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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1667

EFFECT OF STRENGTH AND DUCTILITY ON BURST CHARACTERISTICS OF ROTATING DISKS

By Arthur G. Holms and Joseph E. Jenkins

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SUMMARY

An investigation was conducted to determine the influence of strength and ductility on the room-temperature burst characteristics of solid disks, disks with large-diameter central holes, and disks with small-diameter central holes. Disks were machined from seven materials, two of which were given various heat treatments.

For the solid disks and for the disks having stress concentrations consisting of large- and small-diameter central holes, burst strength increased with increase in tensile strength. The ratio of burst strength to tensile strength was relatively independent of ductility. The strengths of solid disks were reduced by the introduction of large-diameter central holes approximately in proportion to the amount of material removed. Small holes reduced the strength by an amount greater than the amount of section removed but not as much as would be predicted by calculating elastic stresses.

INTRODUCTION

The effect of ductility on the strength of rotating disks has long been a serious concern of machine designers. Functional considerations often require that disks be so designed that stress concentrations are set up in regions that are already highly stressed. If small material defects are to be tolerated, they will also increase the stresses. For disks that have stress concentrations, a material having some ductility is usually selected in order that during rotation small amounts of plastic deformation can redistribute the stresses in a more satisfactory manner. The amount of ductility considered necessary is often obtained at some sacrifice in tensile strength. Because lack of ductility is considered to make a material sensitive to stress concentrations, the designer is confronted with a serious dilemma. Little information is available on which a rational compromise between strength and ductility may be based.

Extensive tests showing the response of disk strength to forging treatment are described in reference 1. Burst tests of several types of disk made from a variety of materials are reported in reference 2. The calculated average stress at burst has been established as a criterion for estimating strengths of disks. Also, the reduction in burst speed caused by a central hole was found to be greater for disks of high ductility than for disks of low ductility. An analytical discussion of the phenomena of plastic deformation of rings and disks showed that the equilibrium of the disks may become unstable under certain conditions that depend on the nature of the stress-strain curve (reference 3). The work of reference 3 leads to the conclusion that a measure of ductility, to be significant for rotating disks, should be related to the occurrence of instability.

An investigation was conducted at the NACA Cleveland laboratory to examine the relation of tensile strength and ductility to the strength of rotating disks. The investigation of ductility requirements of disks having stress concentrations was confined to disks with central circular holes. In order to investigate a range of stress conditions, burst tests were performed on solid disks, on disks with a large central hole, and on disks with a small central hole. The disks were machined from a variety of materials. Curves were plotted for each design to show the influence of tensile strength and ductility on the strength of the disks.

DISKS AND DISK-BURST EQUIPMENT

Disks were fabricated of various materials according to three basic designs. The designs are sketched in figure 1. All disks had parallel sides of 3/8-inch thickness and 10-inch outside diameter. Disks were inspected for defects by radiographic and by magnetic or visual methods. The disks were separated into three classes according to the inspection results. Class 1 included disks that were free from defects; class 2 had irregularities that were judged to be of little consequence; and class 3 consisted of all disks that were considered unsound. Data are reported for disks of classes 1 and 2 and the plotted curves distinguish these classes.

Disk types A and B were machined with a small projecting hub. The diameter of the hub was severely reduced adjacent to the disk (fig. 1) so that the hub would have a minimum strengthening effect

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on the disk. Disks of type C were supported on a special "tulip" (reference 2), as shown in figure 2. During operation, the petals of the tulip expand, which permits the disk to be accelerated into speed ranges in which the central hole expands considerably. The extent to which the tulip petals deform is shown in figure 3.

Power for accelerating the disks to burst speed in a period of about 10 minutes was supplied by a small air turbine. The disks were spun at room temperature in a burst pit, which was evacuated to a pressure of 1 inch of mercury absolute. This low pressure minimized any temperature increases due to air friction. The burst speed was determined by reading a speed indicator at the instant of failure.

The types of material used and the corresponding designs investigated are listed in table I. Conventional methods of material testing were used in measuring the mechanical properties, which are also listed in table I. The tensile specimens (fig. 4) were 1/4 inch in diameter and had A.S.T.M. recommended dimensions. Specimens were cut in a radial direction from material located near the center of disks that had been fabricated and heat-treated in the same manner as the burst disks; the tensile specimens would thus best approximate the properties of the material in the most highly stressed region of the disk.

DISK FRACTURES

Photographs of burst disks, arranged in order of decreasing ductility, are presented in figure 5, which shows that the number of pieces increases with decreasing ductility.

Some disks failed in a plane approximately 45° to the plane of the disk (figs. 5(a) and 5(b)). This failure can be described as a shear failure. Most of the disks failed in a plane normal to the plane of the disks (figs. 5(c) to 5(e)). This type of break is called a cleavage failure. The disks of lowest ductility failed in a plane normal to the surface of the disk, whereas the disks of highest ductility failed in a plane 45° to the plane of the disk. Some disks of intermediate ductility failed with a 45° break, some failed with a 90° break and some failed with a 45° break near the disk surface and a 90° break in the interior, which is similar to the familiar cup-and-cone fracture of a tensile specimen.

Disks in the beryllium-copper series exhibited both shear- and cleavage-type failures. When the beryllium-copper disks were heat-treated to give the maximum hardness obtainable (optimum aged), they failed in a plane normal to the surface of the disk. In this condition, the precipitation phase or gamma phase appears as a shading of the grains, as shown in figure 6(a). Close examination of the photomicrograph shows that the precipitate occurs within the grains along three crystallographic planes. This precipitate prevented slip and thereby increased the resistance of the material to shear. In the solution-quenched condition, grains were free from this type of precipitate (fig. 6(b)) and fracture was along planes 45° to the plane of the disk.

When the beryllium-copper disks were heat-treated to the over-aged condition and spun, fracture on the 45° planes showed that the failure was due to the resolved shear stress on the 45° planes. The precipitation phase was quite extensive but was concentrated in larger particles, as is shown in figure 6(c) by the general background of fine dots. These particles did not act as effectively to prevent slip as did the much smaller particles, which appeared as a shading in the microstructure of the optimum-aged beryllium-copper.

Data on the influence of fine cracks on the strength of rotating disks were obtained from two disks that acquired grinding cracks during the finishing operation. These fine cracks, discovered by magnetic inspection, are shown in figure 7. The disk shown in figure 7(a) was found to have approximately a 30-percent reduction in strength and the disk shown in figure 7(b) was found to have a 36-percent reduction in strength when the burst speeds of these disks were compared with the burst speeds of similar disks of sound material. These disks were of extremely hard material, having a hardness of Rockwell C-60.

MEASURES OF STRENGTH AND DUCTILITY FOR ROTATING DISKS

In selecting the material and the heat treatment for a rotating disk, the designer needs data that indicate the strength and the ductility of the materials available. For convenience in materials testing, these quantities should be determinable from a tensile test rather than from a rotating-disk test.

