NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2397

INFLUENCE OF TENSILE STRENGTH AND DUCTILITY ON STRENGTHS OF ROTATING DISKS IN PRESENCE OF MATERIAL AND FABRICATION DEFECTS OF SEVERAL TYPES

By Arthur G. Holms, Joseph E. Jenkins, and Andrew J. Repko

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1

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2167

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SUMMARY

The significance of tensile strength and ductility in the presence of defects and the strength-reducing effects of several types of defect were investigated for some rotating disks. The types of defect investigated included laminar-type irregularities, eutectic melting, and shrink porosity.

Strengths of disks containing irregularities increased with increasing tensile strength of similar material free from irregularities independently of ductility at ductilities in excess of 14.9-percent elongation. The best compromise between tensile strength and ductility in material containing shrink porosity occurred at 6.8-percent elongation.

Disks having laminar-type irregularities at ductilities above 14.9-percent elongation exhibited no loss in strength due to the irregularities. At 0.0-percent elongation, the same irregularities produced a loss in strength of 42 percent. A material possessing eutectic melting suffered a 23-percent loss in strength at 2.8- and at 14.0-percent elongation. The loss in strength due to shrink porosity varied from an average of 26 percent at 37.5-percent elongation to 58 percent at 2.4-percent elongation.

INTRODUCTION

A significant question to be considered in the specification of chemical composition and mechanical and thermal treatment of rotor disks is the compromise between tensile strength and ductility. High ductility is usually considered desirable for overcoming stress concentrations associated with rotor design or defects that sometimes result from the fabrication procedure. The attainment of high ductility can, however, usually be achieved only by sacrifice in tensile

strength. Information on the optimum combination of tensile strength and ductility for disks in which various types of stress concentrations are expected would therefore be very useful.

An investigation of the relative influence of tensile strength and ductility on the burst strength of rotating disks with and without central holes is described in reference 1. The materials studied in that investigation were free of defects so that the only stress concentrations involved were those associated with disk geometry, such as central holes. Under these conditions, at ductilities higher than approximately 3 percent elongation, the primary variable affecting the bursting strength of a disk was found to be the tensile strength of the disk material. 2167

The stress concentrations associated with defects are greater than those of machined round central holes. Hence, it might be expected that the optimum combination of tensile strength and ductility for disks containing defects might occur at ductilities greater than 3-percent elongation. While studies have been described involving defects in various types of rotor (references 2 and 3), no information apparently exists in the literature on a systematic evaluation of the precise weakening effects of various types of defect and on the significance of ductility in overcoming these defects for rotor application.

In the present report on an investigation conducted at the NACA Lewis laboratory, data will therefore be presented on the strength-reducing effects of various types of irregularity at various ductilities and on the occurrence of an optimum compromise between tensile strength and ductility in the presence of these defects. Data will be presented for qualitatively dissimilar irregularities consisting of laminar discontinuities involving chemical segregations, eutectic melting involving extremely small and finely dispersed discontinuities, and shrink porosity involving rather coarse voids. In this investigation, ductility was varied over a wide range by suitable heat treatment.

DISK DESIGNS

Disks were fabricated according to the two basic designs sketched in figure 1. All the disks had parallel sides, had 10-inch outside diameters, and were 3/8 inch thick, except the disks of beryllium copper, which varied in thickness between 0.497 and 0.570 inch. The method of supporting the disks during spinning and the experimental equipment used are described in reference 1.

2167

MATERIAL DEFECTS

For all the cases investigated, defects were always distributed to include the central region of the disk. Because the maximum nominal stresses occur in the center, the defects were always in a region where their influence would be significant.

Laminar-Type Irregularities

The age-hardenable 18-8 stainless steel was heat-treated to three conditions of ductility, namely, 14.9-percent elongation (tensile strength, 123,600 lb/sq in.) obtained by solution treatment; 17.6-percent elongation (tensile strength, 163,900 lb/sq in.) obtained by overaging; and 0.0-percent elongation (tensile strength, 230,300 lb/sq in.) obtained by aging to produce high-strength properties.

During inspection of the forgings, similar small indications were always found with the magnetic-particle inspection method. Magnetic particles on a disk with a machined finish are shown in figure 2. No irregularities in machined disks were observed by radiographic inspection.

A photomicrograph in the region of one of these indications is shown in figure 3. The type of irregularity that produced the indications observed with magnetic-particle inspection is shown greatly enlarged by the band of dark particles extending across the upper part of the photomicrograph. The band probably contains segregations of inclusions and undissolved carbides. The narrow well-defined bands in the lower part of figure 3 are probably delta ferrite. Photomicrographs of the alloy in the overaged condition and when aged for maximum strength properties are presented in figures 4(a) and 4(b), respectively. The dark square-shaped areas are hardness impressions made with a Vickers type diamond pyramid indenter in a Tukon microhardness tester. The hardness is conventionally regarded as being inversely proportional to the diagonals of the impressions squared. When these impressions (fig. 4) are compared, it may be seen that the segregated areas are softer (have larger indentations) than the matrix, although in figure 4(a) the matrix has been overaged. The segregations in the age-hardenable 18-8 stainless steel are probably areas deficient in the solute phase because of the twinned structure (fig. 4(a)) characteristic of the face-centered cubic (austenitic) phase in iron and furthermore, the hardness of these segregated regions did not perceptably increase with aging, as did the matrix and the delta ferrite regions. The delta ferrite does not appear to constitute a serious metallurgical "notch" as the hardness of delta ferrite and the matrix are approximately the same as shown by the hardness impressions of

figures 4(a) and 5. The austenitic regions probably become severe stress raisers as the ductility of the matrix is decreased from 17.6-percent elongation to 0.0-percent elongation. The presence of carbides or inclusions may contribute to the effectiveness of these regions as stress raisers.

2167

A photomicrograph showing the irregularities and the forging flow lines in the central area of a diametral section of a disk, as brought out by etching, is presented in figure 6. A similar laminar pattern appeared in the fractured surface, as is shown by figure 7. Figures 6 and 7 suggest that the orientation of these irregularities was such as to have a detrimental influence on disk strength, inasmuch as the laminations curve into the highly stressed central region of the disk surface so that they are no longer parallel to the direction of maximum stress. Cracks observed in a disk fragment (fig. 5) suggest that after a crack was initiated in the central region in a segregated area (fig. 8), the cracks propagated along the delta-ferrite grain boundaries.

Eutectic Melting

Radiographic inspection of the cast disks of a magnesium-base alloy showed that they contained irregularities, which extended over an area equal to 30 to 50 percent of the image and were confined to a single segment of the disk. From the radiographic contrast, it is estimated that the irregularities could have been caused by microshrinkage or by eutectic melting. Figure 9(a) reveals these irregularities to be discontinuities caused by eutectic melting. These discontinuities are differentiated from those caused by microshrinkage by the presence of precipitate up to the voids. Microshrinkage causes a general lack of precipitate around the voids. The region free from such irregularities is illustrated by figure 9(b).

Shrink Porosity

The cast disks of beryllium copper contained shrink porosity confined to one irregular central region of the disk. This porosity was of fairly uniform intensity from disk to disk. A typical radiograph is shown in figure 10(a). As shown by figures 10(b) and 10(c), the porous regions were large in comparison with the disk thickness, but as shown in figure 10(a), the porous regions were small in comparison with the total disk volume.

2167

TENSILE DATA

Conventional methods of material testing were used in measuring mechanical properties, which are given in table I. The test sections of the tensile specimens were as shown by figure 4 of reference 1. In all cases, tensile specimens were taken from disks produced in the same manner as the burst disks.

For the age-hardenable stainless steel having significant ductility, the strength of each tensile specimen agreed with the average value of the group within a maximum deviation of 1.6 percent and showed no significant effect of the irregularities. The average values were therefore regarded as representing the strength of the material as unaffected by irregularities.

For the age-hardenable stainless steel having no measurable ductility, a total of eight tensile specimens were taken in random directions from the central regions of two disks. The strengths of individual specimens varied from 168,800 to 230,300 pounds per square inch. A large variation would be expected at zero ductility because of the isolated manner in which the stringer-type irregularities curved into the surface of the disk (figs. 2 and 7). The highest value of the series of tensile values at 0.0-percent elongation (230,300 lb/sq in.) was regarded as an approximation to the strength of the material as unaffected by defects.

For the cast magnesium containing eutectic melting, and for the beryllium copper containing shrink porosity, the properties of the material as unaffected by defects were determined by averaging results of tensile specimens selected from regions indicated to be sound by radiographic inspection.

