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REPORT R-1591

FRACTURE TOUGHNESS
OF
4330V (Mod + Si) STEEL
UNDER PLANE STRAIN CONDITIONS

by

C. M. CARMAN

Ordnance Project TS4-4024
DA Project 5S02-01-008

June 1961



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**FRANKFORD ARSENAL
RESEARCH AND DEVELOPMENT
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June 1961

ABSTRACT

An investigation was conducted to study size effects in notch tension testing and to determine the fracture toughness of 4330V (Mod + Si) steel under plane strain conditions. Fracture studies using circumferentially notched round specimens (0.505, 0.750, and 3 inches in diameter) of 4330V (Mod + Si) steel tempered at 600° and at 850° F, are described.

Using the mathematical model including plastic strain zone correction proposed by Irwin, the data were analyzed and the fracture toughness values were computed. Good agreement was found between fracture toughness values for the small specimens, but a somewhat lower value was found for the 3-in. specimens. This deviation is discussed in light of statistical size effects.

It is concluded that

1. Using different size specimens, Irwin's analysis corrected for plastic strain zone gives good correlation for the measured K_{IC} values provided plane strain conditions are met.

2. For this high strength steel tempered at 600° and 850° F, the size effect observed upon changing specimen diameter (from 0.505 to 3.00 inches) can be partially explained by statistical size effects.

3. For a steel having a yield strength greater than 200,000 psi, a 0.505 inch diameter circumferentially notched round specimen might be large enough provided the sources of error were better understood. At the present time a 0.750 inch diameter circumferentially notched specimen is better for this class of material.

It is recommended that

1. For obtaining plane strain conditions, techniques other than large specimen size be investigated.

2. Fracture studies on high strength materials suitable for recoilless rifle service be continued.

ACKNOWLEDGEMENT

The author wishes to thank Drs. G. R. Irwin and J. M. Krafft, of the Naval Research Laboratory, for their assistance and review of this report.

FRACTURE TOUGHNESS OF 4330V (Mod + Si) STEEL UNDER PLANE STRAIN CONDITIONS

INTRODUCTION

In determining the fracture toughness, K_{IC} , for a given material, it is usually desirable to determine the minimum value the material will exhibit. Normally, this minimum value is obtained under conditions of plane strain, which causes the material to fail in a brittle manner. Therefore, in order to determine the minimum fracture toughness of a material, it is necessary to select an experimental condition that will cause fracture in a brittle fashion. Several such conditions may be considered. Among these are sharp notches (to create high triaxial stresses), large section sizes, low temperature testing, and high strain rates. The study being reported upon is concerned mainly with the value of fracture toughness for increasing specimen sizes.

Brittle fracture in large section sizes has been discussed by several investigators. Lubahn and Yukawa^{(1)*} studied the effect of increasing section sizes in notched bending for a Ni-Mo-V steel at the 110,000 psi tensile strength level. By holding the notch radius constant as the section size was increased from 0.192 inch to 9 inches, the fracture strength was decreased by 43 percent. When the notch geometry was scaled up, the decrease in strength was not as severe.

Lubahn⁽²⁾ has determined the fracture toughness for a series of specimens by using both notch bending and notch tension. The material used in this investigation was of the same general type as was used by Lubahn and Yukawa. A considerable discrepancy was reported for K_{IC} as determined by the bending and tension methods.

Wundt⁽³⁾ has described a method whereby the notch strength is plotted against the unnotched diameter on a log-log scale. In this method, K_{IC} is defined by the value determined for the linear portion of the curve, which has a slope of $-1/2$.

Irwin, in his discussion of the last two papers,^(2, 3) suggested that the correlation among the specimens might be improved if correction is made for the plastic strain at the root of the notch. This is based on a mathematical analysis which must be verified experimentally. This may be accomplished by determining K_{IC} for a series of specimen sizes and including a large diameter specimen where the plastic strain would presumably be small and the correction negligible. If the analysis is valid, the corrected K_{IC} values would then be the same for all specimen sizes.

*See REFERENCES.

Using 0.505 and 0.750 inch diameter notched tensile specimens, the fracture toughness of 4330V (Mod + Si) steel has been determined previously at this arsenal.⁽⁴⁾ Since this steel has been demonstrated to be satisfactory for lightweight recoilless gun construction and possibly for other ballistic devices, it is desirable to determine the K_{IC} of this steel using large diameter specimens, thus verifying the proposed Irwin analysis.