An important factor that complicates the process of relating tensile-test data to disk-test data is the occurrence of instability. Instability of a tensile specimen is best discussed in terms of the

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characteristics of a typical stress-strain curve (fig. 8). This figure shows load divided by original area plotted against unit elongation. The important points on the curve are the proportional limit, the maximum-load point (which determines the ultimate tensile strength), and the fracture point. Strain hardening permits the load on the tensile specimen to be increased until necking occurs and from that point on the load can only decrease. The point where the load goes through a maximum is the instability point of a tensile test.

An analytical discussion of the plastic deformation of rotating rings and disks is given in reference 3, which shows that the equilibrium of the rings and disks may become unstable under certain conditions that depend on the shape of the stress-strain curve of the material. Instability of a disk occurs by additional deformation taking place without increase in speed. Two cases must be distinguished in a comparison of the amount of strain that takes place in a disk at the onset of instability with the amount of strain in a tensile specimen when instability begins:

1. The central-hole disk in which the important stress is uniaxial in the region of maximum stress in a tangential direction at the edge of the hole

2. The solid disk in which equal biaxial tensions exist in the region of maximum stresses at the center of the disk

From reference 4 (p. 273) where s_1 is the uniaxial tensile stress and ϵ_1 is the natural strain in the direction of the applied load, the instability condition for a tensile specimen can be written

$$\frac{ds_1}{d\epsilon_1} = s_1$$

As an approximation, this condition would be expected to apply to a flat sheet in a loading machine with uniaxial tension at the edge of a hole.

Also from reference 4 (p. 273) where s_1 is the numerically largest principal stress and ϵ_1 is the natural strain in the direction of this stress, the instability condition for a solid flat sheet under biaxial tension can be written

$$\frac{ds_1}{s_1} = d\epsilon_1$$

Therefore,

$$\frac{ds_1}{d\epsilon_1} = s_1$$

This criterion of instability of a flat plate in a loading machine is the same as that of a tensile specimen, thus for machine loading of an uniaxially stressed body or for a body subjected to biaxial tension, instability would occur for the same values of principal strains in which the strain considered is the principal strain in the direction of the arithmetically largest principal stress.

Instability in a machine-loaded flat plate or tensile specimen depends on the fact that plastic strain permits increased load on the material through strain hardening and required reduced load on the part through decrease in cross section. The instability point is actually the point at which reduction in load due to loss in area proceeds at a rate equal to the gain in load due to strain hardening.

Another factor is introduced in the case of rotating bodies because strain in a rotating body permits the elements of mass to move at increased radii and thus augment the increase in stress due to increase in speed. Instability in the uniaxially stressed edge of a central hole in a rotating disk or in the biaxially stressed center of a solid rotating disk would thus be expected to occur at a strain in the plane of the disk less than the longitudinal strain in a tensile specimen. Accordingly, if some measurement of deformation of a tensile specimen is to be used as a measure of ductility for rotating-disk purposes, it should involve measurements made either prior to or at most at the instability point of the tensile specimen and should not consist of conventional measures of ductility, such as percent elongation in a specified gage length after rupture. The determination of the exact point on the stress-strain curve corresponding to instability in a disk is discussed in reference 3. This determination requires a knowledge of the entire sequence of deformations of the disk in the plastic range. In the absence of such information, the only statement that can be made is that the instability strain in a disk must lie somewhere between the proportional limit and the instability point of the tensile specimen. Because the exact position of this point is unknown, the plastic strain in a tensile specimen from the proportional limit to the ultimate load point can be used as a practical measure of ductility, which has some probability of being significant in measuring the ductility of rotating-disk materials. With the assumption that the volume of the deforming material does not change appreciably, the transverse strain in a tensile specimen can be related to the longitudinal strain and the transverse plastic strain at the maximum load can be approximated by the change in diameter of a fractured tensile specimen in a region remote from the neck. This reduction in diameter of the nonnecked region of the tensile specimen will be used as the measure of ductility. The extent to which this measure correlates with conventional ductility is shown in figure 9.

If the suitability of the ductilities of two materials such as steel and aluminum are to be compared for a rotating-disk application, the data must be put on such a basis that the density and tensile strengths will not affect the comparison. If a completely brittle material is assumed, the disk would be expected to fail when the maximum stress as calculated by elastic theory becomes equal to the tensile strength. For a given disk shape, this stress is proportional to the density of the material and to the square of the speed. The quotient of the elastic stress at burst divided by the ultimate tensile strength would be unity. If a material of small ductility with different density and tensile strength is compared with that of the brittle disk in order to determine the improvement in disk performance that is solely attributable to the ductility, some measure of this improved performance must be used. The redistribution of stress that occurs when a disk becomes plastic could tend to alleviate the effects of stress concentration and thus permit the ductile disk to burst at a higher speed than the brittle one. A theoretical elastic stress calculated for the higher burst speed would then be expected to exceed the tensile strength and the ratio of calculated elastic stress at burst to tensile strength becomes a parameter, which would be expected to be a function of ductility.

If a disk greatly enlarges before bursting, the actual centrifugal stresses are increased for any given speed because the elements of mass are moving at greater radii. If two materials, A and B, have the same ultimate tensile strengths and if disks made from these materials have the same ratios of calculated elastic stress at burst to ultimate tensile strength, the disk of material B could expand to a greater diameter at burst than that of A. The actual stresses at burst in the disk of material B would be higher than for material A but the fact that the disk of material B could go to a larger diameter before bursting should not be regarded as a desirable attribute of material B, inasmuch as designs of rotating machinery usually require that disk enlargement during operation be held to a minimum. Excluding the case in which a large increase in diameter might be acceptable, the calculated maximum elastic stress at burst is a desirable measure of the strength of a material as used in a disk and this stress becomes a measure of the strength of a disk at any given density. The ratio of elastic stress to ultimate tensile strength is a measure of the desirable stress-redistributing characteristics of the disk material and this ratio should be a function of ductility. For disk purposes, this ratio is in itself a measure of ductility; however, it suffers from the disadvantage that a burst test is required for each ductility determination. Some quantity would be desirable that could be measured during a tensile test, which would satisfactorily correlate with calculated elastic stress in the disk at burst divided by tensile strength. The details of calculating elastic stresses are given in the appendix. The manner in which calculated elastic stress at burst divided by ultimate tensile strength correlates with reduction in diameter in the nonnecked region of a tensile specimen will be discussed in the following section.

QUANTITATIVE RESULTS

The maximum elastic stress, calculated from the solid-disk formula for the burst speeds of the various disks, has been plotted against tensile strength in figure 10. These plots show that disk strength increases with tensile strength but this relation is not strictly linear. Departures of points from the straight lines can be attributed to variables of secondary importance. In order to examine the importance of ductility as one of these variables, the ratio of elastic stress at burst and ultimate tensile strength was plotted against ductility in figure 11. Examination of figure 11 shows that ductility does not have a pronounced influence on the ratio of elastic stress to tensile strength in the range of ductilities used.

