters. In the absence of a standard quantitative test for obtaining values of K_{IC} , several alternatives may be used. One is to use the sharp-edge-notch or the precracked-center-notch specimens described in "Proposed Recommended Practice for Sharp-Notch Tension Testing of High-Strength Sheet Materials".⁽⁵⁾ The resulting information on notch-strength/yield-strength ratios is indicative only of the relative toughness of the sheet material.

Another alternative is to make somewhat arbitrary plane-stress fracture-toughness tests, using center-notched and precracked specimens as described in the above reference to obtain values for K_{IC} . Large center-notched panels also may be used. The procedure is discussed in a Committee report.⁽¹⁴⁾ Data from such tests may be used to estimate critical flaw sizes under plane-stress conditions. However, there are a number of uncertainties in these tests that have not been resolved, such as the effect of thickness, the effect of strain rate, the stress analysis when a relatively large plastic zone occurs ahead of the crack, etc. Therefore, proper interpretation of the data is necessary.

A more practical approach to the problem of determining the effects of small flaws in thin-wall pressure vessels is to induce small cracks in prototype vessels and subject them to hydrostatic tests. This has been done on several Government

programs.^(15,16) The data are summarized in Table 3, and in Figure 4. The data show that cracks of subcritical size do not appreciably affect the burst strength of the vessels. When information has been obtained in this way regarding the critical flaw size, one has an indication of the sensitivity required of the nondestructive testing equipment for identifying flaws in similar production motor cases. After the flaws are located, the same information is helpful in deciding which flaws should be repair welded. Welding repairs for flaws that are substantially smaller than critical size actually may cause damage rather than improvement in the motor-case performance.

This approach is feasible only for small pressure vessels or motor cases having relatively thin walls. However, precracked pressure vessel tests will be required to confirm plane-stress fracture-toughness data obtained on precracked sheet-type specimens when such tests are finally developed.

For relatively thick-wall booster cases of high-strength steel, fracturing at flaws tends to occur under plane-strain conditions. Since fracturing under these conditions occurs with only a limited amount of plastic deformation at the leading edge of the crack, the required stress analysis is not as complex as for the thin-section problem. The status of plane-strain fracture-toughness testing is discussed in a previous section. A limited amount of information has been obtained from hydrostatic tests on thick-wall pressure vessels containing intentional flaws.^(3,6,7) The available information verified the relationship between the fracture-toughness parameter and the critical flaw size for fracture initiation.

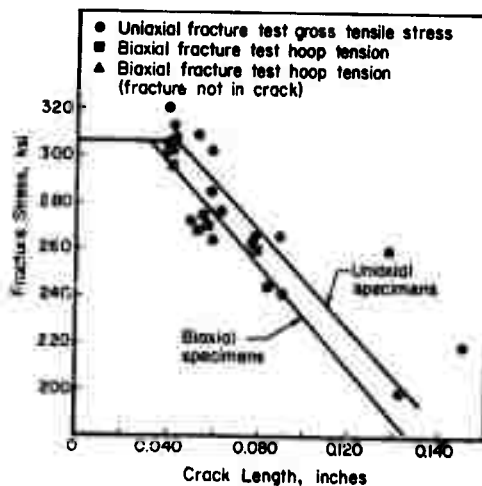


FIGURE 4. FRACTURE STRESS VERSUS CRACK LENGTH FOR PRECRACKED TENSION SPECIMENS AND PRESSURE VESSELS OF 250-GRADE MARAGING STEEL, COLD ROLLED AND AGED TO 305,000 PSI YIELD STRENGTH⁽¹⁶⁾

TABLE 3. HYDROSTATIC TEST DATA ON ALLOY-STEEL PRESSURE VESSELS HAVING INTENTIONAL FLAWS

Steel Type	Pressure-Vessel Dimensions		Flaw Size		Max Wall Stress With Flaw, ksi	Max Wall Stress Without Flaw, ksi	Remarks
	Wall Thickness, in.	Diameter, in.	Length, in.	Depth, in.			
18Ni Maraging (277 ksi Y.S.)	0.040	20	0.030	0.014	331	319	Tested at -65 F. (15)
18Ni Maraging (305 ksi Y.S.)	0.020	6	0.042	0.011	296	304	See Figure 4 for plot of data. (16) Tested at room temperature.
			0.056	0.013	275		
			0.057	0.013	270		
			0.078	0.012	261		
			0.079	0.013	261		
			0.084	0.013	245		
Type 301 Stainless (280 ksi Y.S.)	0.064	12.5	0.050	0.035	352	343	Tested at -65 F. (15) Vessel stretched 15.8 percent on cryoforcing at -320 F.

