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THE CIRCUMFERENTIALLY NOTCHED CYLINDRICAL BAR AS A FRACTURE TOUGHNESS TEST SPECIMEN

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INTRODUCTION

The early work with circumferentially notched cylindrical specimens was concerned mainly with the effects of mild notches and was directed primarily to the simulation of stress concentrations associated with cross sectional changes in machined parts (e.g., Ludwik, ref. 1) and in an attempt to elucidate the effects of triaxial stress states on the technical cohesive strength and notch ductility of metallic alloys (e.g., McAdam, ref. 2 and Sachs, ref. 3). More recently the notched cylindrical specimen has been used by Cox and Low (ref. 4) in a study of the effects of triaxiality on void formation and growth in high strength steels.

When sharply notched (notch radius $<$0.001 inch) or fatigue cracked, the notched cylinder has certain advantages as a fracture toughness specimen. In particular, it can provide high stress gradients and high constraint to plastic deformation up to and throughout the fracturing process. However, these advantages are balanced by problems associated with specimen preparation and testing as well as a relatively inefficient use of material in K_{Ic} tests as compared with the present ASTM E-399 standard plate specimens.

This paper will present a brief review of the application of the notched cylinder as a screening specimen for use in sorting materials in respect to their relative levels of plane strain fracture toughness and a discussion of fracture mechanics applications including Irwin's important contributions in this area. In addition, practical problems encountered in application of this specimen will be presented.

ALLOY SCREENING APPLICATIONS

Early Developments

A little over 30 years ago Sachs and co-workers introduced the sharply notched cylindrical specimen as a means for investigating the so-called notch sensitivity of high strength steels. These early investigations (refs. 5 and 6) established the effects of notch depth and notch root radius on the nominal notch strength values. It was clearly shown that the effect of notch root radius was dependent on the tensile strength level of the alloy and at high strength levels the notch strength decreased rapidly with decreasing root radius. The size effect was recognized but not investigated and the specimen major diameter was fixed at D = 0.5 inch and the notch diameter at d = 0.35 inch (notch depth = d/D = 0.707). It was further shown that the ability of the notch cylindrical specimen to distinguish differences in notch strength among different metal conditions having the same yield strength increased with increasing notch sharpness. For this reason the notch radii were held to one mill which was the lowest value consistently obtainable with the high strength steels. For all the high strength low alloy steels investigated sufficiently ductile conditions possessed a notch strength to tensile ratio of 1.5*. Ratios less than this value indicated notch weak-

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*Studies of the influence of notch depth (6) showed that the upper limit of the notch strength ratio for these steels was $2 - (d/D)^2$.

ing. However, it was recognized that to be useful in distinguishing between the relative notch sensitivity of various steels this ratio had to be less than about 1.0. No attempts were made to produce natural cracks in these specimens nor was the stated purpose of the test to measure the sensitivity of the steels to the presence of crack-like defects. In fact, 30 years ago there was no general recognition that cracks or crack-like defects were significant factors in reducing the load carrying capacity of structures made from high strength steels. The early work on notch sensitivity was never criticized because the notches were not sharp enough but rather that they were too sharp to represent any practical situation of high stress concentration that might be encountered in service.

This state of ignorance concerning the soundness of high strength structural components and their sensitivity to flaws was abruptly changed by the unexpected hydrotest failures of the Polaris motor cases in the late 1950's. In 1969 the ASTM was asked by the DOD to organize a special committee whose job was the recommendation of test methods for evaluating the crack propagation resistance of high strength alloys. This Special Committee on Fracture Testing of High Strength Materials is now the ASTM E-24 Committee on Fracture Testing of Metals. Irwin was active on this committee from its inception and quickly recognized the value of the sharply notched cylindrical bar as a test specimen useful for judging the relative fracture resistance of materials under plane strain conditions such as might be encountered in the failure of heavy sections of high strength structures. In 1962 the Special ASTM Committee issued a report (ref. 7) which reviewed the effects of various geometrical variables on the notch strength of cylindrical specimens and recommended a sharply notched cylindrical specimen essentially identical to that used in the early investigations by Sachs. This report contained suggestions as to how sharply notched cylindrical specimens might be fatigue cracked. However, as will be discussed later, this process has proven difficult to control and is probably unnecessary for the use of the specimen in a fracture toughness screening test.