The theory that a disk should fail when the calculated elastic stress is equal to the ultimate tensile strength would require that the plotted points of figure 11(a) all have ordinate values of unity. The theory that a disk should fail when the average stress on a diametral section is equal to the ultimate tensile strength would require the plotted points to fall along the upper dotted line where the ordinate value is 1.238. (The method of locating this line is given in the appendix.) This concept of average stress was introduced in reference 2. The average stress is the centrifugal force on one-half of the disk divided by the area of a diametral section. All the points for perfect disks were found to lie between these two lines and the calculated elastic stress at burst was found to be as high as 120 percent of the ultimate tensile strength (fig. 11(a)).

The influence of ductility on the ratio of calculated elastic stress at burst divided by ultimate tensile strength is shown in figure 11(b), for which the burst speeds were measured for disks having $1\frac{1}{2}$-inch-diameter central holes and the stresses were calculated according to the formula for a solid disk. The solid-disk formula was used so that the calculated stress would show the reduction in load-carrying capacity due to the central hole. These disks burst with a maximum calculated elastic stress of about 97 percent of the tensile strength, as compared with 120 percent for the solid disks. The theory that these disks should break when the elastic stress calculated for a disk with a $1\frac{1}{2}$-inch-diameter central hole is equal to the ultimate tensile strength would require that the plotted points have ordinate values of 0.498. (See appendix.) The theory that these disks should break when the average stress on a diametral section is equal to the ultimate tensile strength would require the points to lie along the upper dotted line with an ordinate value of 1.056. Disks of intermediate ductility come fairly close to values predicted from the average-stress theory and the sparce data for disks of high ductility suggest that the strength of the disk with a large central hole decreases as ductility increases in the range of high ductility. One factor that may have contributed to the early failure of the very ductile disks with large central holes is that expansion of the central hole would permit added stress due to tulip pressure, as evidenced by figure 3.

Results of data obtained from the bursting of disks with 1/16-inch-diameter central holes have been plotted in figure 11(c). The theory that these disks should burst when the elastic stress calculated for a disk with a 1/16-inch-diameter central hole is equal to the ultimate tensile strength would require that the plotted points have ordinates of 0.500. The theory that these disks should break when the stress on a diametral section is equal to the ultimate tensile strength would require the points to lie on the upper dotted line with ordinate of 1.223. The data points lie between these two conditions.

The influence of ductility on the relative strength of solid disks and disks having central holes is shown in figure 12. Because the elastic stress in any disk is proportional to the square of the speed, the strength of the disk with a hole relative to that of the solid disk can be expressed as the ratio of the squares of the burst speeds. The plotted points were obtained by averaging the burst speeds squared of disks of given strength and ductility and dividing by the average of burst speeds squared for solid disks of the same material and heat treatment. In the range of ductility investigated, the reduction in strength due to the large hole can be quite well approximated by the decrease in diametral section, as is shown in figure 12(a) by the fact that the points lie approximately along the line with an ordinate value of 0.850. The hole with a diameter of 15 percent of the outer diameter produced a strength reduction of about 18 percent. The influence of ductility on the comparative strengths of disks with 1/16-inch-diameter central holes and solid disks is shown in figure 12(b). No great reduction in strength was observed. The strength reduction was somewhat greater than would be expected only on the basis of decreased diametral section, which would be the case if the points fell along the upper dotted line with an ordinate value of 0.994. The hole with a diameter of 0.6 percent of the outer diameter produced a strength reduction of about 5 percent. This reduction is much less than the 50-percent reduction, which would be predicted by calculating elastic stresses.

A two-fold effect of using disks with central holes in rotating machinery could be expected. One effect is the reduction in rupture strength of the disk. These data show that this effect is small and can be readily estimated. Another effect, which has not yet been evaluated, is the amount of dynamic unbalance that might occur because of yielding around a central hole. If this effect proves to be unimportant, designs of disks with central holes can be used to more advantage than is now recognized. Such advantages include use of through shafts with straddle-mounted bearings.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effect of strength and ductility on the burst characteristics of rotating disks:

1. For solid disks and for disks having stress concentrations consisting of large- and small-diameter central holes, disk strength increased with increase in tensile strength in the range of ductilities investigated (3.4 to 52.8 percent conventional elongation). This trend occurred even though an increase in tensile strength usually involved a decrease in ductility.

2. The ratio of disk strength to tensile strength was relatively independent of ductility for solid disks and for disks with central holes.

3. The strength of solid disks was reduced by the introduction of large central holes approximately in proportion to the amount of material removed. (A hole having a diameter of 15 percent of the outer diameter produced a strength reduction of about 18 percent.)

4. Small holes reduced the strength by an amount greater than the amount of section removed. (A hole having a diameter of 0.6 percent of the outer diameter produced a strength reduction of about 5 percent.) In no case was the reduction in strength near the value of 50 percent, which would be predicted by calculating elastic stresses.

5. The strength of low-ductility disks was drastically reduced by the presence of fine cracks.

6. The number of fragments of burst disks increased as ductility decreased.

7. The most ductile materials failed in a plane approximately at 45° to the plane of the disk, whereas the least ductile materials failed in a plane normal to the disk.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, April 8, 1948.

APPENDIX - CALCULATION OF AVERAGE AND ELASTIC STRESSES

Symbols

The following symbols are used in this report:

A area of diametral section, sq in.

a radius of central hole, in.

b radius of disk, in.

F total centrifugal force on diametral section, lb.

r_a radius to centroid of semicircle of radius a, in.

r_b radius to centroid of semicircle of radius b, in.

s_1 numerically largest principal stress

ϵ_1 natural strain in direction of s_1

ν Poisson's ratio, 0.3

ρ mass density of disk material, lb sec^2/in.^{4}

σ_r radial stress, lb/sq in.

σ_θ tangential stress, lb/sq in.

ω angular velocity, radian/sec

Solid-Disk Elastic Stress

The elastic stresses are greatest at the center of a solid disk (reference 5, p. 68) where

$$\sigma_r = \sigma_\theta = \frac{3 + \nu}{8} \rho \omega^2 b^2$$

For most of the materials tested, ν has a value of about 0.3. The greatest variation from 0.3 occurred for the aluminum-base alloy, which had a value of ν of 0.33. Inasmuch as this value represents a 1-percent variation in the calculated elastic stress, the calculated elastic stress at burst, which can be regarded only as a parameter because plastic flow occurs before burst, was based on the assumption that $\nu = 0.3$ for all materials.