SIGNIFICANCE OF DUCTILITY IN PRESENCE OF VARIOUS TYPES OF DEFECT

The strength of the disks is reported in terms of the calculated elastic stress at burst. The significance of this parameter is discussed in reference 1. The elastic stress at burst is the maximum stress in a solid parallel-sided disk calculated for the observed burst speed and is therefore proportional to the square of the burst speed and to the density of the material, and is based on the original dimensions of the disk. The calculated elastic stress at burst is a measure of the load sustained by the disk material up to the point of bursting, and is therefore a useful parameter for measuring

the effects of tensile strength and ductility when the materials investigated vary in density. The calculated stress at burst is not an index of the merit of a material for rotating-disk application because it involves the product of burst speed squared and the density. The burst speed or the burst speed squared alone would be a satisfactory index of merit. 2167

In reference 1, a relation between disk strength and tensile strength is strongly predominant and plots of disks strength divided by tensile strength against ductility show no observable influence of ductility. Presumably, ductility is a factor in the strength of any structure containing defects. The material adjacent to the defects undergoes plastic flow and consequent stress relief in the vicinity of stress concentrations. In investigating the possible influence of ductility on a correlation between the strength of disks containing defects and tensile strength, the assumption was made that the ductility of the material adjacent to but not including the defects is significant and therefore the ductility of sound material is reported in all cases. The ductility was measured on tensile specimens taken from regions unaffected by defects.

Strengths of disks having laminar-type defects, eutectic melting, and shrink porosity are plotted against the corresponding tensile strength of sound material in figure 11. The relation previously established (reference 1) for disks of sound material and moderate ductility is shown by the straight line. (The data for sound disks of reference 1 yield an average value of 1.152 for the ratio of disk strength to tensile strength for solid parallel-sided disks.) The disks possessing laminar-type defects (fig. 11(a)) increased in strength with increasing tensile strength for ductilities in excess of 14.9-percent conventional elongation. When the tensile strength was further increased (with a total loss of measurable ductility), a serious loss of disk strength occurred. The data points for disks containing eutectic melting (fig. 11(a)) show no significant effect on the disk strength due to a change in ductility from 2.8- to 14-percent elongation. Similarly, figure 11(b) shows no significant change in disk strength due to a change from 2.8- to 14.0-percent elongation for the disks containing eutectic melting. The disks having shrink porosity (fig. 11(b)) showed increased disk strength with increasing tensile strength until maximum disk strength was reached at a ductility of 6.8-percent elongation, after which further increase in tensile strength reduced the disk strength, corresponding to a decrease in ductility to 2.4-percent elongation. The straight line corresponds to an average value of 0.935 for the ratio of disk strength to tensile strength previously observed for sound disks with $1\frac{1}{2}$-inch-diameter central holes.

2167

SIGNIFICANCE OF SEVERAL TYPES OF DEFECT AT VARIOUS DUCTILITIES

For the solid disks having measurable ductility, the ratios of disk strength to tensile strength were divided by 1.152 (the average ratio of disk strength to tensile strength of reference 1); for the disks with holes, the ratios of disk strength to tensile strength were divided by 0.935 (the average ratio of disk strength to tensile strength of reference 1) and these values were plotted against ductility in figure 12. For solid disks of zero ductility, a value of unity could be expected for the ratio of disk strength to tensile strength, and hence the values of disk strength divided by tensile strength were plotted directly on figure 12 for the age-hardenable 18-8 stainless steel with no measurable ductility.

These values were all plotted on the same coordinates under the assumption that the ratio of the strength of a disk with a hole to the strength of a solid disk established in reference 1 would apply to the present investigation where the disks with holes have irregularities similar to those of the solid disks. In all cases for a given material, the ordinates for the solid disks lie within the same region as the data for disks with holes.

The occurrence of plotted points of figure 12 with ordinate values significantly less than unity can be attributed to the strength reducing effect of the defects. The greatest loss in strength (average of 58 percent) occurs for the disk containing shrink porosity and having a ductility of 2.4-percent elongation. Increasing ductility to 37.5-percent elongation steadily reduces the influence of the defects (average of 26-percent reduction in strength at 37.5-percent elongation).

The average loss in strength for the disks with laminar-type irregularities and no measurable ductility was 42 percent when compared with an expected value of unity for the ratio of disk strength to tensile strength. Heat treatments producing a ductility equal to or exceeding 14.9-percent elongation gave data points lying above the line established by previous data showing that in the presence of ductility in excess of 14.9-percent elongation, the particular laminar-type irregularities investigated produced no loss of disk strength.

The loss in strength caused by eutectic melting is about the same for the material of 2.8-percent elongation as for the material of 14.0-percent elongation; and the average loss in strength as compared with previously established ratios of disk strength to tensile strength was 23 percent.

SUMMARY OF RESULTS

The results obtained from an investigation of the influence of tensile strength and ductility in the presence of material and fabrication defects, and the results obtained from an investigation of the strength reducing effects of some particular defects are as follows: 2167

1. The influence of tensile strength and ductility on disk strength in the presence of defects was such that in two cases an optimum compromise between tensile strength and ductility occurred at a ductility less than 15-percent elongation. In a third case, no influence of ductility was observed. In particular:

(a) Disks forged from an age-hardenable 18-8 stainless steel having laminar-type irregularities increased in strength with increasing tensile strength for ductilities in excess of 14.9-percent elongation. When the tensile strength was further increased (with a total loss of measurable ductility) a serious reduction in disk strength occurred.

(b) No significant variation in strength was observed for cast disks of a magnesium-base alloy possessing eutectic melting when ductility was changed from 14- to 2.8-percent elongation with tensile strength remaining essentially constant.

(c) Cast disks of beryllium copper containing shrink porosity increased in disk strength with increasing tensile strength until the highest disk strength observed occurred with a ductility of 6.8-percent elongation. Below 6.8-percent elongation, the disk strength decreased despite the increased tensile strength.

2. When compared with performance previously observed for disks not containing irregularities, losses in disk strength for the defects investigated varied from 23 percent to 58 percent. In particular:

(a) Disks forged from an age-hardenable 18-8 stainless steel with laminar-type irregularities at ductilities above 14.9-percent elongation suffered no loss in strength due to the irregularities. At 0.0-percent elongation, the same irregularities produced a reduction in strength of 42 percent.

(b) Eutectic melting in disks cast from a magnesium-base alloy produced a 23-percent loss in strength at 2.8- and at 14.0-percent elongation.

(c) The loss in disk strength due to shrink porosity varied from an average of 26-percent at 37.5-percent elongation to an average of 58-percent at 2.4-percent elongation for cast disks of beryllium copper.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, January 24, 1951.

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1. Holms, Arthur G., and Jenkins, Joseph E.: Effect of Strength and Ductility on Burst Characteristics of Rotating Disks. NACA TN 1667, 1948.

2. Fonda, L. B.: High Temperature Disk-Forging Developments for Aircraft Gas Turbines. Trans. A.S.M.E., vol. 70, no. 1, Jan. 1948, pp. 1-9; discussion, pp. 9-12.

3. Rankin, A. W., Boyle, C. J., Moriarty, C. D., and Sequin, B. R.: Thermal Cracks in Turbine and Generator Rotor Forgings. Mech. Eng., vol. 72, no. 7, July 1950, pp. 559-566.

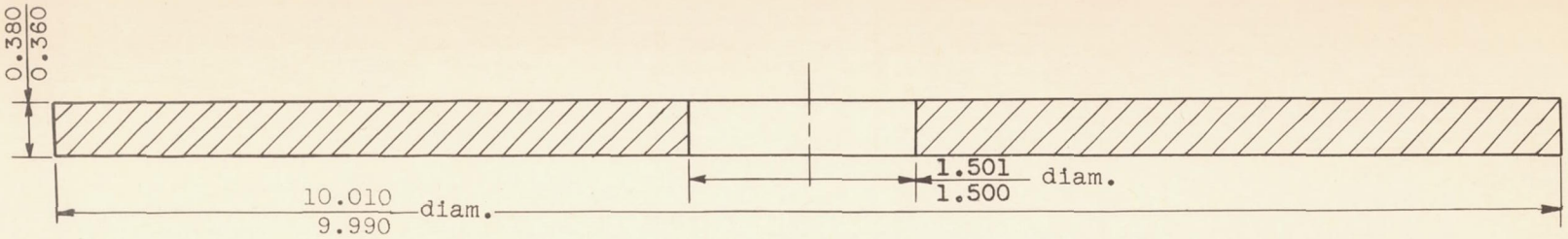
TABLE I - DISK MATERIALS, PROPERTIES, AND DESIGNS INVESTIGATED

Material	Tensile Properties		Disk design
	Ultimate strength of sound material (lb/sq.in.)	Ductility of sound material (percent elongation) (c)	
Cast beryllium copper	154,500	2.4	(a)
	148,300	6.8	(a)
	81,200	24.4	(a)
	67,600	37.5	(a), (b)
Forged age-hardenable 18-8 stainless steel	230,300	0.0	(b)
	123,600	14.9	(b)
	163,900	17.6	(b)
Cast magnesium base alloy	36,600	2.8	(a), (b)
	37,400	14.0	(a), (b)

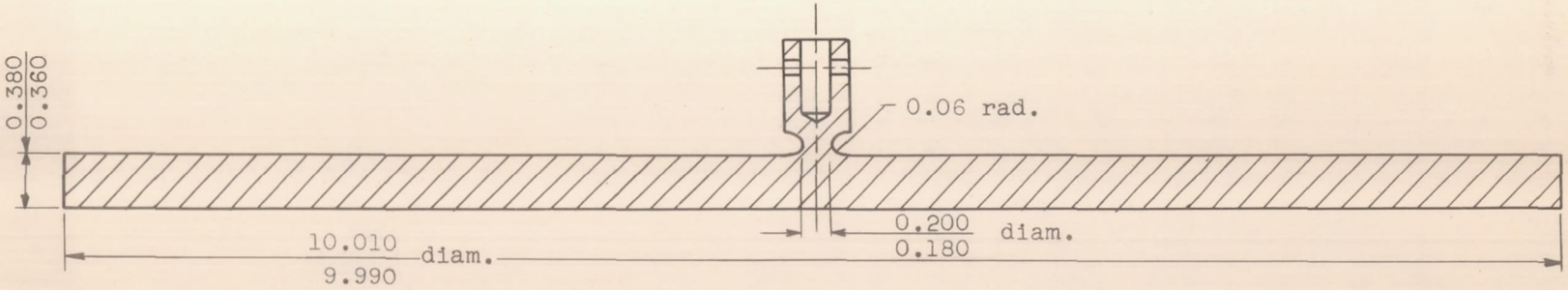
[a]Disk with $1\frac{1}{2}$-in.-diam. central hole (fig. 1(a)).