Examples of the use of the sharply notched cylinder as a fracture toughness screening test are illustrated in figures 1 and 2. The notch strengths of four low alloy steels are shown as a function of the tensile strength in figure 1. At notch to tensile strength ratios below about 1.0 the 0.5 inch diameter specimen is able to clearly distinguish differences in the toughness of these alloys. It should be noted that only small differences exist among these steels in smooth bar elongation and reduction of area, and these variations do not correlate with the differences in the notch strengths. A comparison of the notch strengths of quenched and tempered and austempered structures is shown in figure 2 as a function of hardness for a chromium steel. The austempered structure contains intermediate transformation products (mainly banite) as well as untempered martensite. The superiority in toughness of the tempered martensitic structure is clearly indicated by the notch strengths.

Proposed ASTM Method for Sharp Notch Testing

It would seem reasonable to conclude that a ranking of alloys at a given tensile or yield strength level in terms of their sharp notch strength would be the same as their ranking in terms of plane strain fracture toughness as determined by the ASTM E-399 test method. With this thought in mind the ASTM E-24 Committee has prepared a draft method of test entitled "Sharp Notch Tension Testing of Thick High Strength Aluminum and Magnesium Alloy Products with Cylindrical Specimens." The test sections for the two proposed specimens are shown in figure 3. No mandatory method of gripping these test sections will be specified, rather a limit will be placed on the maximum bending stress measured at a specified load using a special evaluation specimen. It is hoped that the smaller one (D = 0.5 inch) will be generally useful in mill quality control and that the larger one (D = 1.06 inch) will be required only for tests on the toughest alloys. It is anticipated that the use of these specimens will substantially reduce the cost of qualifying mill products on the basis of K_{Ic} specifications. Thus, a minimum sharp notch strength would be specified rather than a K_{Ic} value providing that a satisfactory correlation can be demonstrated between the sharp notch strength and K_{Ic} for the range of metal conditions that is expected to be encountered. A further discussion of the use of the notched cylindrical specimen in testing aluminum alloy products is given by Kaufman (ref. 8) in a paper which also presents data on those features of specimen preparation and testing which can influence the notch strength.

FRACTURE MECHANICS APPLICATIONS

General Comments

The notched cylinder has been referred to as a plane strain specimen; however, this designation is not strictly correct although the specimen does provide high constraint to plastic flow. Plane strain in a rectangular coordinate system corresponds to a situation where the stresses, strains and displacements are functions of only two coordinates, say y and z with the displacement and strain in the x direction being zero. This is the condition which we assume exists near the center of the thickness in a plane strain fracture toughness test on a plate specimen when the thickness is sufficient. For the notched cylinder the usual coordinate system is r, θ and z. Considering the r - θ plane, a point on a radius will move inward under load producing a radial strain ε_r and a tangential strain $\varepsilon_\theta = u_r/r$ even though the tangential displacement is zero. Thus, there will be three nonzero strains ε_r, ε_θ and ε_z all functions of r and z but not of θ. This is not a condition of plane strain.

Stress Intensity Solutions

In 1956 Irwin published in an NRL Report (ref. 9) an approximation to what he called the crack extension force tendency for the circumferentially cracked cylinder. Using that approximation and data obtained by Sachs on sharply notched 75S-T6 (now 7075 T6) aluminum cylindrical specimens, Irwin calculated a critical value of $\mathcal{G}$ as 100 in-lbs/in^2. Converting this to K we obtain a value of about 33 ksi-in$^{1/2}$ which is not far different from the presently accepted average value of 27 ksi-in$^{1/2}$

for this alloy. The higher value obtained by Irwin was due in part to the fact that the specimens were not fatigue cracked. It is interesting to note that the Abstract page of the NRL Report contains a brief statement under the heading PROBLEM STATUS: "This is an interim report; work on the problem is continuing." Nearly 20 years later the work is still continuing and will in all probability continue for many more years. This flow of research is not surprising when one considers the scope of application of Irwin's concepts to both metallurgy and structural design.