Average Stress

The average stress is obtained by dividing the centrifugal force on one-half of the disk by the area of a diametral cross section. For a disk of unit thickness

$$F = \frac{\pi b^2}{2} \rho r_b \omega^2 - \frac{\pi a^2}{2} \rho r_a \omega^2$$

$$r_b = 0.424b$$

$$r_a = 0.424a$$

$$A = 2(b - a)$$

$$\frac{F}{A} = \frac{0.424\pi \rho \omega^2}{4} \left(\frac{b^3 - a^3}{b - a}\right)$$

For the solid disks where $a = 0$

$$\frac{F}{A} = \frac{0.424\pi \rho \omega^2}{4} b^2$$

Ratio of Solid-Disk Elastic Stress to Solid-Disk Average Stress

The ratio of solid-disk elastic stress to solid-disk average stress is

$$\frac{\sigma_\theta}{\frac{F}{A}} = \frac{\frac{3 + \nu}{8} \rho \omega^2 b^2}{\frac{0.424\pi \rho \omega^2}{4} b^2}$$

$$= \frac{3 + \nu}{8} \frac{4}{0.424\pi} = \frac{3.3}{0.848\pi}$$

$$= 1.238$$

Thus, if a disk should fail when average stress is equal to ultimate tensile strength, the corresponding point on a plot of the ratio of elastic stress to ultimate tensile strength against ductility would have an ordinate value of 1.238.

Ratio of Solid-Disk Elastic Stress to

Average Stress for Disk with Hole

The ratio of the elastic stress in a solid disk to the average stress in a disk with a 1/16-inch-diameter central hole is

$$\frac{\sigma_\theta}{\frac{F}{A}} = \frac{\frac{3 + \nu}{8} \rho\ \omega^2\ b^2}{\frac{0.424\pi\ \rho\ \omega^2}{4} \left(\frac{b^3 - a^3}{a - b}\right)}$$

$$= \frac{3.3}{0.848\pi}\ \frac{b^2}{b^2 + ab + a^2}$$

$$= \frac{3.3}{0.848\pi}\ \frac{25}{25.316} = 1.223$$

Similar computation for a disk with a $1\frac{1}{2}$-inch-diameter central hole yields

$$\frac{\sigma_\theta}{\frac{F}{A}} = 1.056$$

Elastic Stress in Disk with Hole

The maximum elastic stress in a disk with a central hole is the tangential stress at the inner boundary (reference 5, p. 69) and is

$$\sigma_\theta = \frac{3 + \nu}{4} \rho\ \omega^2 \left(b^2 + \frac{1 - \nu}{3 + \nu}\ a^2\right)$$

Ratio of Elastic Stress in Solid Disk

to Elastic Stress in Disk with Hole

The ratio of the calculated elastic stress in a solid disk to the elastic stress in a disk with a central hole is

$$\frac{\sigma}{\sigma_\theta} = \frac{\frac{3+\nu}{8}\rho\,\omega^2 b^2}{\frac{3+\nu}{4}\rho\,\omega^2\left(b^2 + \frac{1-\nu}{3+\nu}a^2\right)}$$

$$= \frac{1}{2\left(1 + \frac{0.7}{3.3}\frac{a^2}{b^2}\right)}$$

When a 1/16-inch-diameter central hole is used, this ratio is 0.500; when the hole is of $1\frac{1}{2}$-inch-diameter, the ratio is 0.498.

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TABLE I - DISK MATERIALS, MATERIAL PROPERTIES, AND DESIGNS INVESTIGATED

Material	Rockwell hardness		Brinell hardness number	Tensile-test properties				Designs investigated
	B	C		Ultimate strength (lb/sq in.)	Conventional elongation percent[a]	Conventional reduction in area (percent)	Reduction in nonnecked diameter (percent)	
Steel, SAE 1078		38		159,000	3.4	3.6	0.8	A, B, C
		28		130,000	5.3	6.0	2.0	A, B, C
	94	15		104,000	7.9	10.3	2.5	A, B, C
	91	4		91,000	15.1	22.3	6.0	A, B, C
	88	8		89,000	13.3	14.5	4.5	A, B, C
Beryllium-copper	113	42		190,000	5.0	9.2	.8	A, C
	95			104,000	21.2	48.2	6.0	A, C
	83			87,000	29.2	53.0	8.2	C
	68			73,000	34.4	60.9	9.0	A, C
	61			68,000	43.3	64.0	16.9	A, C
Steel, SAE 1035	80			93,000	20.8	29.3	7.5	A, C
Aluminum-base alloy	76			68,000	6.5	8.7	1.4	A, C
60-40 Brass	42		74	58,000	46.1	63.2	15.2	C
Stainless steel	78		132	85,000	52.8	75.6	14.4	C
Nickel-base alloy		34		163,000	21.6	19.9	8.2	A, B, C