Since the practice recommended for plane-strain fracture-toughness testing has become available only recently, nonstandard methods were used in the earlier fracture-toughness studies of high-strength steel plate for solid-propellant boosters.

One of the outstanding studies in this area was that conducted by Aerojet-General Corporation in evaluating maraging steels for large booster motors. (17,18) The specifications developed on this program for maraging steel used in a large booster motor were eventually used in a later program in fabricating a 260-inch-diameter motor case that was successfully proof tested and test fired. (19) In the initial program, plane-strain fracture-toughness tests were made on specimens representing a number of heats of maraging steel and welds in these steels. Fracture-toughness correlation studies were conducted, using part-through-crack tensile specimens, center-notch tensile specimens, notch-bend test specimens, and precracked Charpy specimens. Air-melted, vacuum-degassed, and vacuum-arc-remelted heats of 18Ni maraging steel having yield strengths over the range from 200,000 to 300,000 psi were evaluated. These tests indicated that the highest yield strength that would provide the required level of fracture toughness for large motor cases was 235,000 psi for vacuum-arc-remelted maraging steel. The significant point is that the primary requirement was adequate fracture toughness to minimize the possibility of premature failure on proof testing and during static firing tests.

In a similar program for fabricating and testing 260-inch-diameter motor cases of maraging steel conducted by Thiokol Chemical Corporation and Newport News Shipbuilding and Drydock Company, the first motor case (SL-1) failed on proof testing. (10) Failure occurred at about 56 percent of the intended proof pressure. Examination of the fractures revealed two flaws, one being the primary origin of fracture and the other appeared to be a secondary origin of fracture. These defects were located in submerged arc welds under manual TIG repair welds. This motor case was

fabricated from air-melted 18Ni maraging steel of 250 grade. The fracture toughness of the submerged arc welds was not adequate to tolerate the defects that were revealed in the fractures. In this instance, nondestructive testing did not reveal these flaws before final aging and no inspection was conducted after final aging. This program has demonstrated the need for close cooperation among those responsible for material selection, welding, and nondestructive testing in order to minimize occurrence of premature failures. Because of complications in trying to determine K_{IC} values equivalent to the stress-intensity factors representative of the weld materials in the areas of the flaws, an accurate correlation of flaw size and fracture stress was not feasible. However, the failure analysis based on plane-strain fracture-toughness measurements and the size of the flaw at the fracture origin is described in the report. (10)

The results of these programs indicate that plane-strain fracture-toughness data can be applied when selecting materials and heat treatment for large thick-wall motor cases of high-strength steel, if the nondestructive inspection procedures are sufficiently sensitive to detect flaws of critical size.

Pressure Vessels Other Than Motor Cases

The situation in the establishment of fracture-toughness criteria for pressure vessels other than motor cases is much the same as for motor cases.

When there is no weight limitation, pressure vessels for pressurized gases or storage of liquids often are made of lower strength steels. If there is a weight limitation, the corrosive conditions or temperature conditions often dictate the use of high-strength stainless steels, aluminum, titanium, or nickel-base alloys.

However, maraging-steel pressure vessels have been fabricated for high-pressure gas storage. For these applications, the same fracture-toughness criteria apply as discussed in the previous section.

Landing Gear

Steels for landing gear are put into service at higher strength levels than are any other major structural components. At maximum design loads, some of the stresses in landing gear may approach the yield strength. According to information from the Bendix Corporation, the following four steels are used for the major landing gear components. (20)

Steel Type	Aircraft Designations	Tensile Strength Range, ksi
AISI 4340 (AMS 6414)	707, C-141, Electra	260 to 280
300 M (or 4340 M)	C-5A, 720, 727-200, 737, 747, 2707	280 to 300
988V40 (AMS 6423)	F4, RASC	260 to 280
N-11	B-70	--

Additional information from Grumman Aircraft Engineering Corporation indicates that landing-gear forgings for the F-111A are made of 4330 V Mod. steel vacuum-arc remelted and heat treated to 220-240-ksi tensile strength. (21) Axles for these gear are D6ac steel at 260-280 ksi, and pins and other small parts are AISI 4340 steel at 260-280 ksi.