MATERIAL AND HEAT TREATMENT

The composition of the 4330V (Mod + Si) steel used in this investigation is given in Table I.

Table I. Chemical Composition of 4330V (Mod + Si) Steel

<u>C</u>	<u>Mn</u>	<u>S</u>	<u>P</u>	<u>Cr</u>	<u>Ni</u>	<u>Mo</u>	<u>V</u>	<u>Si</u>
0.34	0.98	0.005	0.015	0.95	1.82	0.42	0.14	1.37

This material was received as a 6-inch square billet forged from Bethlehem Steel Company Heat 21K631.

All specimens of this steel were oil quenched from 1650° F. Half of the specimens were tempered for 4 hours at 600° F, to develop the optimum combination of strength and ductility. The remainder of the specimens were tempered at 850° F, to embrittle the steel.

A 3 inch diameter sample of this steel, hardened and tempered at 600°F, was sectioned and a Rockwell C hardness survey made. The results are shown in Figure 1. It may be seen that the steel has sufficient hardenability to develop full properties in a 3 inch diameter section.

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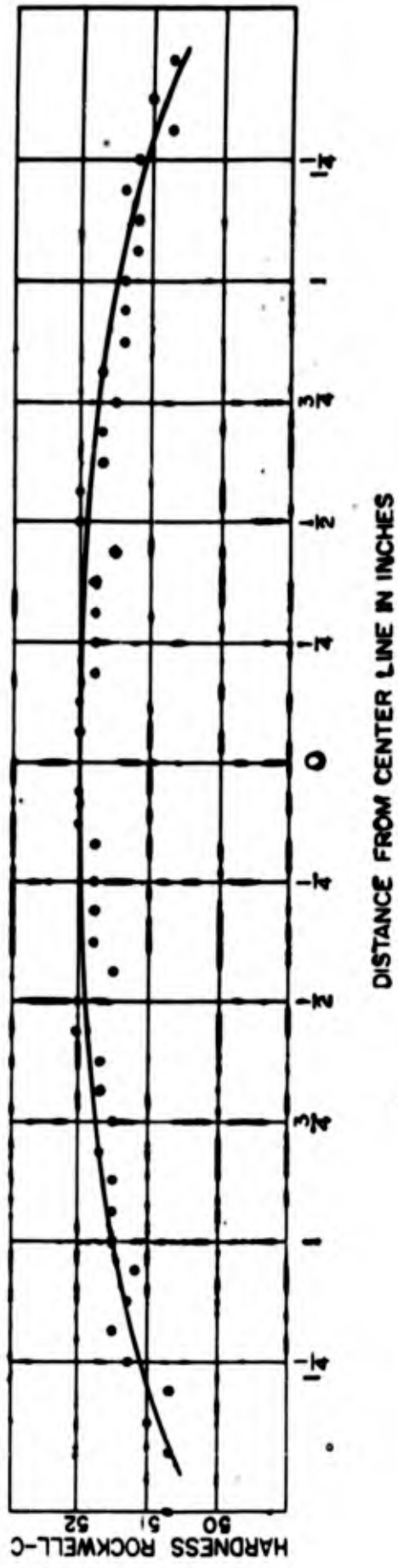


Figure 1. Hardness Survey of Oil Quenched 3 inch diameter Round of 4330V (Mod + S1) Steel

EXPERIMENTAL PROCEDURES

Circumferentially notched rounds, 0.505, 0.750, and 3.000 inch diameter, were used for this investigation. (Drawings of these specimens are shown in Figure 2.) The specimens were machined 0.020 inch oversize before heat treatment. After heat treatment, the specimens were ground to size and notched, using a thread grinder.

The 0.505 and 0.750 inch diameter specimens were tested using a special aligning fixture, as originally described by Sachs.⁽⁵⁾ The 3 inch diameter specimens were broken, using the five million pound testing machine at the Aeronautical Structures Laboratory at the Philadelphia Naval Base. Electrical resistance strain gages, placed 120° apart around the circumference, were used to assure alignment. (This arrangement is shown in Figure 3.)

The K_{IC} values were calculated using the following equations and plastic strain zone corrections as developed by Irwin^(6, 7) and described in a previous report.⁽⁴⁾ The equation for uncorrected K_{IC} follows.

$$K_{IC} = 0.233 \sigma_n \sqrt{\pi D} \quad (1)$$

where

K_{IC} is a stress field parameter describing the stress elevation at the advancing end of the crack;

σ_n is the notch strength;

D is the major diameter of the specimen.