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

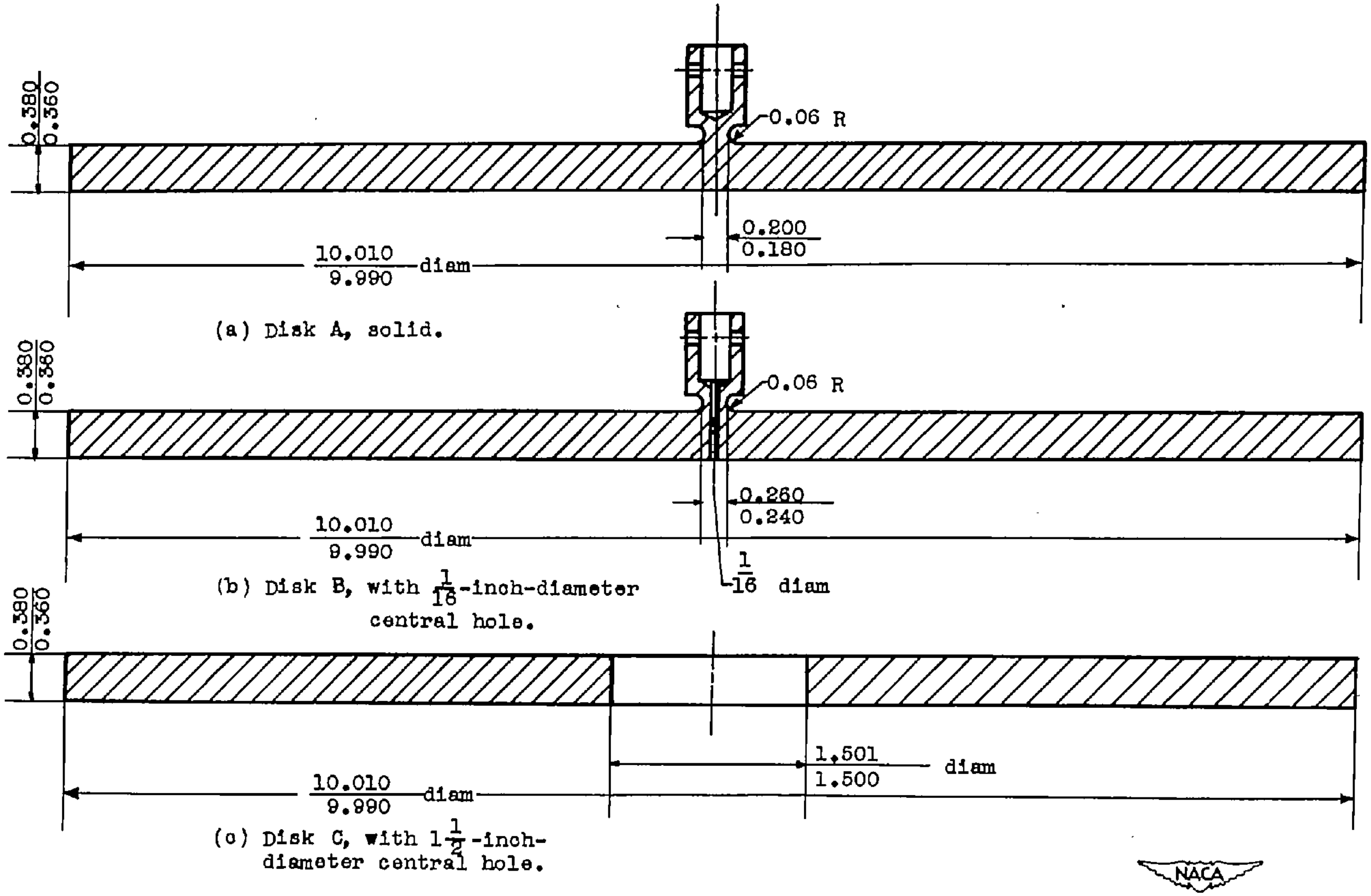

Figure 1. - Disk designs. (Dimensions in in.)

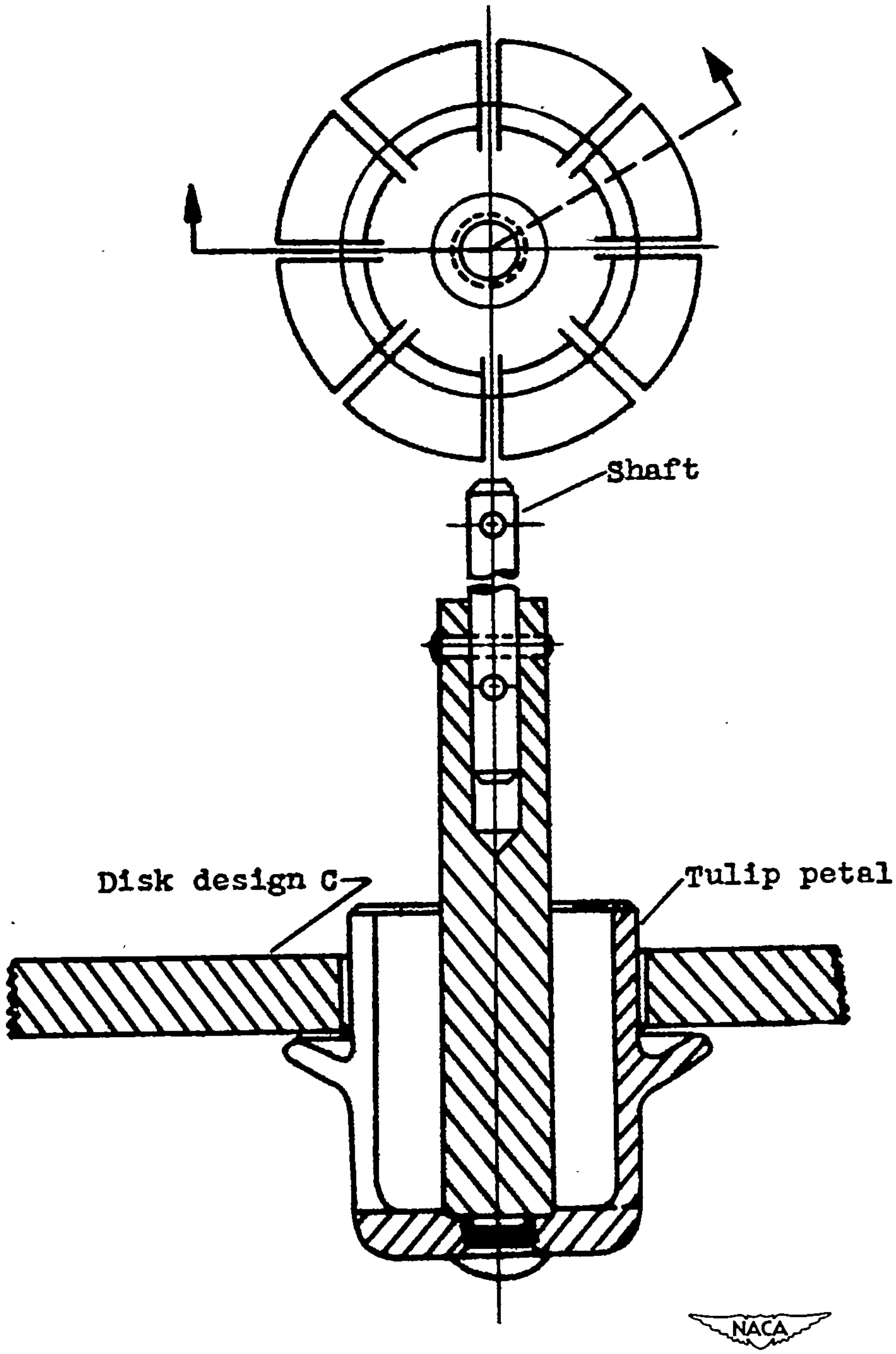

Figure 2. - Tulip design for disk C.

Figure 3. - Expansion of tulip petals with central-hole expansion. Initial diameter of hole, $1\frac{1}{2}$ inches; hole diameter at time of photograph, $2\frac{1}{2}$ inches.

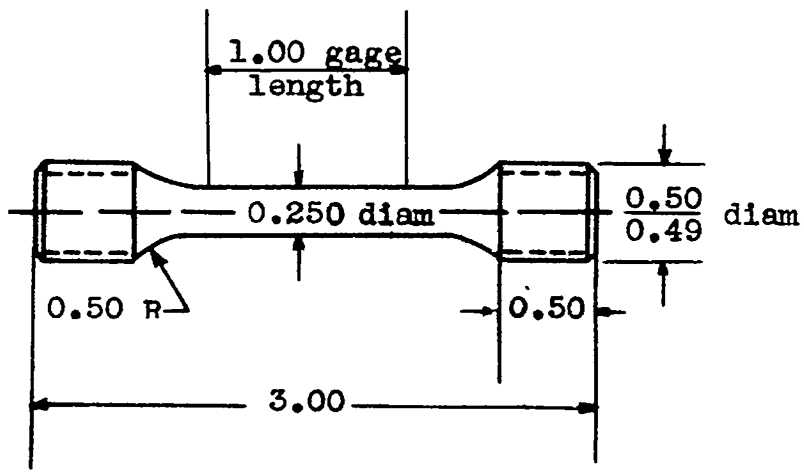

Figure 4. - Tensile specimen. (Dimensions in in.)