[b]Solid disk (fig. 1(b)).

[c]1-inch gage length, 1/4-inch-diameter specimen.



(a) Disk with $1\frac{1}{2}$-inch-diameter central hole.



(b) Solid disk.

Figure 1. - Disk designs. (Dimensions in inches.) Thickness of cast beryllium copper disks was 0.497 to 0.570.

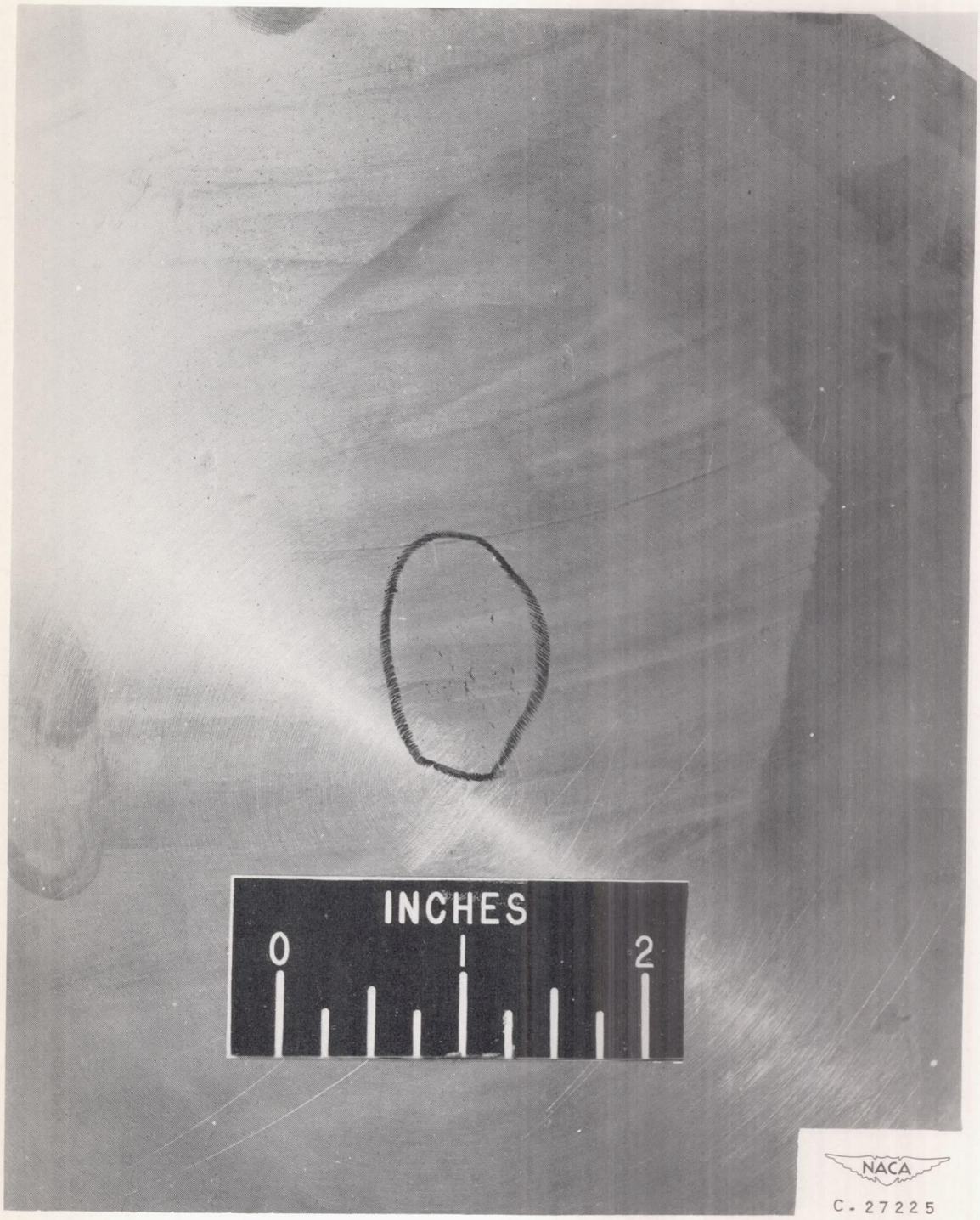


Figure 2. - Centrally located magnetic-particle indications on surface of solution-treated age-hardenable 18-8 stainless-steel disk.