The equation for K_{IC} corrected for plastic strain zone is

$$K_{IC} \left[1 - \frac{pK_{IC}^2}{2\pi \sigma_y^2 d} \right]^2 = 0.233 \sigma_n \sqrt{\pi D} \quad (2)$$

where

p is a proportionality constant

d is the minor diameter

σ_y is the uniaxial tensile yield strength.

There is some question as to the exact value to be used for p . It has been suggested that $p = 0.95$ for general yielding and that $p = 0.74$ to allow for some strain hardening. For this work it appears that

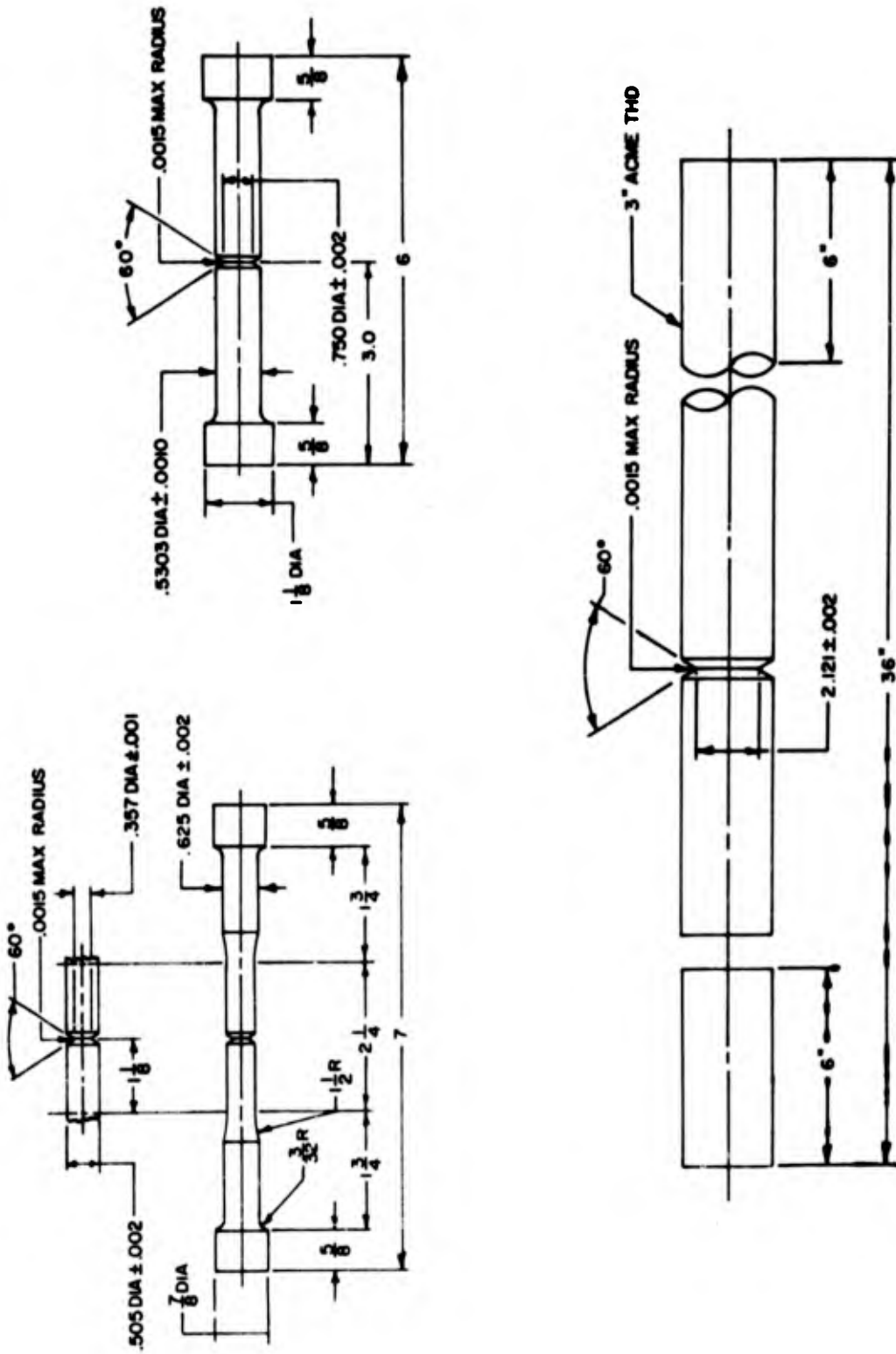


Figure 2. Drawings of Notched Specimens Used

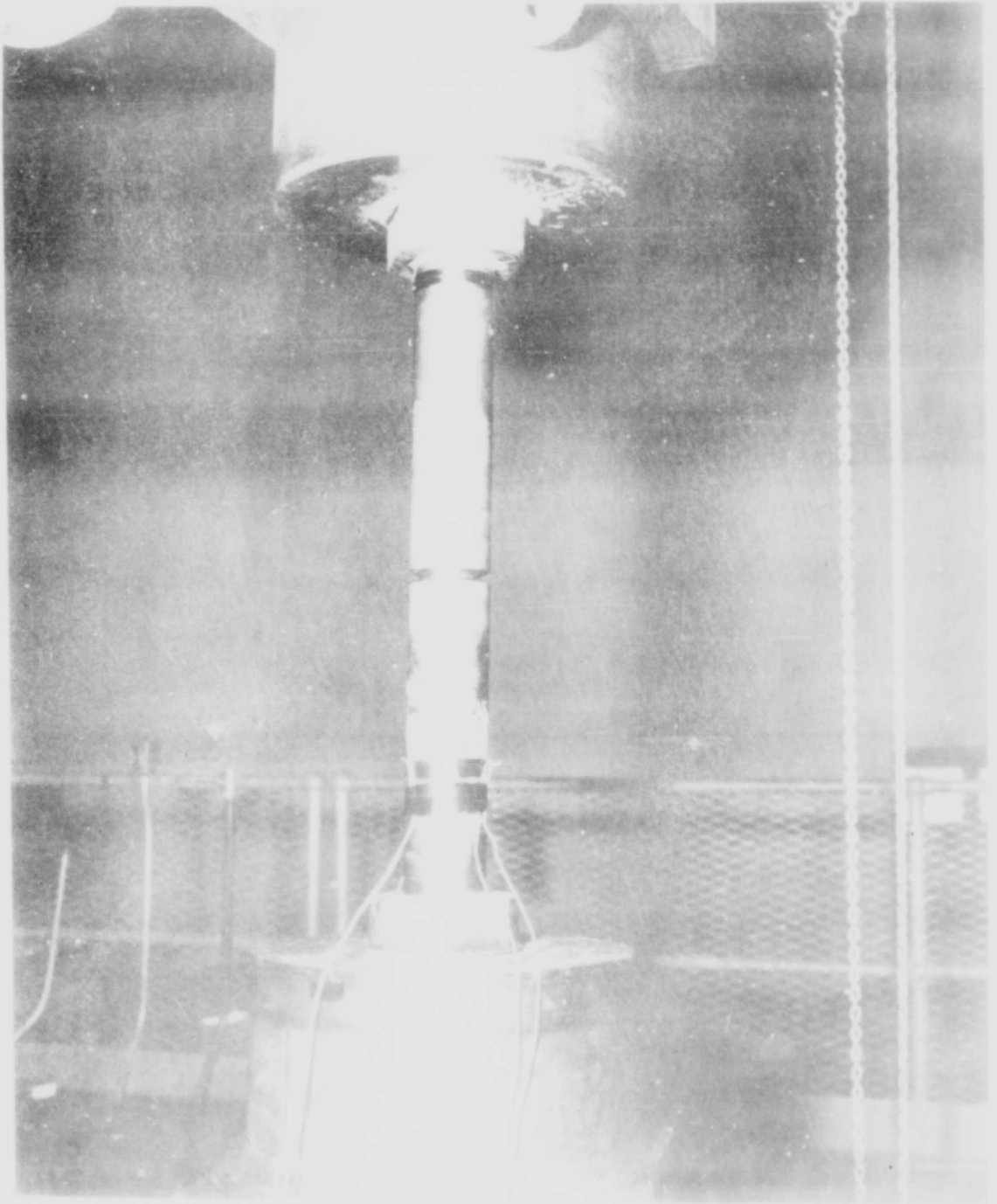


Figure 3. Specimen set up for Test in 5,000,000 lb Testing Machine

$p = 0.74$ (for calculation purposes, $p = 1/\sqrt{2}$) is a reasonable value since most ultrahigh strength steels show some strain hardening. A more suitable value may be determined by obtaining a good fit of extensive experimental data when such information becomes available.