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(a) Beryllium-copper disk. Reduction in diameter of tensile specimen in nonnecked region, 16.92 percent.

Figure 5. - Appearance of disk fragments.

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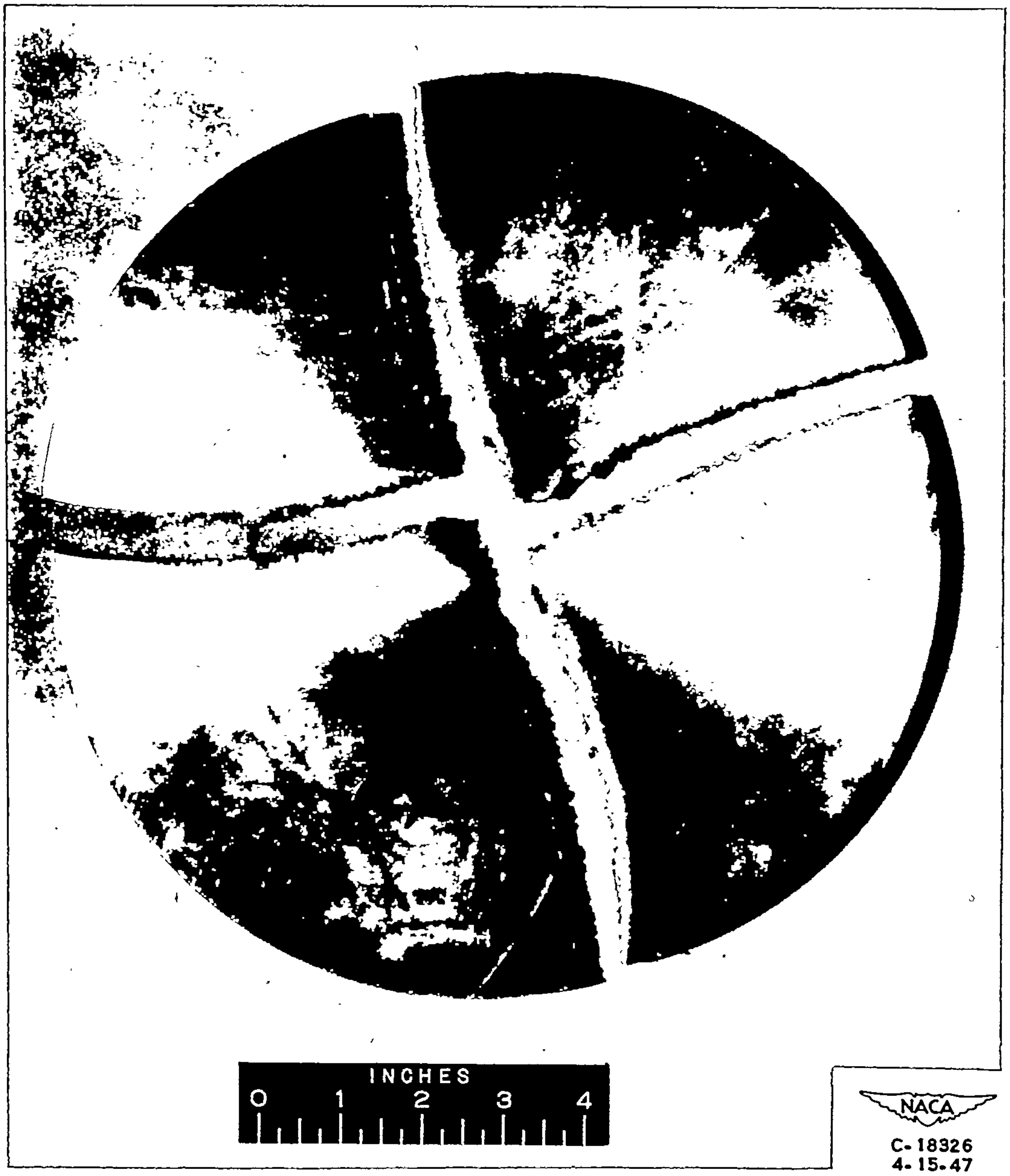
(b) Beryllium-copper disk. Reduction in diameter of tensile specimen in nonnecked region, 9.04 percent.

Figure 5. - Continued. Appearance of disk fragments.



(c) Steel disk, SAE 1078. Reduction in diameter of tensile specimen in nonnecked region, 5.98 percent.

Figure 5. - Continued. Appearance of disk fragments.

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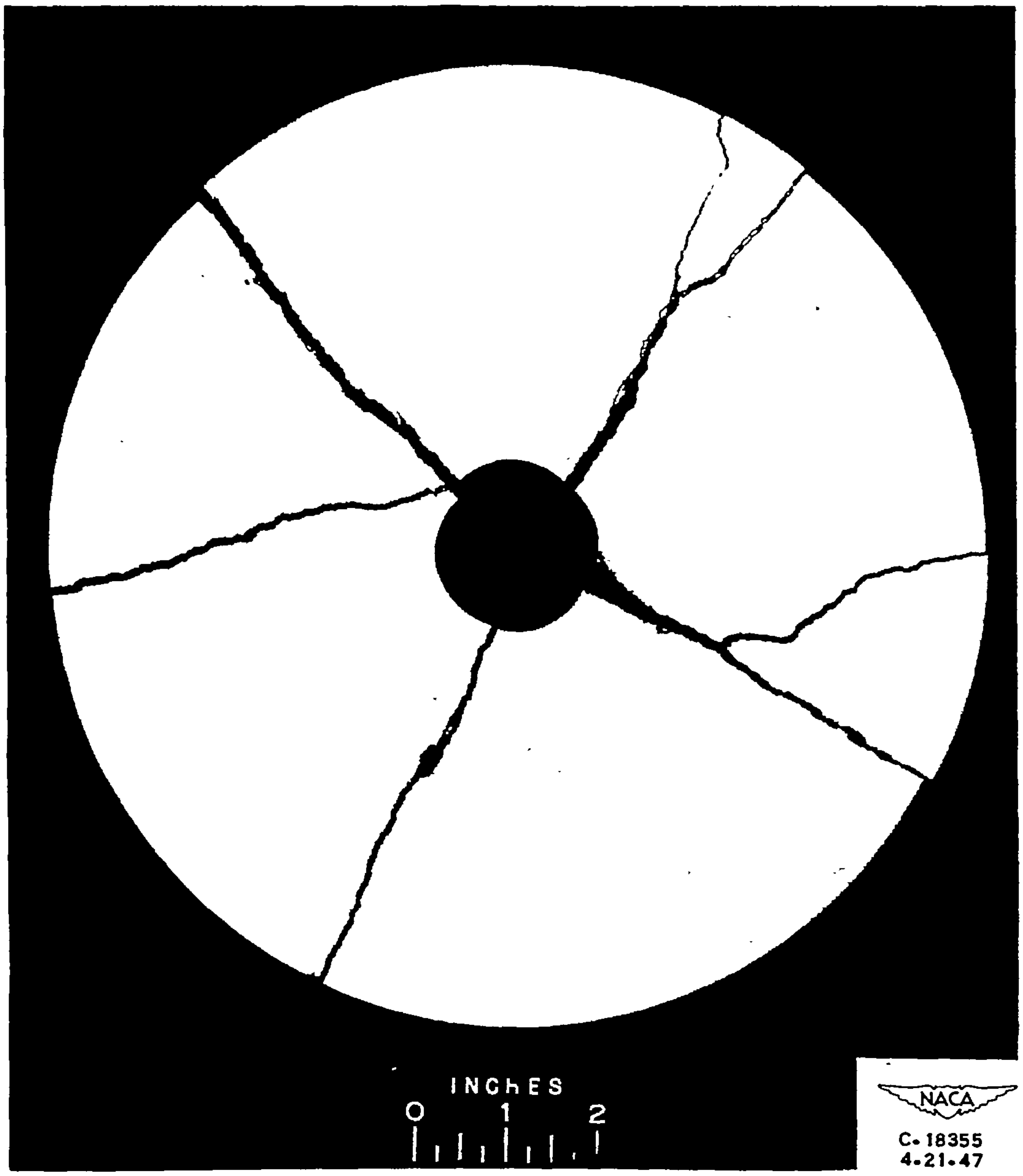