At Grumman, all alloy steels for aircraft components are vacuum-arc remelted to achieve highest quality and best toughness. The general opinion at Grumman is that, since the cost of vacuum-arc-remelted (VAR) alloy steels has declined in recent years, the improved quality is worth the extra cost. With all alloy steels from VAR heats, there is no chance for mixing air-melted and VAR heats. Vacuum-degassed steel apparently does not meet their quality requirements.

At the beginning of the F-111 program forging billets for the landing gear were required to have a minimum 15-foot-pound Charpy V-notch energy at -65 F. This was not practical for steels in the 260-280 ksi strength range, and the requirement was eased after the program had begun. The D6ac steel and the 4330 V Mod. steel are purchased under General Dynamics specifications. The Charpy V-notch impact requirement, when it applies, is dependent on the cross section of the forging billet. However, most significance is placed on the transverse ductility of tensile specimens obtained from the forging billets and heat treated to the same strength as the forgings. The transverse ductility is the same as the reduction in area in transverse tensile specimens (RAT).

Vacuum-arc-remelted 300M steel forgings (0.40 to 0.45 percent C) at 280-300 ksi tensile strength are being used in landing gear for the C-5A cargo aircraft. (22) These are exceptionally large forgings and require large forging billets. At the beginning of the C-5A program, there was a 15-foot-pound Charpy V-notch energy requirement at -65 F for transverse specimens of the forging billets. However, the large billets had not received sufficient reduction on forging from the largest available VAR ingots to achieve this level of toughness at the high strength level. The highest impact values that were obtained for the large billets under the specified testing conditions were 5 to 9 foot-pounds, according to information from Lockheed-Georgia Company. Although the hot working received by the billets during their reduction to the landing-gear forgings substantially improves the toughness of

the material, the object of the initial tests is to qualify the billets before the forging operation. The material that does not qualify can be rejected before it is subjected to the costly forging operations.

Because of this problem, Lockheed-Georgia has been authorized to qualify the forging billets by means of RAT values from tensile specimens. Lockheed personnel believe that this is a much more useful means of qualification, and they have obtained statistical data to verify this conclusion. In order to obtain correlation with fracture-toughness data, samples from the 300 M alloy steel billets are being sent to the Air Force Materials Laboratory for fracture-toughness tests.

The above information was confirmed by the Bendix Corporation, which has the responsibility for fabricating landing gear for a number of military and civilian aircraft. Among these is the landing gear for the F4. The main forgings for this landing gear are made from billets of air-melted 988V40 (AMS 6423) alloy steel (aircraft quality) and are heat treated to 260-280-ksi tensile strength. (20) There are no toughness requirements for these components. However, heat-treated tensile specimens representative of the landing gear must meet minimum reduction-in-area-transverse (RAT) values.

According to additional information from the Bendix Corporation, the selection of steels for landing gear will be influenced by heat-treating procedure as well as by fracture-toughness considerations. In order to minimize the distortion that is usually experienced during the normal austenitizing and oil-quenching operations, Bendix has installed a new ausbay heat-treating unit that is large enough for C-5A landing-gear components. In this unit, the landing-gear components are austenitized in a controlled atmosphere furnace, quenched in a salt bath at 1000 F (at the nose of the S curve), then transferred to a salt bath at 400 F or to an oil quenching tank. This treatment is followed by the regular tempering treatment. The alloy steels to be heat treated by this method must have sufficient hardenability and extended transformation times at 1000 F for thorough hardening. Alloy steels that can be hardened satisfactorily by this method include AISI 4340, 300M, and AMS 6423. Achieving minimum distortion is significant, because this indicates low residual stresses.

As a result of this limited survey of fracture-toughness requirements of steels for landing gear, it is obvious that there is little if any application of fracture-toughness testing to the selection of alloy steels, qualification of forging billets, or forgings for landing gear.

In nondestructive inspection of forgings for landing-gear parts, one source reported that magnetic-particle inspection was the only method used. Others reported that they used magnetic-particle, penetrant, and ultrasonic methods. X-ray inspection was used only when welding was employed during fabrication. Because of the high strength level and high service stresses, the critical flaw sizes for landing gear are expected to be very small (about 1/8 inch long at the surface) for AISI 4340 steel at a tensile strength of 265,000 psi and yield strength of 220,000 psi when subjected to a tensile stress of 180,000 psi,

assuming the length of the crack is four times its depth. Repeated loading and corrosive conditions can cause growth of small flaws or cracks. Therefore, careful inspection of landing gear in service is warranted.