The above equation may be written in the form:

$$x \left[1 - \frac{x^2}{2} \right]^2 = 0.233 \left(\frac{\sigma_n}{\sigma_y} \right) \quad (3)$$

where $x = \frac{K}{\sqrt{\pi D \sigma_y}}$.

The equation is plotted in Figure 4 for computation purposes. It will be seen at values of x approaching 0.63, equation (3) predicts a pronounced departure of σ_n from proportionality to inverse square root of specimen size and a trend toward a maximum value of $1.74 \sigma_y$.

The calculated values if K_{IC} are given in Table II. It will be seen that Irwin's analysis including a plastic strain zone correction appears to give good agreement among K_{IC} values for 0.505 and 0.750 inch specimens. The 3 inch diameter specimens gave somewhat lower values of K_{IC} .

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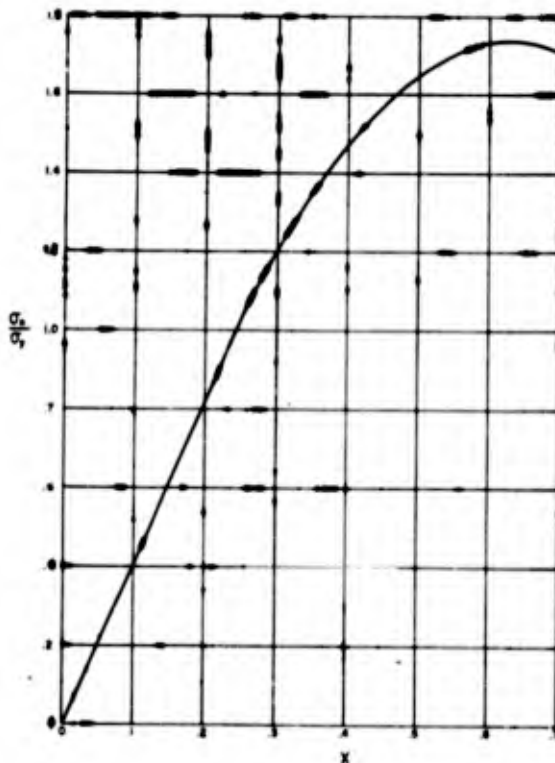


Figure 4. Influence of the Added Effective Notch Depth ($r_{ys}/2 \sqrt{2}$) upon the Relation of Net Section Stress to Inverse Square Root of Specimen Diameter for circumferentially notched Round Tensile Specimens (Irwin⁷)

Table II. Tensile Properties of 4330V (Mod + Si) Gun Steel

Tempering Temperature* (°F)	Notch Strength (psi)	K _{IC} (psi √in.)	
		Uncorrected	Corrected
0.505 inch Diameter Notched Specimen			
600	260,000	76,500	86,100
	269,000	79,100	89,200
	270,000	79,500	89,200
850	212,000	62,400	68,200
	190,000	55,900	60,500
0.750 inch Diameter Notched Specimen			
600	231,000	83,000	88,700
	237,000	85,200	91,800
	231,000	83,000	88,800
850	177,500	63,800	66,600
	182,400	65,500	69,200
1.25 inch Diameter Notched Specimen**			
600	196,900	91,000	94,300
	196,300	90,000	94,300
	190,400	88,000	92,200
3.00 inch Diameter Notched Specimen			
600	106,780	76,400	76,300
	109,780	78,500	79,400
	107,020	76,600	76,300
850	79,332	56,700	56,300
	77,193	55,200	54,600
	72,519	51,900	53,600

*600° F tempered steel - 207,000 psi Yield Strength (0.10% offset)
262,000 psi Tensile Strength

850° F tempered steel • 174,500 psi Yield Strength (0.10% offset)
232,000 psi Tensile Strength

**Data supplied by Dr. J. M. Krafft, Naval Research Laboratory

In these tests, since a size factor of six (from 0.5 to 3.0 inch) has been tested, it is expected that statistical size effects may play a part. A semiquantitative analysis can be applied to fracture size effect experiments in terms of extreme value statistics, sometimes called "worst flaw" theory.^(8, 9) The simplest analysis of this type is the one introduced by Weibull.⁽¹⁰⁾ Essentially, the dominant flaws are assumed to be randomly distributed and independent. The symbol S represents the stress level limitation imposed by a particular flaw acting independently. Weibull assumed the probability per unit volume (P_S) of flaws of given S values could be represented as shown in the following equation.

$$P_S dS = n \left(\frac{S}{\sigma}\right)^{n-1} dS \quad (4)$$

σ is a very large, fixed stress of no great theoretical importance. The important parameter is n . Large flaws become increasingly frequent relative to small flaws as n is reduced. The value of this analysis rests primarily on its relative mathematical simplicity, since this analysis does not account for all the variables which may be present in the flaw population. In particular, the parameter n serves a useful purpose in providing a one-parameter description of the magnitude of an observed fracture stress size effect.