(d) Steel disk, SAE 1078. Reduction in diameter of tensile specimen in nonnecked region, 4.52 percent.

Figure 5. - Continued. Appearance of disk fragments.

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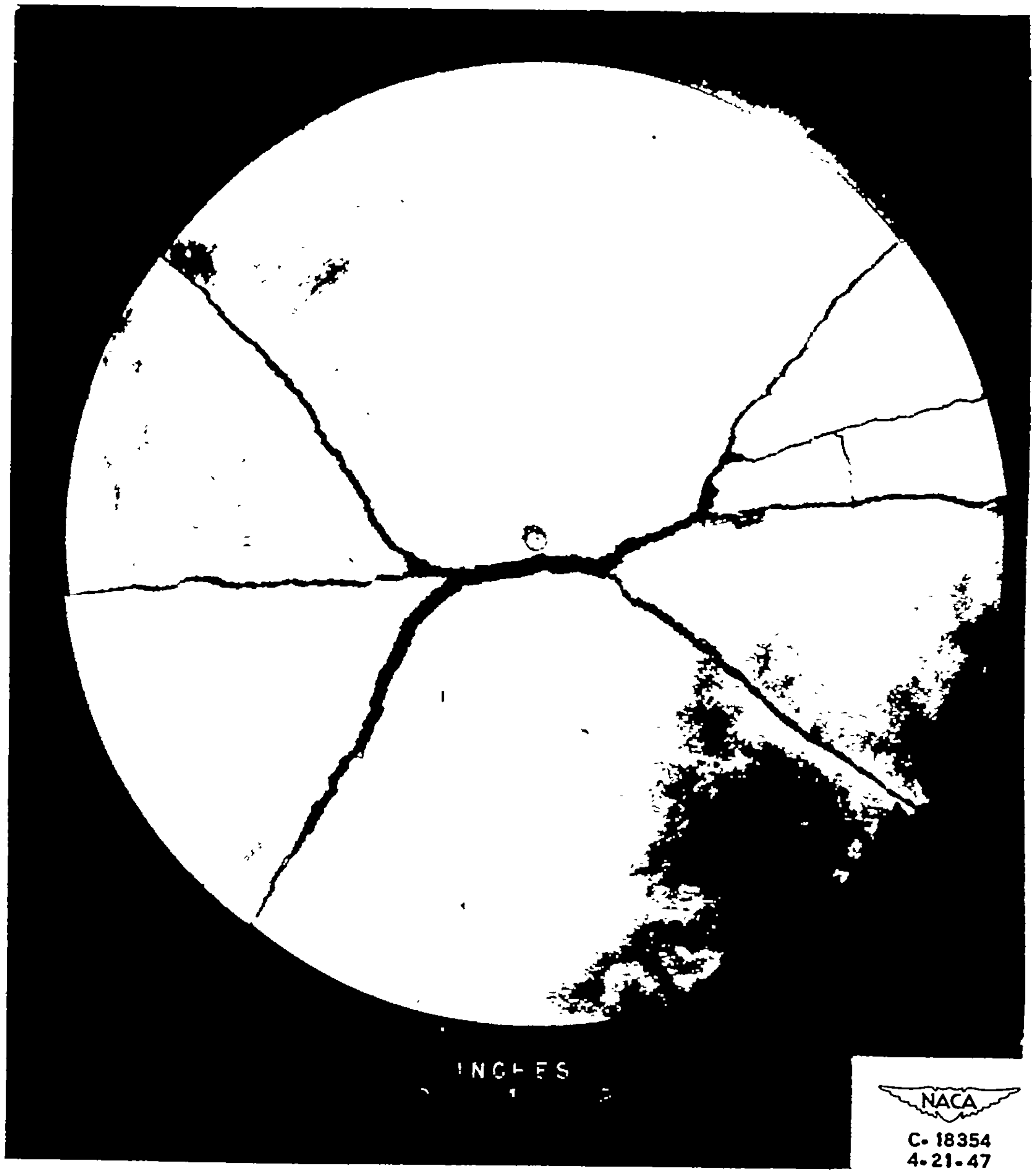

(e) Steel disk, SAE 1078. Reduction in diameter of tensile specimen in nonnecked region, 4.52 percent.

Figure 5. - Concluded. Appearance of disk fragments.