Aircraft Structural Components Other Than Landing Gear

The F-111 and C-5A aircraft contain a number of structural components of high-strength steel.

The carry-through fitting for the wing pivots and the outboard-pivot fittings for the F-111 are of D6ac steel forgings and weldments heat treated to 220-240-ksi tensile strength (190-ksi minimum yield strength).⁽²³⁾ Information from General Dynamics/Fort Worth indicates that fracture-toughness specimens representative of the forgings and plates are tested in order to insure adequate fracture toughness. Both center-notched-and-precracked tensile specimens and notched-and-precracked bend specimens are used. The type of specimen used presumably is dependent on the thickness of the metal in the forging or plate which it represents. The method used in testing the bend specimens is the same as the ASTM-recommended practice discussed previously. (See page 6) According to General Dynamics, the fracture-toughness tests are very sensitive to variations in quality of the material and processing variables. The K_{Ic} data from these tests have not been applied to stress analysis for estimating critical crack sizes at General Dynamics/Fort Worth, but if the K_{Ic} values are lower than the accepted minimum values, either the steel quality or the heat treatment is not satisfactory.

Some bulkhead forgings for the F-111 are of D6ac steel heat treated to 220-240-ksi tensile strength. Some of the other structural components for the F-111 also are D6ac steel forgings that are heat treated to 260-280-ksi tensile strength.

Most of these structural components are fabricated by welding of forgings. The weld areas in the components are very thoroughly inspected by radiographic, ultrasonic, and magnetic-particle procedures. If any defects are observed, they are ground out and the repair area is rewelded.

In the C-5A airframe, 300M steel forgings (VAR) are being used for a number of components, such as fittings, hinges, pins, etc.⁽²²⁾ A few parts of the landing-gear auxiliary structure are made of AISI 4340 steel (VAR) at 260-280 ksi tensile strength. A few forgings of D6ac steel heat treated to 260-280 ksi tensile strength also are used in the airframe. No fracture-toughness testing is involved in qualifying any of these forgings.

According to information from Grumman, 4330 V Mod. steel (VAR) at 220-240-ksi tensile strength is the steel used for many airframe components fabricated at Grumman.⁽²¹⁾ No fracture-toughness requirements are specified for these components, other than the limited Charpy V-notch requirements in the purchase specification for the forging billets.

Arresting hooks for naval aircraft represent a critical application of alloy steels

at high strength levels. These hooks have been made of 4330 V Mod., AISI 4340, D6ac, and maraging steels. However, no further information is available on the preferred alloy, its strength level or the evaluation of the steel for this application.

Gun Tubes

Gun tubes such as those used for 175-mm M113 and 105-mm M68 cannon represent critical applications by the Army for high-strength steels. For many years, there has been a continuing effort to obtain quality alloy steel for gun tubes, since the service requirements are unusually severe. Because of a fracture in service in Vietnam of one 175-mm M113 gun tube, this fractured tube and a number of others were subjected to an extensive mechanical-property study at Watervliet Arsenal.⁽²⁴⁾ The traditional qualification tests for gun tubes are tensile tests and V-notch Charpy impact tests, made on specimens obtained in the transverse direction from disks cut from one or both ends of the forged tube. The impact tests are made at -40 F and at room temperature.

In the above investigation, 38 175-mm M113 gun tubes from three vendors were sectioned in order to obtain test specimens from specified locations in each tube. Particular significance was placed on reduction in area for ductility and in Charpy V-notch energy for toughness. Results of the program indicated that the variation in these properties within a given tube and from one tube to another was significant. For this application, there was sufficient variation in the toughness in the transverse direction to be readily detected in the Charpy V-notch test data. The overall range for all Charpy data obtained at -40 F was from 4 foot-pounds to 25 foot-pounds. Precracked Charpy specimens also were obtained in the transverse direction using disks cut from the gun tubes and tested at -40 F. Data from these tests also indicated a wide scatter in W/A values (fracture energy in inch-pounds/residual fracture area in square inches). At -40 F, the W/A value for each tube was from 100 to 800 in-lb/in.², while the overall range for all specimens was from 150 to about 1070 in-lb/in.².