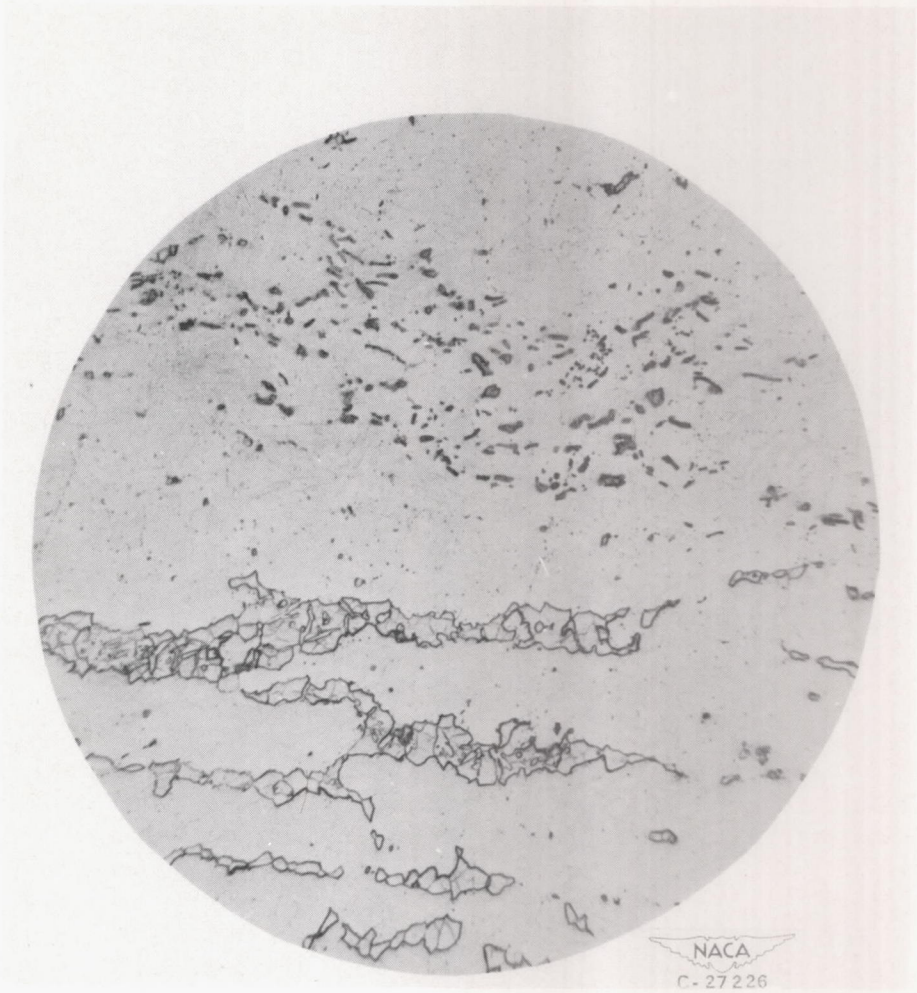
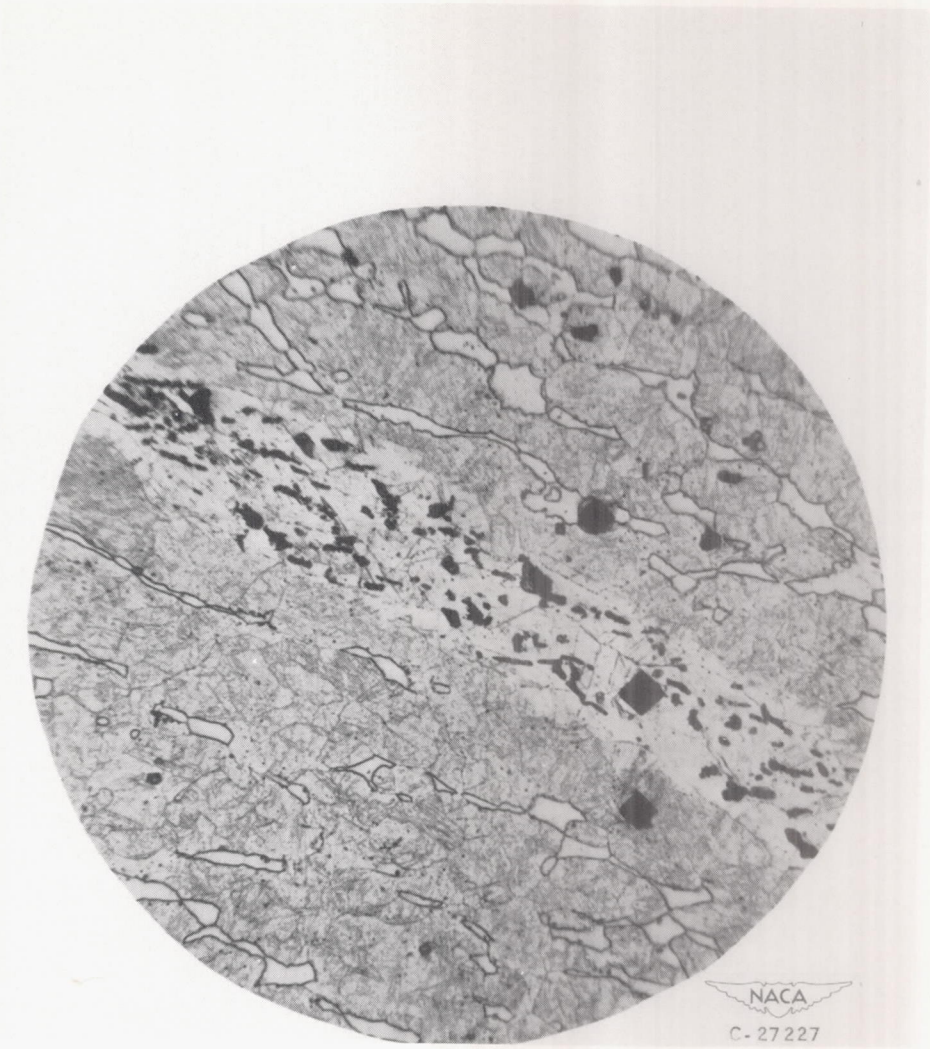
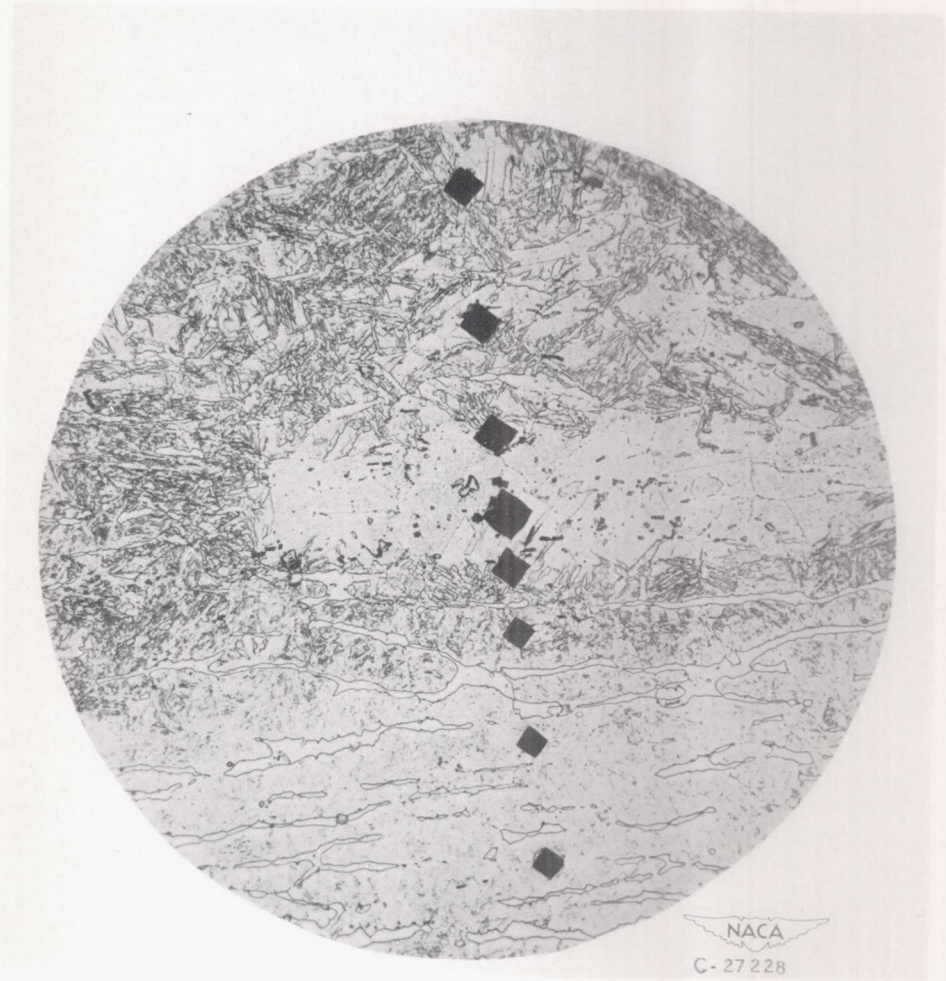


Figure 3. - Segregations observed in area disclosed by magnetic-particle indications of solution-treated age-hardenable 18-8 stainless-steel disk shown in figure 2. Electrolytically etched in oxalic acid; X250.



(a) Overaged specimen; tensile strength, 163,900 pounds per square inch.

Figure 4. - Tukon microhardness survey made in segregated area of age-hardenable 18-8 stainless-steel disk electrolytically etched in oxalic acid; X250.



(b) High hardness specimen; tensile strength, 230,300 pounds per square inch.

Figure 4.- Concluded. Tukon microhardness survey made in segregated area of age-hardenable 18-8 stainless-steel disk electrolytically etched in oxalic acid; X250.

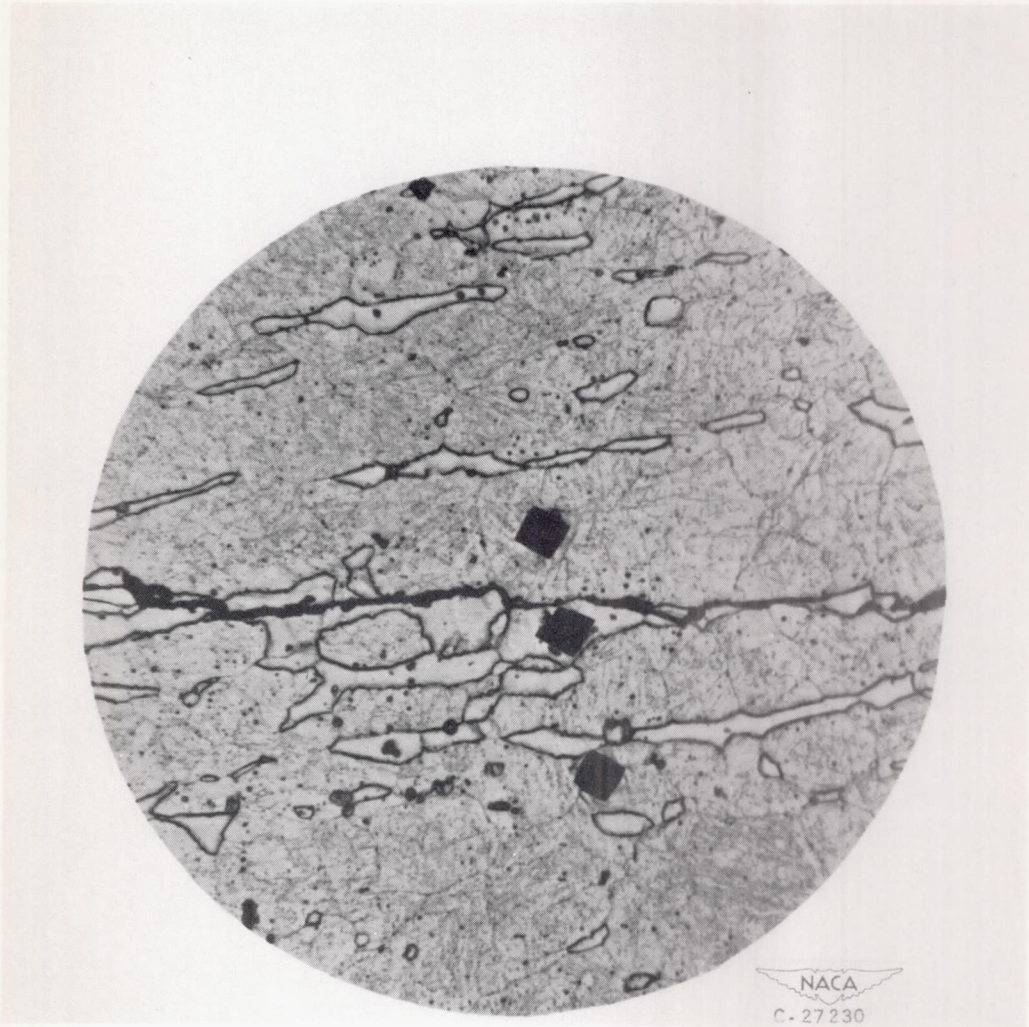


Figure 5. - Crack propagation along delta-ferrite grains of overaged (tensile strength, 163,900 lb/sq in.) age-hardenable 18-8 stainless-steel disk. Dark square-shaped areas are Tukon microhardness impressions. Electrolytically etched in oxalic acid; X500.