As a contribution to the work of the ASTM Special Committee on Fracture Testing of High Strength Materials in 1961, Irwin developed a more accurate estimate of stress intensity factors for the circumferentially cracked cylinder. This solution was based on the stress concentration factors given in Peterson's tables, and made use of the relation:

$$K = \lim_{\rho \to o} \sigma_{max} (\pi\rho)^{\frac{1}{2}}$$

where σ_{max} is the maximum stress at the notch root and ρ is the notch root radius. Considering that $\sigma_{max} = K_t \sigma_n$, this may be rewritten in terms of ρ/D and in the same form

$$K = \sigma_n (\pi D)^{\frac{1}{2}} \lim_{\rho \to o} \tfrac{1}{2} K_t (\rho/D)^{\frac{1}{2}} = \sigma_n (\pi D)^{\frac{1}{2}} N$$

where K_t is the theoretical stress concentration factor which can be obtained from Peterson's tables in terms of ρ/D and d/D where d is the notch diameter and D is the major diameter. The coefficient N was evaluated by selecting given values of d/D and plotting $K_t (\rho/D)^{\frac{1}{2}}$ as a function of $(\rho/D)^{\frac{1}{2}}$. The resulting curves which were nearly straight lines were extrapolated to $\rho/D = 0$. As an aid in developing the relation between N and d/D the solution for an edge crack in a half plane was used to fix the approach of this relation toward d/D = 1 and the fact that $K_t\ (2\rho/d)^{\frac{1}{2}}$ approaches unity as $2\rho/d$ approaches zero was used to fix the approach toward d/D = 0. The complete result of Irwin's approximation is shown in figure 4 which shows the coefficient N as a function of d/D. Added to this representation are the results obtained by Benthem and Koiter (ref. 10) who make use of the solution for the edge crack in a half plane and a penny shaped dam between two half spaces to produce asymptotic solutions for d/D approaching unity and d/D approaching zero respectively. A cubic interpolation is used to approximate the values of N over the entire range of d/D. Bueckner (ref. 11) employed essentially the same method but made use of Neuber's formula for deep notches to fix the approach of the coefficient toward d/D = 0. His results cannot be distinguished on figure 4 from those obtained by Benthem and Koiter. More recently Bueckner (20) provided a more rigorous treatment of the problem which did not depend on interpolations between asymptotic solutions. These results are shown as points in figure 4. Irwin's solution lies somewhat below those obtained by other investigators. This difference may be due in part to differences in the interpolation formulae characterizing the various solutions. While Irwin did not directly use an interpolation formula, Peterson's tables were developed from an interpolation procedure used by Neuber to obtain stress concentration factors for notches of intermediate depth. Another source of the difference may be associated with difficulties in extrapolation of Peterson's tables to $\rho/D = 0$. All the information given in figure 4 shows the highest stress intensity factor corresponds to a $d/D = 0.707$.

K_{Ic} Determinations

There is only a small amount of published information which relates to comparisons between K_{Ic} values determined with fatigue cracked notched cylinders and those determined with plate specimens (refs. 12, 13 and 14). It is difficult to make meaningful comparisons on the basis of these data because at the time the tests were made there were no generally accepted standards for measuring K_{Ic} and the plate specimen data was analyzed somewhat differently by the different investigators. However, for relatively brittle steels Wei and Lauta (ref. 12) report essentially the same K_{Ic} values for fatigue cracked notched rounds as obtained with carbonitrited edge notched plate tension specimens. In contrast, data reported by Carmen et al (ref. 13) show very substantial differences between K_{Ic} values obtained with fatigue cracked notched cylinders and edge cracked plate tension specimens for several high strength aluminum alloys. Similar discrepancies were noted by Senn (ref. 14) for high strength conditions of 4340 steel. Both Carmen et al and Senn show toughness values for fatigue cracked notch rounds higher than those obtained using the plate specimens. It would be expected that the notched cylinder would "select" the failure direction of lowest toughness in the notch plane and that this behavior could result in differences in K_{Ic} between plate specimens and notched cylindrical specimens cut from the same stock. However, this effect could not explain the discrepancies noted above. Clearly, considerable additional data is needed to make a useful comparison between K_{Ic} values determined by cylindrical specimens and plate specimens.