In another program conducted at Watervliet Arsenal, Charpy V-notch specimens and precracked Charpy specimens were used in characterizing the toughness of a series of 105-mm M68 gun tubes.⁽²⁵⁾ Again, a considerable spread in data was observed for both the standard Charpy and precracked Charpy data. However, statistical evaluation of the data obtained by both methods indicated that the precracked Charpy data provided a normal distribution, while the standard V-notch data represented a bimodal distribution. This effect reduces the validity of a direct comparison of the data. Actually, some of the standard V-notch specimens had fractured in the same way as had the precracked specimens, because of inclusions or flaws at the roots of the notches.

These results indicate that additional studies on fracture toughness of gun tubes are warranted. Advanced studies are being conducted at Watervliet Arsenal on the fracture problem.⁽⁴⁾

According to information from Watervliet Arsenal, a correlation has been obtained between

K_{IC} data and W/A values from precracked Charpy specimens with 0.032-inch side notches. Furthermore, the minimum Charpy V-notch energy requirement has recently been raised from 10 to 15 foot-pounds for gun tubes. This has been achieved by minimizing the residual elements in the heats of steel. An evaluation of vacuum-degassed and vacuum-arc-re melted heats of gun steel has failed to show a significant difference in toughness. However, vacuum-degassed heats exhibit a significant improvement in toughness over air-melted heats. This improvement accounts for the increase in the minimum-impact requirement from 10 to 15 foot-pounds. New alloy steels and various hot-cold working procedures and heat treatments are being evaluated in attempts to further improve toughness.

Gun tubes represent a critical application for fracture-toughness studies, since cracks are developed in service in a heat-check pattern on the inside surfaces of the tube near the breech end. Once the cracks are started, they become larger each time the gun is fired. The problem is to determine how long the gun can remain in service after the cracks have been initiated before complete fracture of the tube is imminent. The shock-loading effect, the heating effect of the charge, the corrosion effect of the gases in the tube, the possibility of a low-temperature environment, and the stress-concentration effect at the rifling notches are some of the factors to be considered in analyzing the problem of crack initiation and propagation in gun tubes. Since these factors are peculiar to the gun-tube application, the development of specific test methods for gun-tube steels may be required to provide quantitative information on their fracture-toughness characteristics. At the present time, however, the Charpy impact test is the primary test for indicating toughness of gun tubes.

Recoilless-Rifle Tubes

Alloy-steel tubing for recoilless rifles is a relatively thin-wall material and therefore is not amenable to plane-strain fracture-toughness testing. However, potential alloy steels for recoilless-rifle tubing were evaluated in 1962 at Frankford Arsenal, using sheet-type specimens of edge-notched and center-notched-and-precracked design. (26) These specimens were fractured on tensile loading, and K_{IC} values (for plane-stress fracturing) were reported. Data were obtained for each of the steels (Type 410 stainless, 4330 V [Mod. + Si], AMS 6434, D6ac, Airsteel X200, 300M, H-11 and AM350-CRT) at various tempering temperatures. The yield strength and toughness of each of the steels were compared in selecting the alloy steel and heat treatment that gave the best balance of strength and toughness for the application. Following these tests, firing tests were conducted to evaluate recoilless-rifle tubes of 4330 V (Mod + Si) steel. The firing tests apparently proved the 4330 V (Mod + Si) steel to be satisfactory for this type of service.

At Watervliet Arsenal, Timken seamless tubing of AISI 4337 steel is currently being used in production of the 106-mm recoilless rifle. The tubing is heat treated to a yield strength of 130,000 to 160,000 psi. Precracked impact

specimens (thinner than standard Charpy specimens) have been used to determine the relative toughness values of the steel in these tubes.

When a standard procedure has been developed for plane-stress fracture-toughness testing, evaluation of steels for recoilless-rifle tubes would be one application for the test.

CANADIAN MILITARY APPLICATIONS

Available reports from the Department of Energy, Mines and Resources in Ottawa indicate that plane-strain fracture-toughness tests have been made on high-strength steel armor plate and steels for hydrofoils. (27,28) The armor plate was a silicon-chromium-molybdenum steel with zirconium and boron added (XAR-30) and was 1/4 inch thick. After heat treating, it had an equivalent surface hardness of 495 Brinell and an equivalent center hardness of 410 Brinell. Single-edge-notch specimens for tensile loading were obtained from both the longitudinal and transverse directions in the plate. Fatigue cracks were developed at the roots of the notches. Since the plate did not have uniform hardness through the thickness, the data have only limited value. However, the results showed a significant difference in toughness between the longitudinal and transverse directions, the effects of low-temperature testing, and the effects of distilled water and seawater environments on the toughness of the plate. Such information could be useful to the designer and might be used for failure analysis in the event that brittle fractures occur in service.