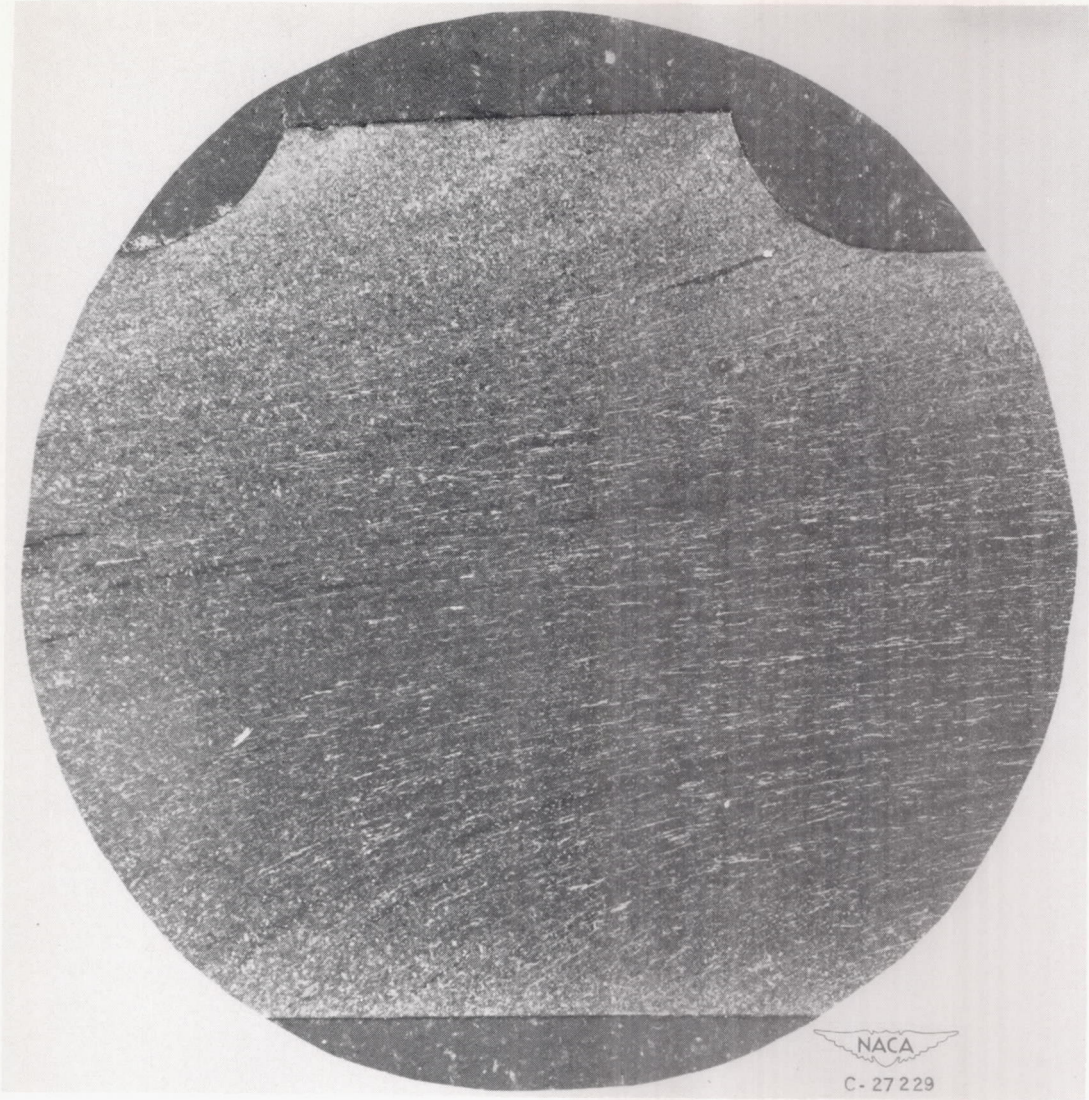


Figure 6. - Segregations in central area of overaged age-hardenable 18-8 stainless-steel disk. Etchant, Kallington; X12.

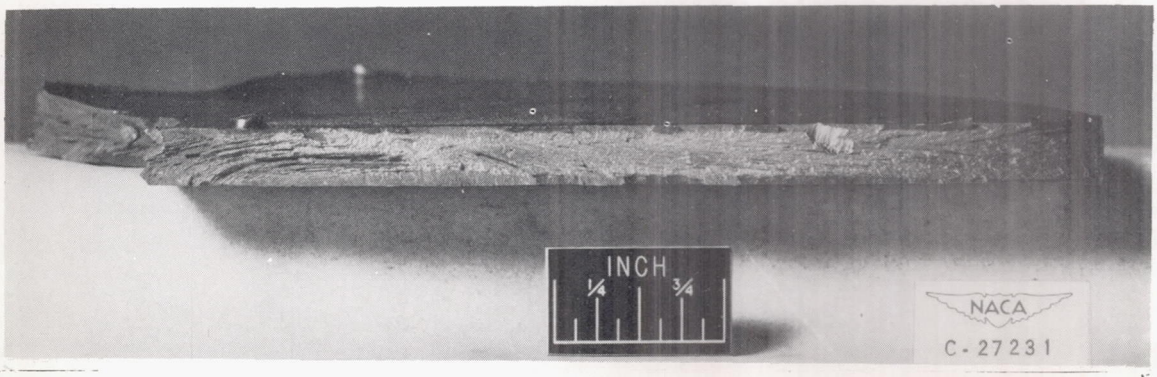


Figure 7. - Disk fracture illustrating unfavorable orientation of segregated area approaching surface at center of age-hardenable 18-8 stainless-steel disk.