From Equation (4), the average strengths S_1 and S_2 observed in tests of two sizes of specimen are related to the flaw distribution regions V_1 and V_2 , as shown in Equation (5).

$$\left(\frac{S_1}{S_2}\right) = \left(\frac{V_2}{V_1}\right)^{1/n} \quad (5)$$

In considering fracture tests of circumferentially notched rounds, a small annular ring of material beneath the notch corresponds to V , which is proportional to the diameter of the specimen. Since K is a stress field parameter describing the stress elevation at the advancing end of the crack, K may be substituted for S and the equation written as follows:

$$\left(\frac{K_1}{K_2}\right) = \left(\frac{D_2}{D_1}\right)^{1/n} \quad (6)$$

Davidenkov, Shevandin, and Wittman⁽¹¹⁾ investigated the size effects of a commercial metal under extremely brittle conditions and found an n value of 25. Using this value for n and solving Equation (6) for the statistical size effect for the 0.505 and 3 inch diameter specimens, the results in Table III were obtained.

Table III. Size Effects for 4330V (Mod + Si) Steel

Tempering Temperature (°F)	Size Effect	
	Calculated	Observed
600	1.07	1.15
850	1.07	1.16

If the material, mathematical model, and testing procedure were perfect, there would be an upward trend in K_{IC} as the notch depth increases, which is indicated by the data for the 0.505, 0.750, and 1.25 inch diameter specimens. While the data for the three inch diameter notch specimens show a decrease, approximately 50 percent of this effect may be explained by the use of extreme value statistics.

The fracture appearance of the specimens of 4330V (Mod + Si) steel are shown in Figures 5, 6, and 7. All of these specimens showed a brittle fracture appearance.

Irwin⁽¹²⁾ has developed an expression for determining the minimum size of specimen needed for reliable K_{IC} values allowing for plastic strain zone. The equation is

$$K_{IC \text{ max}} = \sqrt{0.385 \sigma_y^2 D}$$

Solving this equation, using a yield strength of 200,000 psi and a diameter of 0.500 inch, gives a $K_{IC \text{ max}}$ of 89,400 psi $\sqrt{\text{inch}}$. This value represents approximately the average value for the 4330V (Mod + Si) steel tempered at 600° F, and would be a marginal situation. Under these conditions, the use of a 0.750 inch diameter specimen would give better data.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that

1. Using different size specimens, Irwin's analysis corrected for plastic strain zone gives good correlation for the measured K_{IC} values provided plane strain conditions are met.

2. For this high strength steel tempered at 600° and 850° F, the size effect observed upon changing specimen diameter (from 0.505 to 3.00 inches) can be partially explained by statistical size effects.

3. For a steel having a yield strength greater than 200,000 psi, a 0.505 inch diameter circumferentially notched round specimen might be large enough provided the sources of error were better understood. At the present time a 0.750 inch diameter circumferentially notched specimen is better for this class of material.