In 1965, the foils of the prototype model of the Royal Canadian Navy's hydrofoil vessel were to be manufactured of 18Ni maraging steel (250 grade). Other steels, of lower strength and higher toughness, also were considered for this application; these included 12Ni maraging steel and HP 9Ni-4Co steel. Toughness of a laboratory heat and a commercial heat of 12Ni maraging steel was evaluated using standard V-notch Charpy impact specimens and precracked Charpy specimens. Information on the final results of tests obtained on this program is not available.

The importance of adequate fracture toughness in military applications of high-strength steels is being recognized in Canada and several Canadians are active on the subcommittee program of ASTM Committee E24.

UNITED KINGDOM MILITARY APPLICATIONS

Most of the British programs on fracture-toughness testing of steels are under the jurisdiction of the Navy Department Advisory Committee on Structural Steel and the Inter-Group Laboratories of the British Steel Corporation (formerly BISRA). In the Navy programs, steels and weldments have been divided into these categories: (29)

- (a) Steels with yield strengths up to 90 ksi
- (b) Steels with yield strengths between 90 and 180 ksi
- (c) Steels with yield strengths greater than 180 ksi.

For steels and weldments having less than 180-ksi yield strength, tests to indicate fracture initiation conditions and fracture propagation conditions include the Wells wide-plate test, the Pellini explosion-bulge test, the Robertson isothermal wide-plate test, the drop-weight test, the drop-weight-tear test, and the Navy tear test; all of these have been considered by the Navy Department Advisory Committee. The V-notch Charpy impact test is considered suitable for quality-control purposes if correlated with intermediate- or large-scale tests.

For steels having yield strengths greater than 180-ksi, the Navy Department Advisory Committee has agreed that the linear elastic fracture mechanics approach is the most appropriate for fracture-toughness evaluation. (30) Much of the research on fracture-toughness testing of high-strength steels is being conducted by the Inter-Group Laboratories of the British Steel Corporation and by 25 cooperating laboratories associated with the High Strength Steels Working Group. (31,32) Steels which have been evaluated on these programs include low-alloy steels of the following compositions:

Chemical Composition, percent

Specification	C	Si	Mn	S	P	Ni	Cr	Mo	V
NOM	0.45	0.79	0.44	0.008	0.012	1.72	1.31	0.88	0.23
F8539	0.39	1.45	1.15	0.006	0.008	1.80	0.09	0.40	0.24
EN308	0.27	0.20	0.53	0.009	0.012	3.98	1.11	0.14	--

These steels may be heat treated to yield strengths in the range of 180 to 260 ksi (tensile strength range 200 to 310 ksi). Maraging steel also has been evaluated in one of the programs. These steels might be applicable to landing gear, other aircraft forgings, missile motor cases, and other types of pressure vessels. Emphasis, however, has been placed on familiarization with the testing methods among cooperating laboratories and determination of the limitations of the testing methods rather than on testing a certain alloy for a specific application. Testing methods usually involved notched-and-precracked bend specimens and single-edge-notch tensile specimens proposed originally by members of ASTM Committee E24. As a result of these programs, each of the cooperating laboratories has gained experience in making plane-strain fracture-toughness tests. No information is available at the present time regarding plans for imposing requirements for minimum fracture-toughness values on British military components of high-strength steels. However, as more high-strength components are used in various military applications, there will be an increased demand to meet minimum fracture-toughness standards. Eventually, this will apply to high-strength aluminum and titanium alloys as well as to high-strength steels.

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13. ABSTRACT

This Memorandum discusses the current situation on the inclusion of fracture-toughness testing requirements in specifications for high-strength steels used for military applications. The Memorandum was prepared at the request of The Technical Cooperation Program (TTCP), and contains information from Canadian and British members of that program, as well as U. S. information. Military applications discussed include missile motor cases, aircraft landing gear, gun tubes, armor plate, and hydrofoils.

14. KEY WORDS	LINK A		LINK B		LINK C	
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