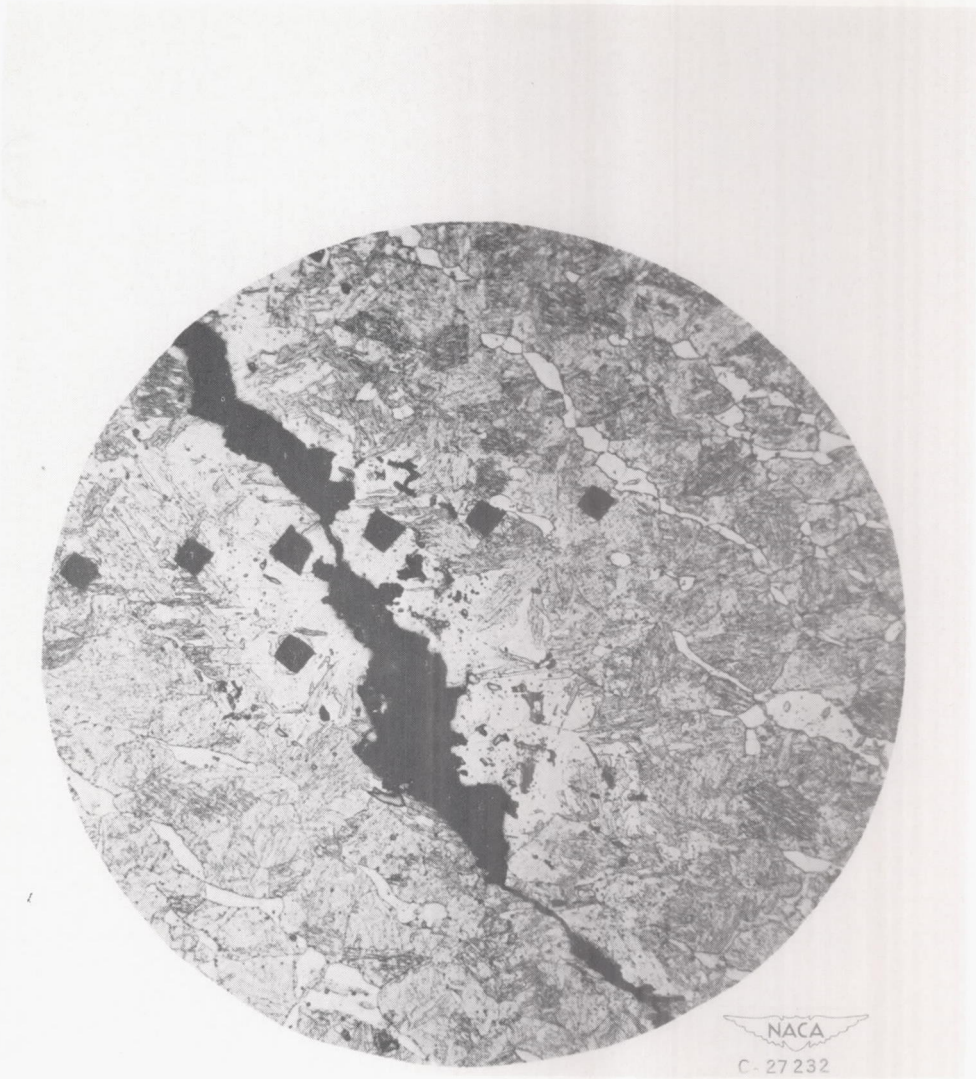
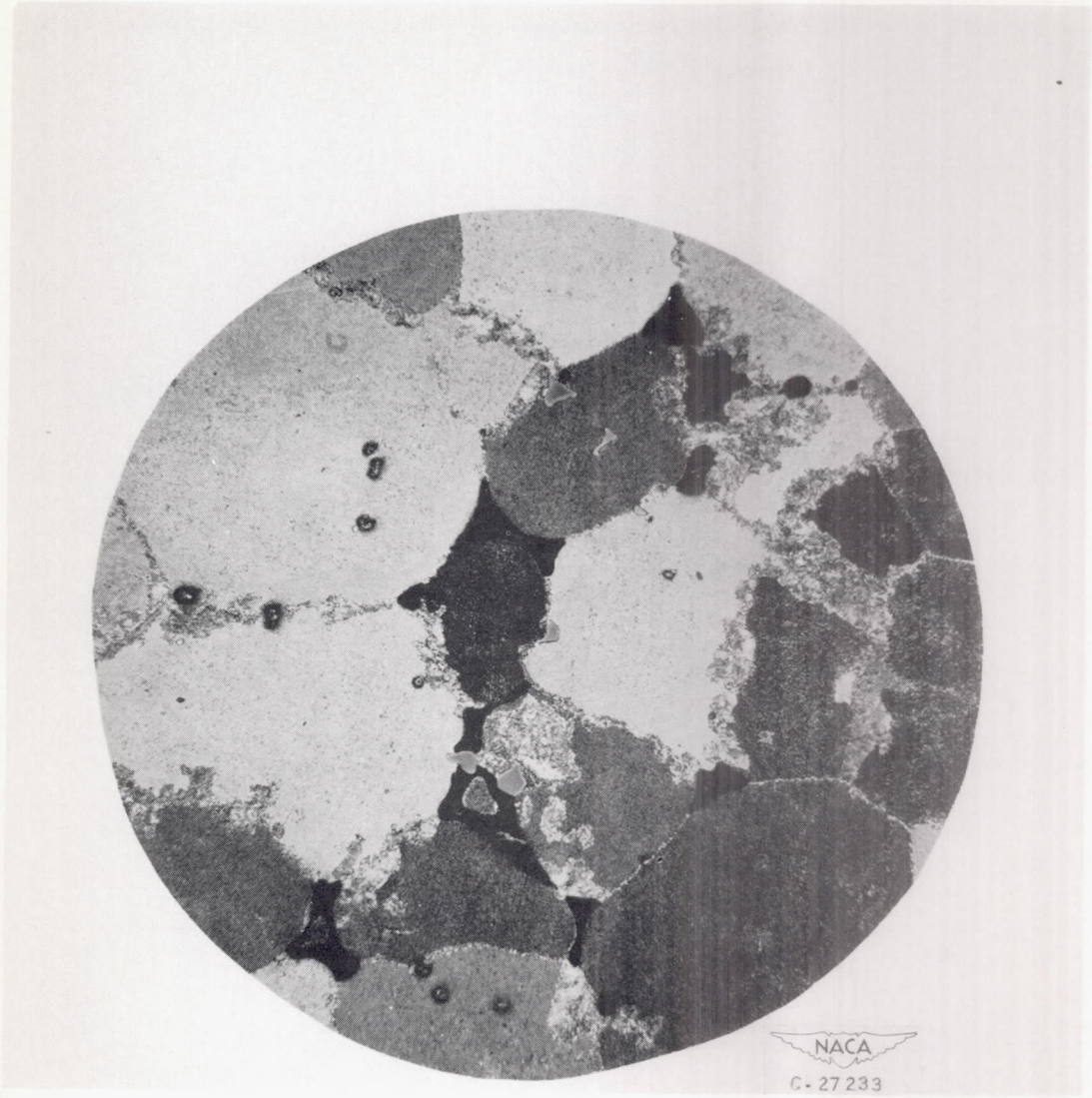
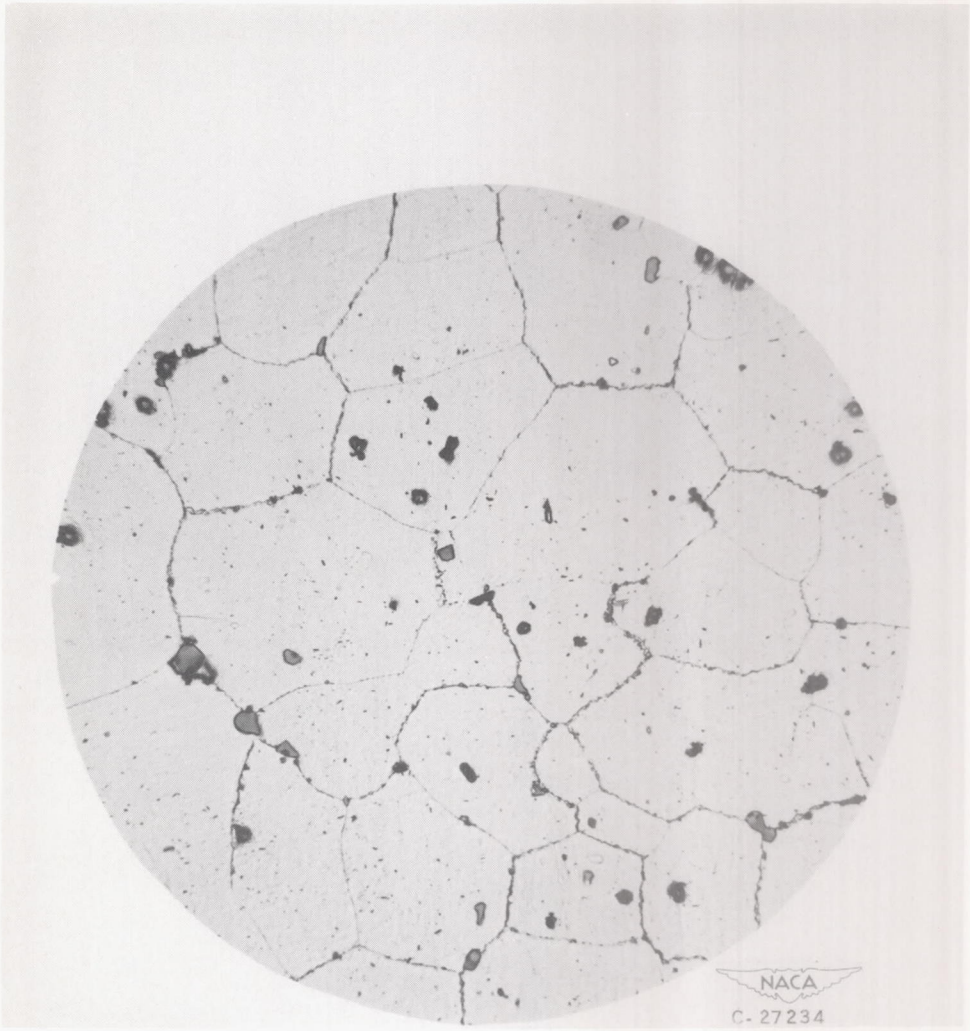


Figure 8. - Crack propagation in segregated area near center of overaged (tensile strength, 163,900 lb/sq in.) age-hardenable 18-8 stainless-steel disk. Electrolytically etched in oxalic acid; X250.