It is concluded that

1. For obtaining plane strain conditions, techniques other than large specimen size be investigated.

2. Fracture studies on high strength materials suitable for recoilless rifle service be continued.

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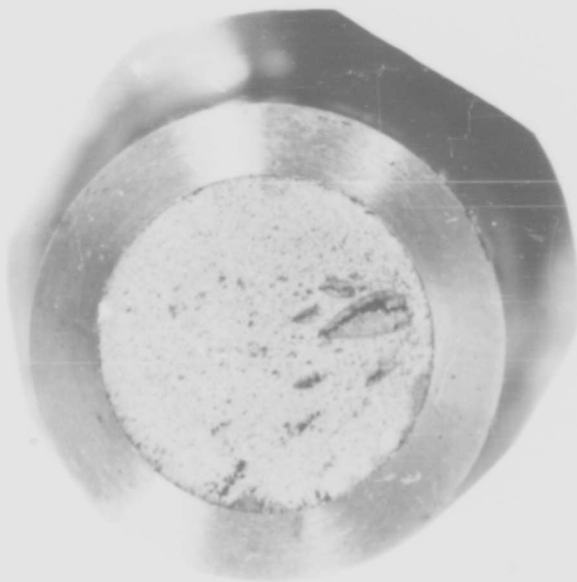
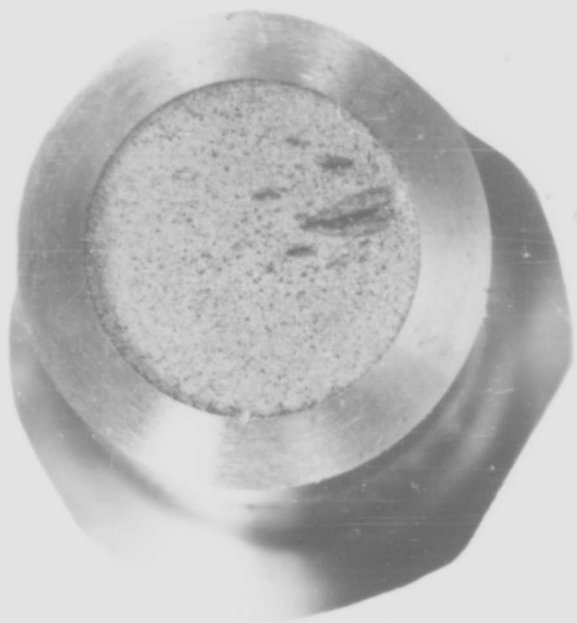


Figure 5. Fracture Appearance of 0.570 inch specimen of 4330V (Mod + Si) Steel Tempered at 600° F

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Figure 6. Fracture Appearance of 3 inch specimen of 4330V (Mod + S1) Steel Tempered at 600° F

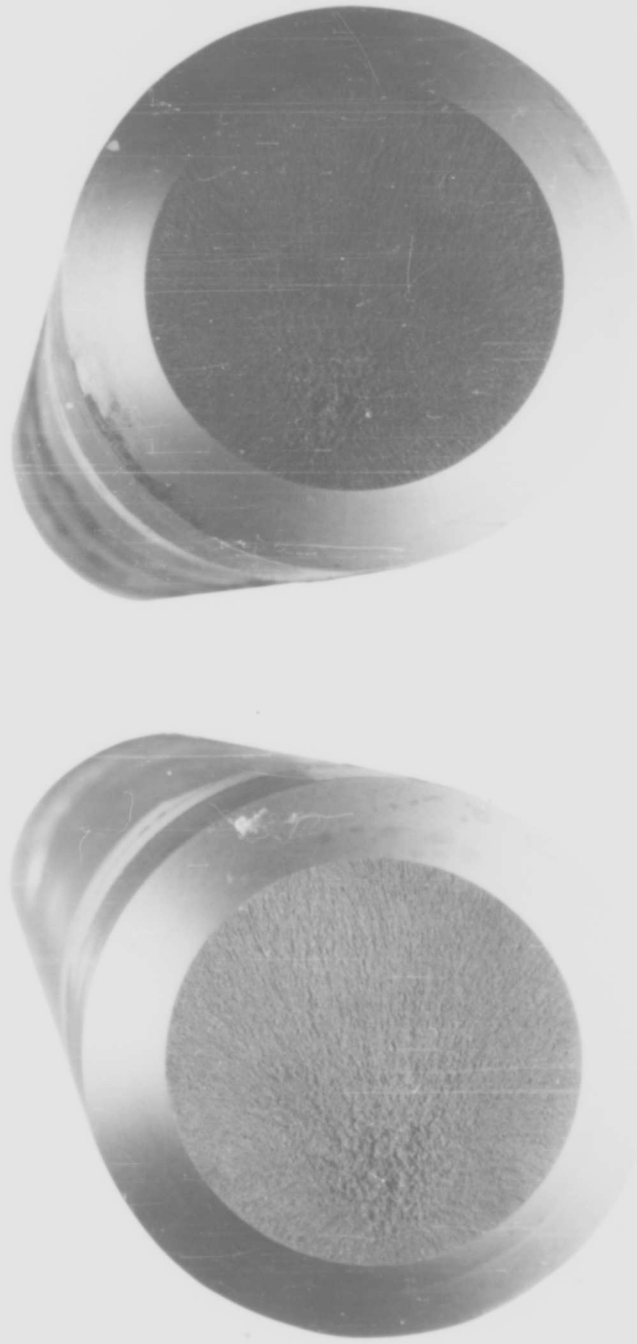


Figure 7. Fracture Appearance of 3 inch specimen of 4330V (Mod + Si) Steel Tempered at 850° F

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are met.
2. For this high strength steel tempered at 600° and 850° F, the size effect observed upon changing specimen diameter (from 0.505 to 3.00 inches) can be partially explained by statistical size effects.
3. For a steel having a yield strength greater than 200,000 psi, a 0.505 inch diameter circumferentially notched round specimen might be large enough provided the sources of error were better understood. At the present time a 0.750 inch diameter circumferentially notched specimen is better for this class of material.
It is recommended that
1. For obtaining plane strain conditions, techniques other than large specimen size be investigated.
2. Fracture studies on high strength materials suitable for recoilless rifle service be continued.