Fatigue Cracking

The problem here is twofold: (1) to develop a crack that is concentric with the longitudinal specimen axis under controlled conditions of loading, and (2) to determine when a crack of sufficient depth has been produced. Generally, fatigue cracking has been done in reversed bending useing an engine lathe, although there is no reason why tension fatigue could not be used if proper precautions are taken to obtain satisfactory alignment. When using a lathe the specimen may be mounted between centers and a radial force applied through a bar mounted on the crossfeed which has on its end a pair of ball bearing wheels which span the notch. A controlled amount of initial radial load is obtained by moving the crossfeed to cause the wheels to press on the specimen. The bending moment may be approximated from measurements of the specimen deflection. The K values can be calculated using the solutions provided by Benthem and Koiter (ref. 10). If the equipment is sufficiently rigid this method has the advantage that the load decreases as the crack develops. The alignment that can be obtained using machine shop lathes may not be good enough to permit satisfactory fatigue cracking and this can only be learned from experience. A special holding fixture for the specimen has been developed by Mylonas (ref. 15) which provides adjustments to control misalignments when fatigue cracking is done in a lathe. If the test material is not sufficiently isotropic in its fatigue characteristics there is no way to produce a concentric fatigue crack.

Determination of crack initiation is often difficult even when using a tool makers microscope. Depending on the material, roughness at the notch root due to plastic flow can be confused with cracking. Unfortunately, there is no way of determining the crack depth from observations on the surface and crack depth measurements must be made on the fractured surface. Problems associated with fatigue cracking the notched cylinder have been important factors in discouraging its use as a specimen for K_{Ic} determination. Obviously, we need a much better understanding of how the conditions of fatigue cracking influence the fracture strength before fatigue cracking conditions can be prescribed for the purposes of standardization.

Eccentricity of Loading

The importance of ensuring a low eccentricity of loading when testing notch cylindrical specimens was pointed out a long time ago by Sachs and Lubahn (ref. 5). Later papers by Brown and co-workers (refs. 16 and 17) discuss the problem in detail and show that a few thousands of an inch misalignment between the load axis and the specimen axis can significantly reduce the measured notch strengths. The forthcoming ASTM method of test for the sharply notched cyldrical specimen will include a recently developed design (ref. 1) for an axial alignment fixture for use with threaded specimens. This fixture (fig. 6) grips each end of the specimen in a precision machined collet which is concentric with and an integral part of a rod that contains cross flexures at its other end and immediately adjacent to a threaded stud for attachment to a tensile machine. This design has the advantage that the specimen is isolated from misalignments external to the fixture by the frictionless flexures and that the threaded specimen is centered by tightening the collet and therefore aligned with the rod longitudinal axis. The performance of this fixture has been evaluated using a special specimen, figure 5, having a small reduced section which simulates the notch. The reduced section is provided with four foil resistance strain gages placed on cylindrical elements 90° apart. Each gage has an active element 0.010 inch in the circumferential direction and 0.909 inch long. The results obtained indicated that the cross flexures were able to effectively isolate the specimen from substantial displacements (0.20 inch) of the tensile machine loading points one from the other. Systematic rotations of the specimen and fixtures show that the maximum fiber stress in bending was consistently less than 1.2 ksi for an average tensile stress on the net section of the evaluation specimen of 30 ksi. This corresponds to "4 percent bending" at a load well below the minimum that would be expected in testing the most brittle aluminum and magnesium alloys with a one-half inch diameter notch specimen. At higher loads one would expect lower values of percent bending.

Specimen Size Requirements

It has been generally accepted that the size of a notched cylindrical specimen should be sufficient to ensure that the average net section stress at fracture does not exceed 1.1 times the uniaxial yield strength. As previously pointed out (ref. 19) calculations made on this basis show the specimen to be relatively inefficient in use of material and load as compared with plate bend specimens. At that time, the present size requirements for K_{Ic} tests had not been developed and the calculation of K_{Ic}

measurement capacity was based on a net stress to yield strength ratio limit. It seems logical that the same size requirements to be applied to the notched cylinder as to the ASTM E-399 plate specimens. Thus, the notch depth (D-d)/2 (see fig. 4 for symbols) should be no less than 2.5 K_Q^2/σ_{YS}^2 and the notch diameter should be no less than 5 K_Q^2/σ_{YS}^2 where K_Q is the stress intensity based on the maximum load of the notch specimen and σ_{YS} is the 0.2 percent offset yield strength of a smooth specimen. On the basis of these criteria it is possible to calculate the minimum specimen diameter required to determine K_{Ic} for a material of a given yield strength as a function of d/D. This requirement expressed in terms of a specimen size factor $D/(K_Q/\sigma_{YS})^2$ is plotted against d/D in figure 7. Added to this representation are the limiting values of the net stress to yield strength ratio σ_N/σ_{YS} for K_{Ic} determination based on the small scale yielding criterion used in ASTM E-399. These were calculated making use of the K calibration given in figure 4.