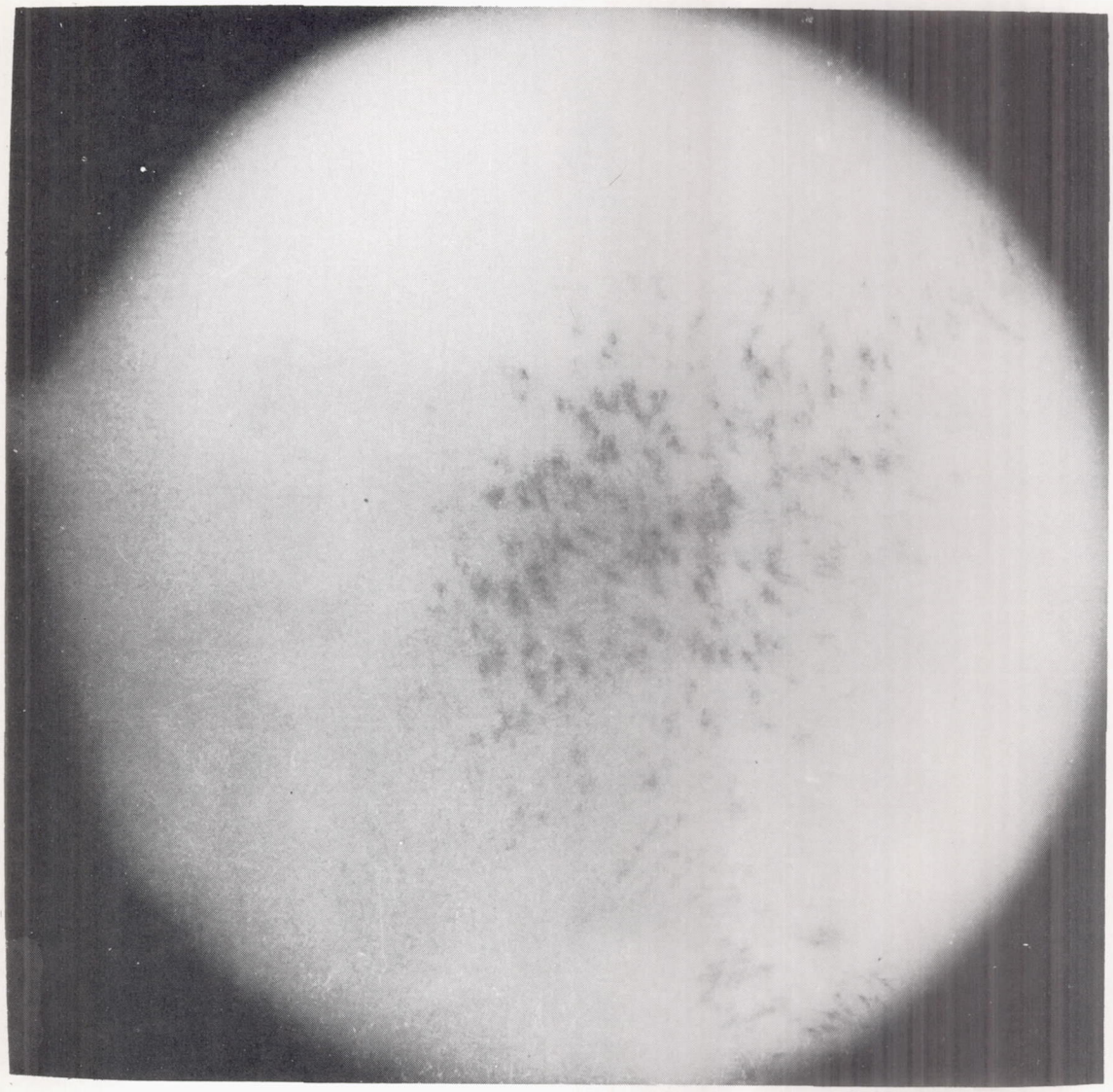
(a) Eutectic melting in semicircular region of disks.

Figure 9. - Cast magnesium-alloy disk solution-treated and aged. Etchant, ethylene glycol plus 1-percent nitric acid and water; X250.



(b) Outer area of disks that appear sound.

Figure 9. - Concluded. Cast magnesium-alloy disk solution-treated. Etchant, ethylene glycol plus 1-percent nitric acid and water; X250.



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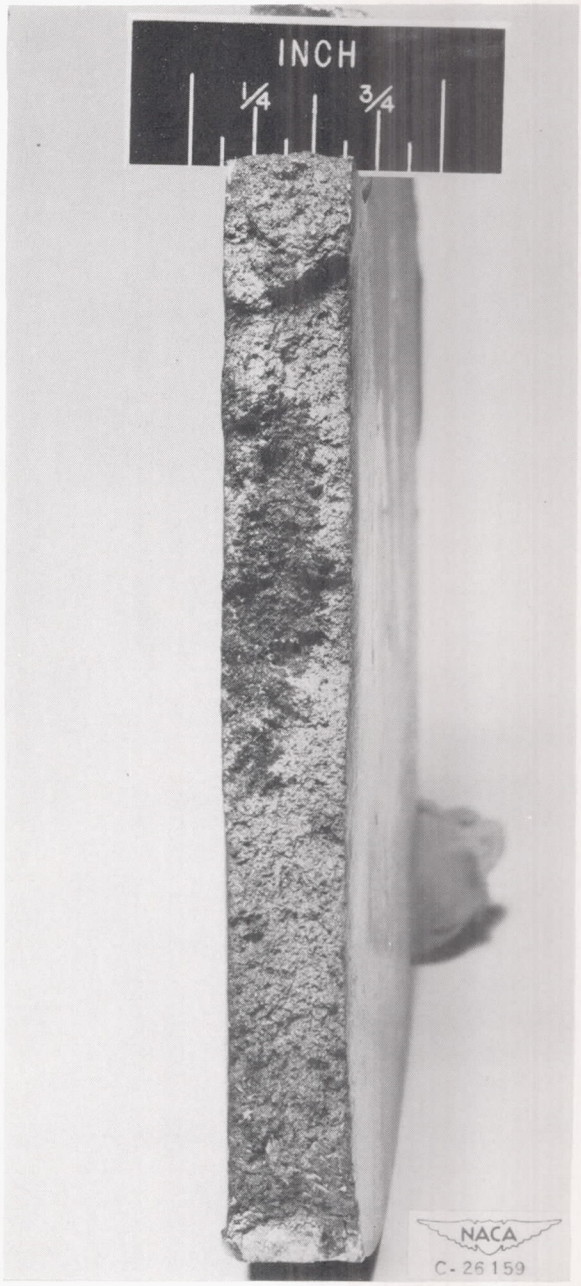
(a) Radiograph of typical shrinkage area.

Figure 10. - Cast beryllium copper disk.

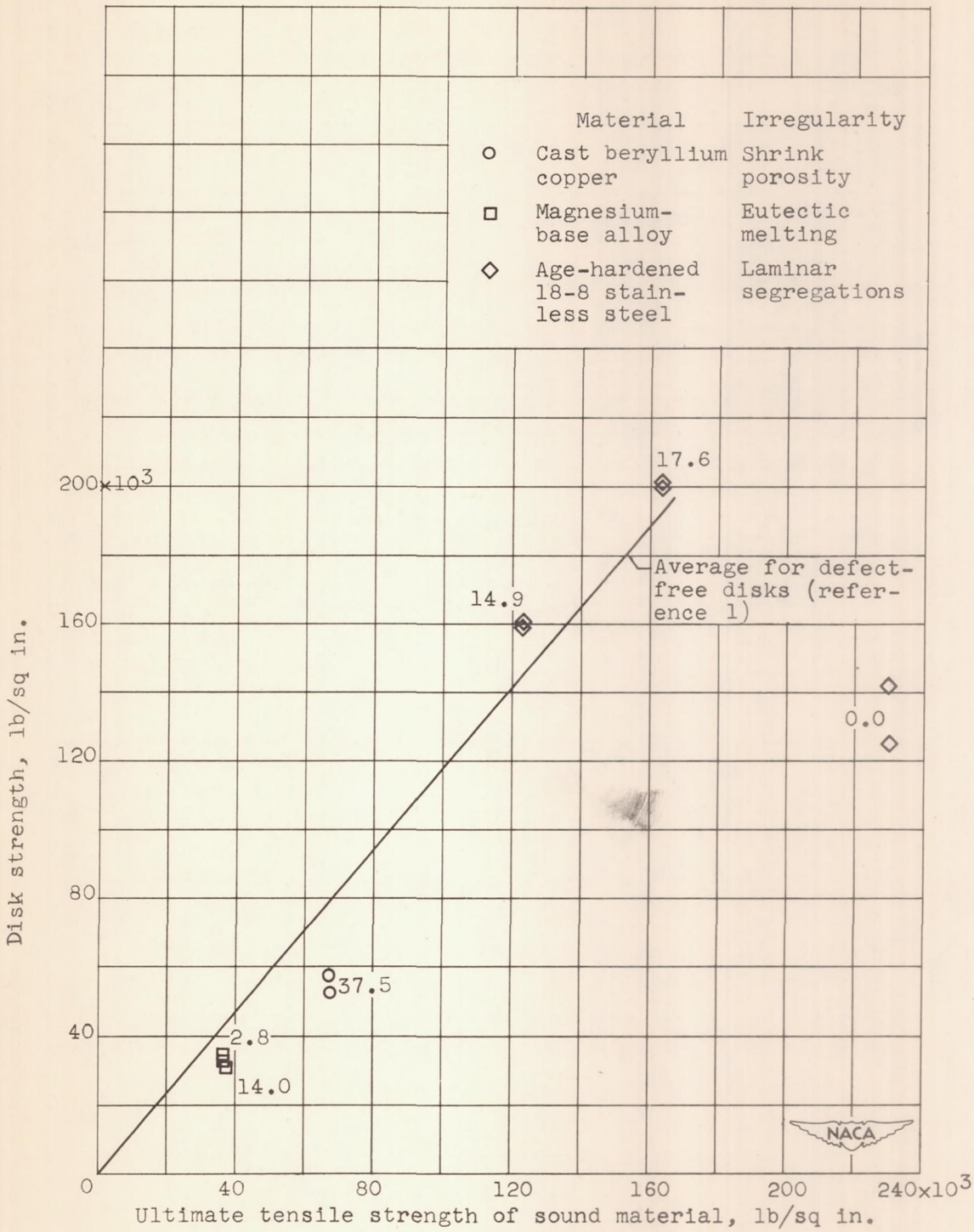


(b) Shrinkage area as revealed by fracture.