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<p>AD- R-1591</p> <p>FRANKFORD ARSENAL, Research and Development Group, Philadelphia 37, Pa. FRACTURE TOUGHNESS OF 4330V (Mod + S1) STEEL UNDER PLANE STRAIN CONDITIONS by C. M. Carman</p> <p>Report R-1591, June 1961; 21 pages incl illus and tables; OCO Project TS4-4024; DA Project 5502-01-008</p> <p>An investigation was conducted to study size effects in notch tension testing and to determine the fracture toughness of 4330V (Mod + S1) steel under plane strain conditions. Fracture studies using circumferentially notched round specimens (0.505, 0.750, and 3 inches in diameter) of 4330V (Mod + S1) steel tempered at 600° and at 850° F, are described.</p> <p>Using the mathematical model including plastic strain zone correction proposed by Irwin, the data were analyzed and the fracture toughness values were computed. Good agreement was found between fracture toughness values for the small specimens, but a somewhat lower value was found for the 3-in. specimens. This deviation is discussed in light of statistical size effects.</p> <p>It is concluded that</p> <ol style="list-style-type: none"> 1. Using different size specimens, Irwin's analysis corrected for plastic strain zone gives good correlation for the measured K_{IC} values provided plane strain conditions 	<p>UNCLASSIFIED</p> <p>1. Metallurgy 2. Recoilless Guns 3. Iron Alloys 4. Ultrahigh Strength Steel 5. Fracture</p> <p>I. Carman, C. M. II. TS4-4024</p> <p>DISTRIBUTION LIMITATIONS: None; obtain copies from ASTIA</p>	<p>AD- R-1591</p> <p>FRANKFORD ARSENAL, Research and Development Group, Philadelphia 37, Pa. FRACTURE TOUGHNESS OF 4330V (Mod + S1) STEEL UNDER PLANE STRAIN CONDITIONS by C. M. Carman</p> <p>Report R-1591, June 1961; 21 pages incl illus and tables; OCO Project TS4-4024; DA Project 5502-01-008</p> <p>An investigation was conducted to study size effects in notch tension testing and to determine the fracture toughness of 4330V (Mod + S1) steel under plane strain conditions. Fracture studies using circumferentially notched round specimens (0.505, 0.750, and 3 inches in diameter) of 4330V (Mod + S1) steel tempered at 600° and at 850° F, are described.</p> <p>Using the mathematical model including plastic strain zone correction proposed by Irwin, the data were analyzed and the fracture toughness values were computed. Good agreement was found between fracture toughness values for the small specimens, but a somewhat lower value was found for the 3-in. specimens. This deviation is discussed in light of statistical size effects.</p> <p>It is concluded that</p> <ol style="list-style-type: none"> 1. Using different size specimens, Irwin's analysis corrected for plastic strain zone gives good correlation for the measured K_{IC} values provided plane strain conditions 	<p>UNCLASSIFIED</p> <p>1. Metallurgy 2. Recoilless Guns 3. Iron Alloys 4. Ultrahigh Strength Steel 5. Fracture</p> <p>I. Carman, C. M. II. TS4-4024</p> <p>DISTRIBUTION LIMITATIONS: None; obtain copies from ASTIA</p>
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2. For this high strength steel tempered at 600° and 850° F, the size effect observed upon changing specimen diameter (from 0.505 to 3.00 inches) can be partially explained by statistical size effects.
3. For a steel having a yield strength greater than 200,000 psi, a 0.505 inch diameter circumferentially notched round specimen might be large enough provided the sources of error were better understood. At the present time a 0.750 inch diameter circumferentially notched specimen is better for this class of material.
It is recommended that
1. For obtaining plane strain conditions, techniques other than large specimen size be investigated.
2. Fracture studies on high strength materials suitable for recoilless rifle service be continued.

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