If we accept the same small scale yielding criterion for the notched cylinder as for the plate specimens d/D would be set at 0.5 rather than 0.707. The corresponding net stress to yield strength ratio would be 0.75 and the size factor would be 10. These values may be compared with 1.1 and about four corresponding to the generally accepted d/D = .707. Thus, the conclusion is that the size requirements for the notched cylindrical specimen should be increased for K_{Ic} measurement. While this conclusion is based on an analysis that is consistent with that applied to the plate specimens we have no direct experimental evidence relating to size requirements in the notched cylindrical specimen.

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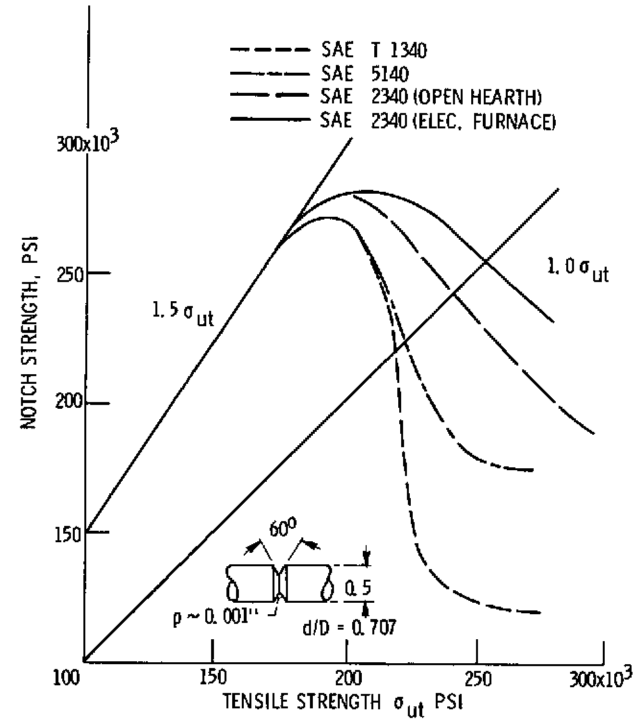

Figure 1. - Sharp notch tensile strength as a function of conventional tensile-strength level for several low-alloy steels.

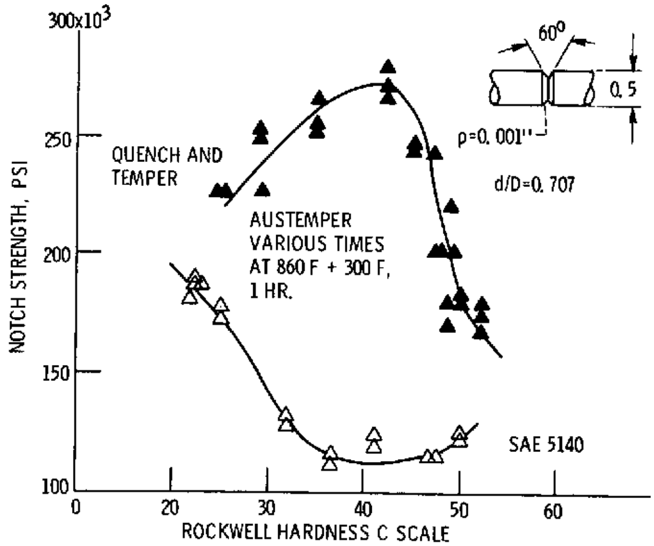

Figure 2. - Sharp notch tensile strength as function of hardness for SAE 5140 oil-quenched and tempered or austempered.