Figure 10. - Continued. Cast beryllium copper disk.

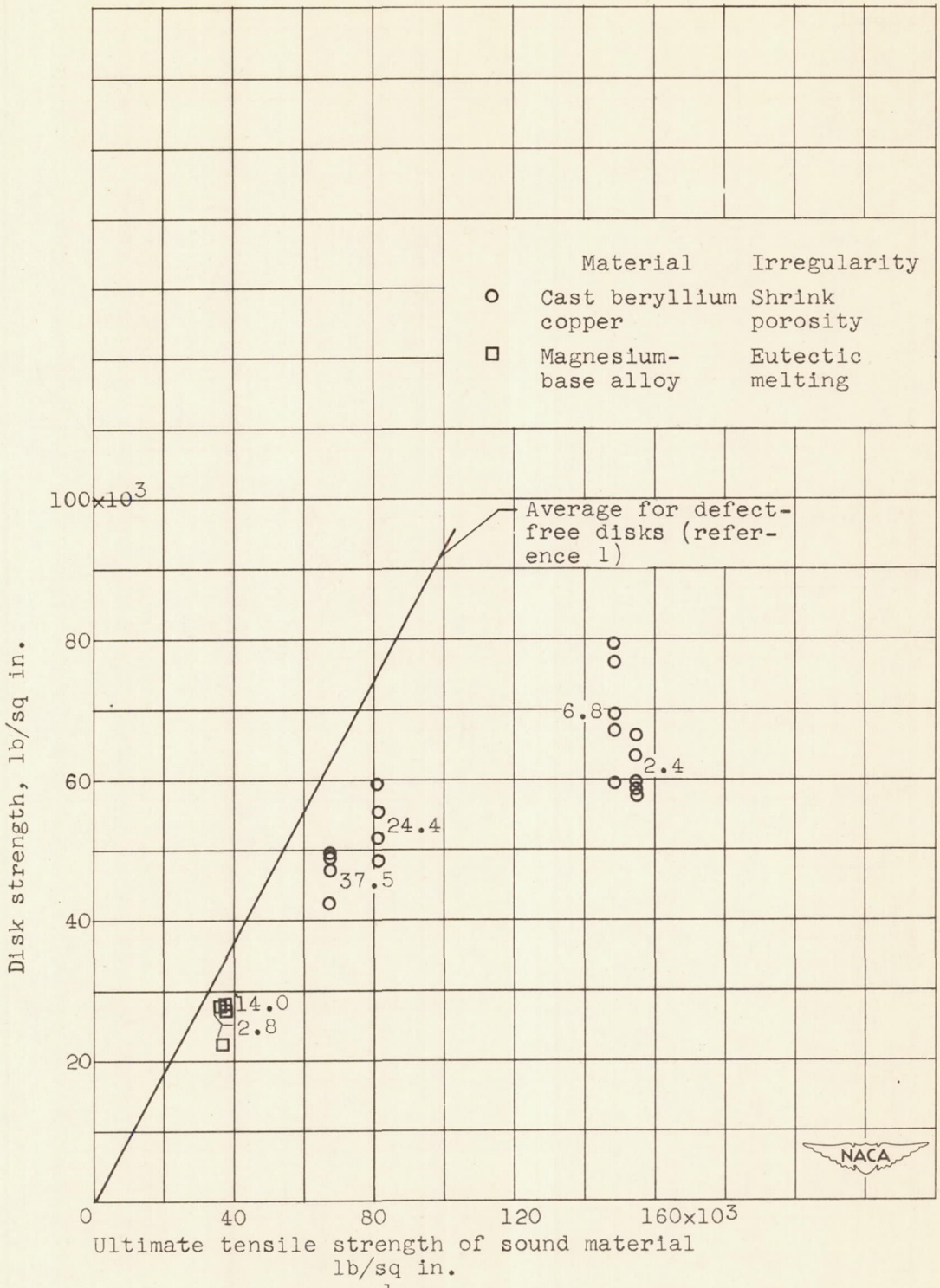
(c) Enlarged view of shrinkage area shown in figure 10(b); X11.

Figure 10.- Concluded. Cast beryllium copper disk.



(a) Solid disks.

Figure 11. - Relation between disk strength at burst and ultimate tensile strength of material remote from area of defects. Values beside data points indicate percent elongation.



(b) Disks with $1\frac{1}{2}$-inch-diameter central holes.

Figure 11. - Concluded. Relation between disk strength at burst and ultimate tensile strength of material remote from area of defects. Values beside data points indicate percent elongation.

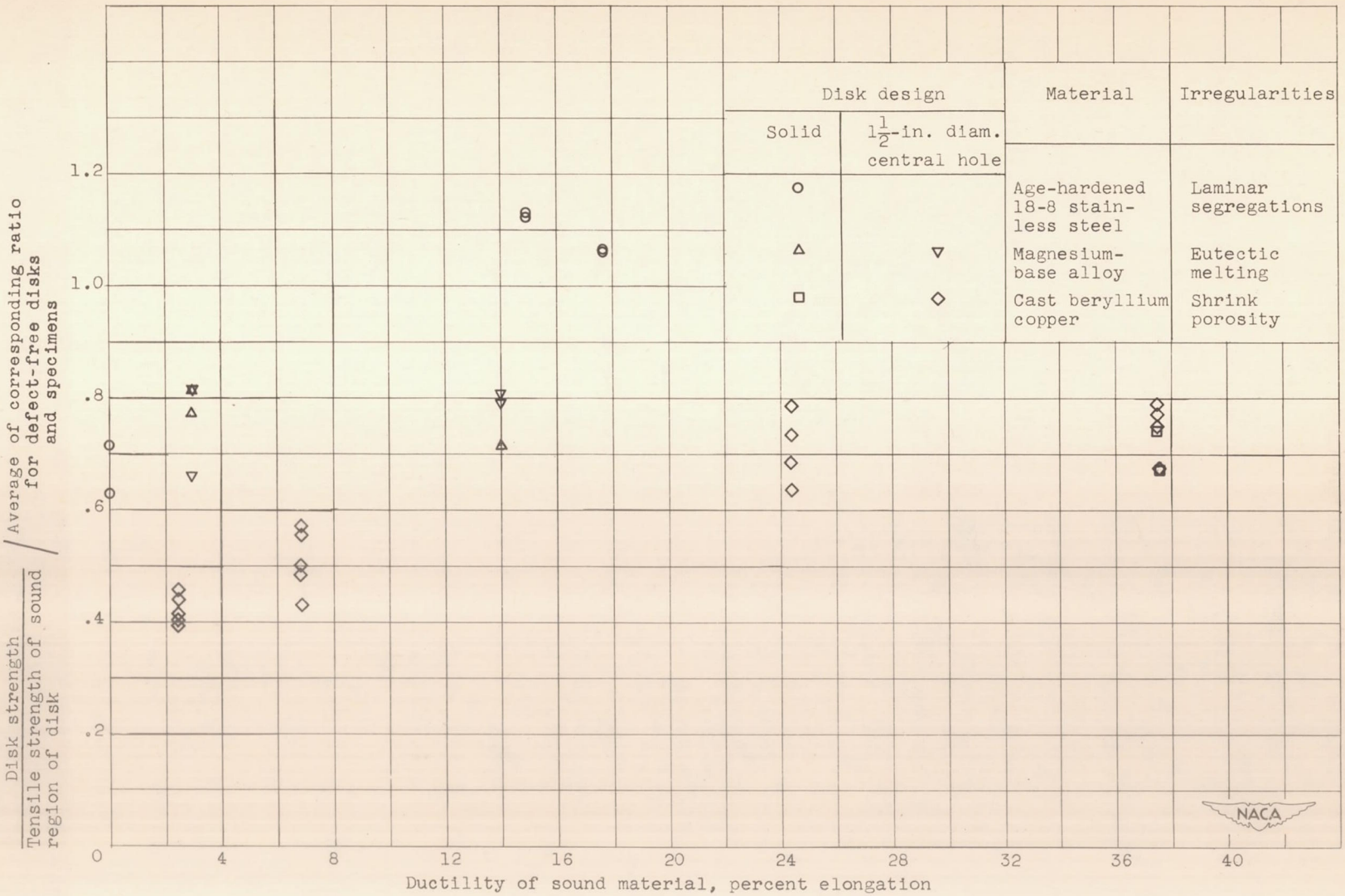


Figure 12. - Relation between ductility and utilization of tensile strength.