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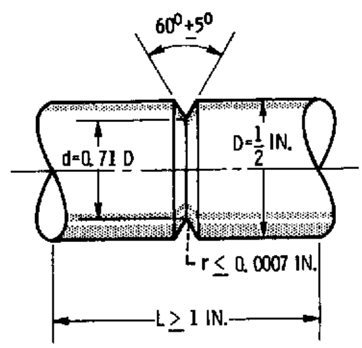
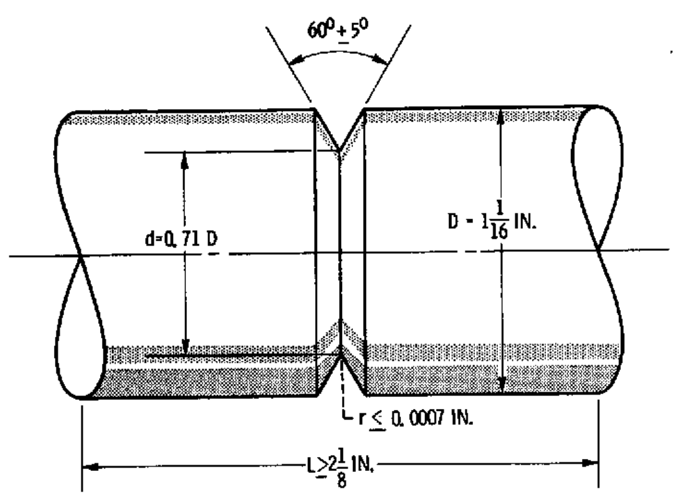


$\frac{1}{2}$ IN. DIAM. TEST SECTION



$1\frac{1}{16}$ IN. DIAM. TEST SECTION

Figure 3. - Test sections of sharply notched cylindrical tensile specimens proposed by the ASTM E-24 task group.

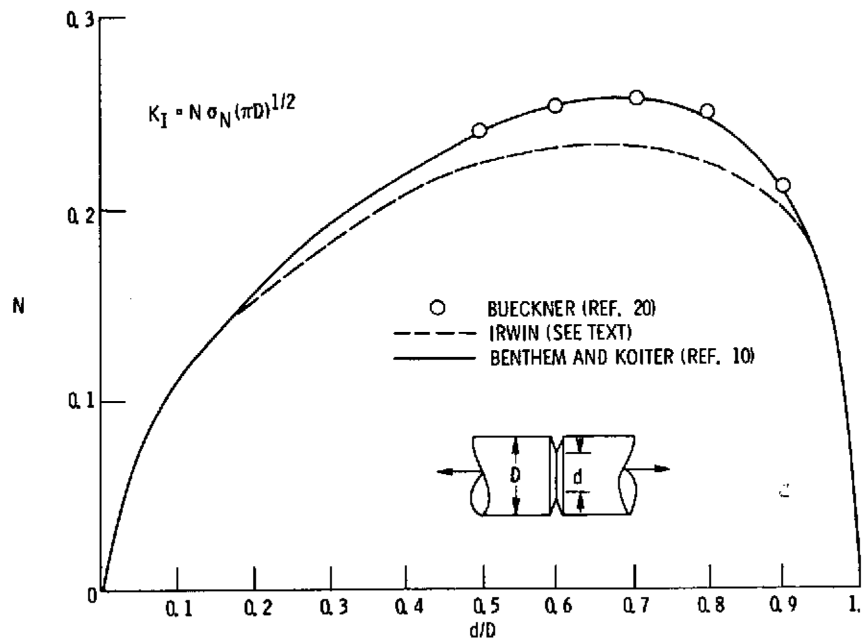


Figure 4. - K calibrations for the notched cylindrical specimen

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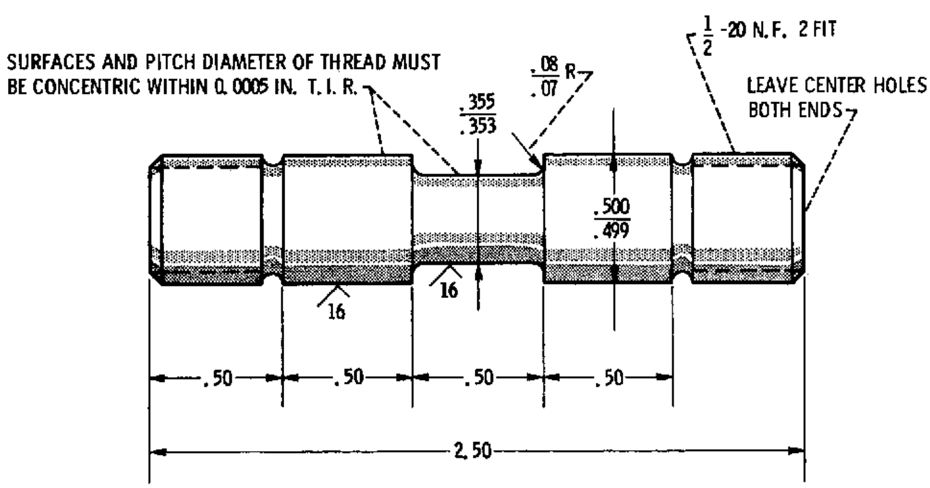

Figure 5. - Alignment evaluation specimen. (Dimensions in inches.)

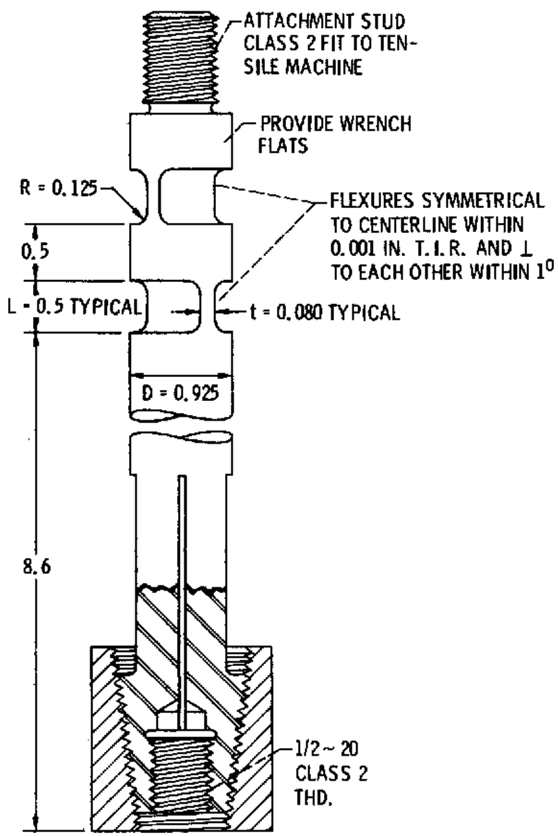

Figure 6. - Axial alignment fixture for use with threaded specimens.

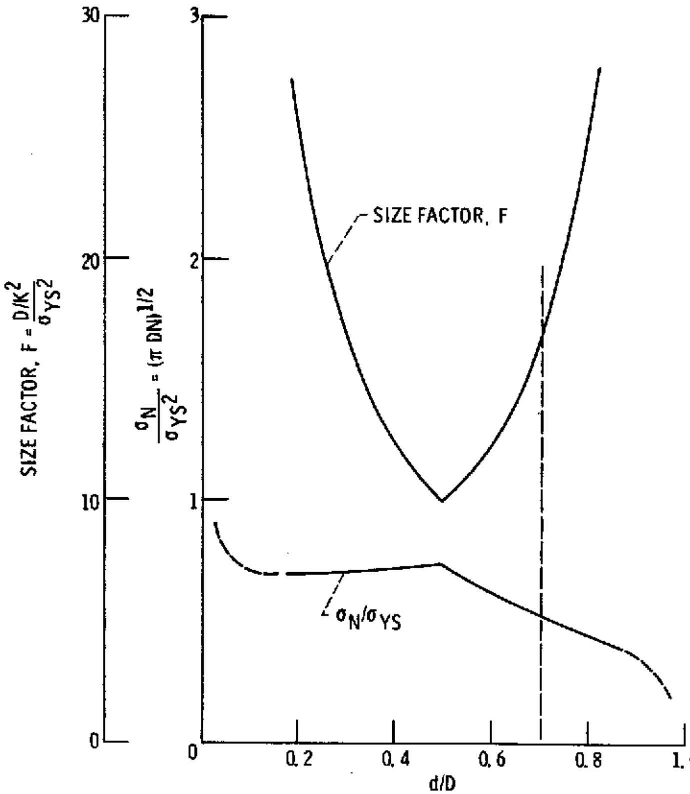

Figure 7. - Specimen size factor and limiting net stress to yield strength ratio for notched cylindrical specimens.