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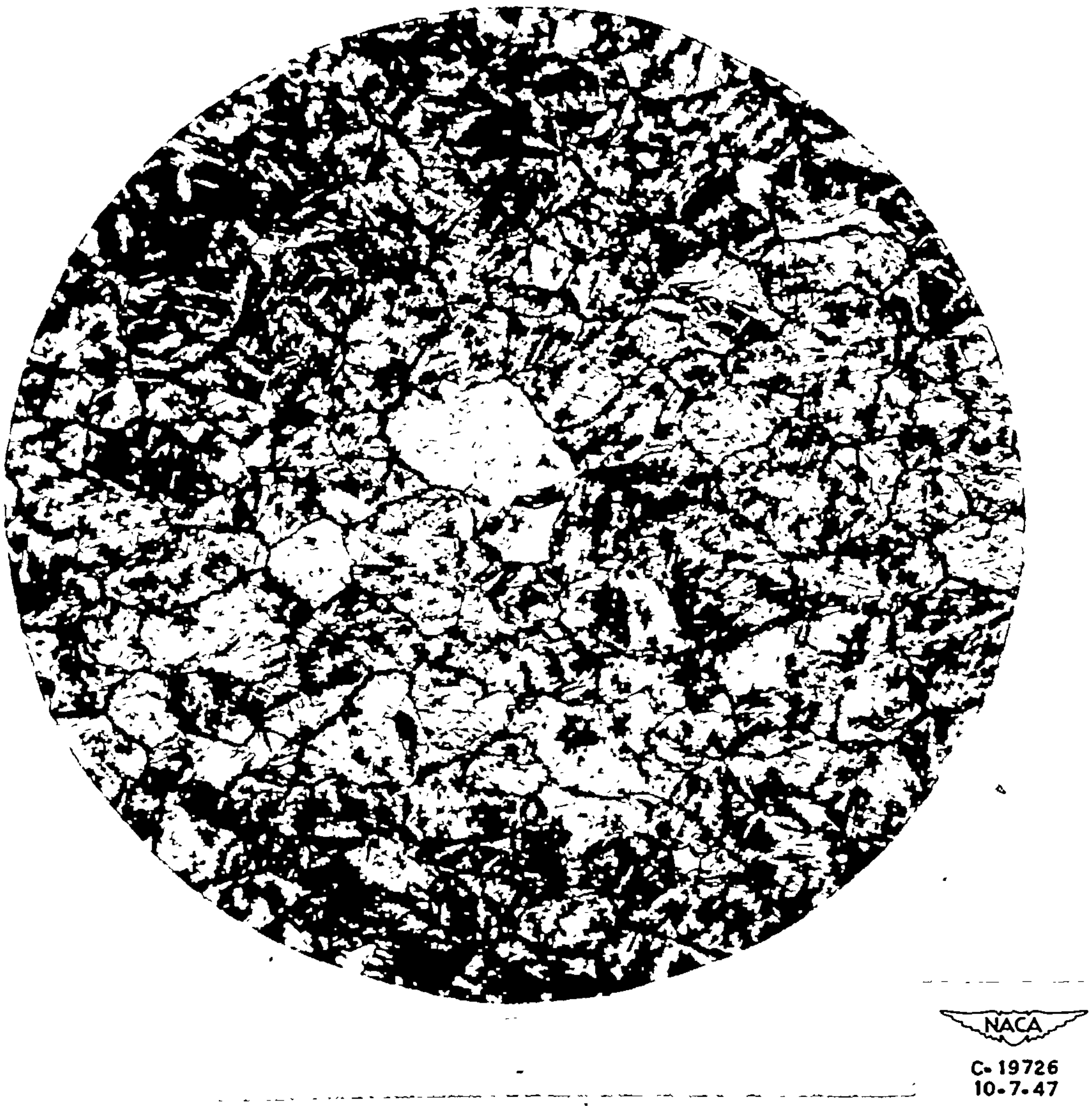
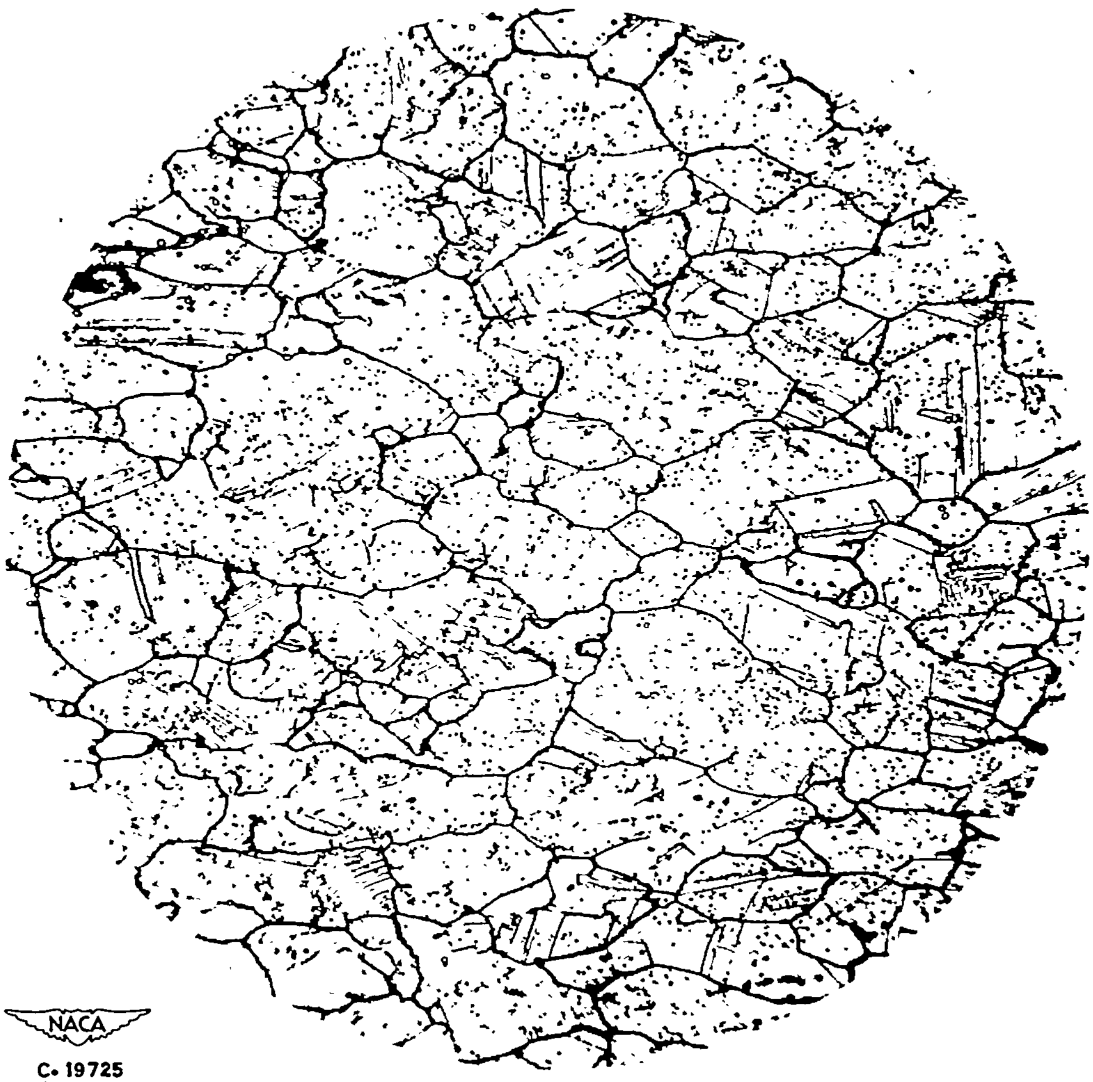


(a) Optimum aged material.

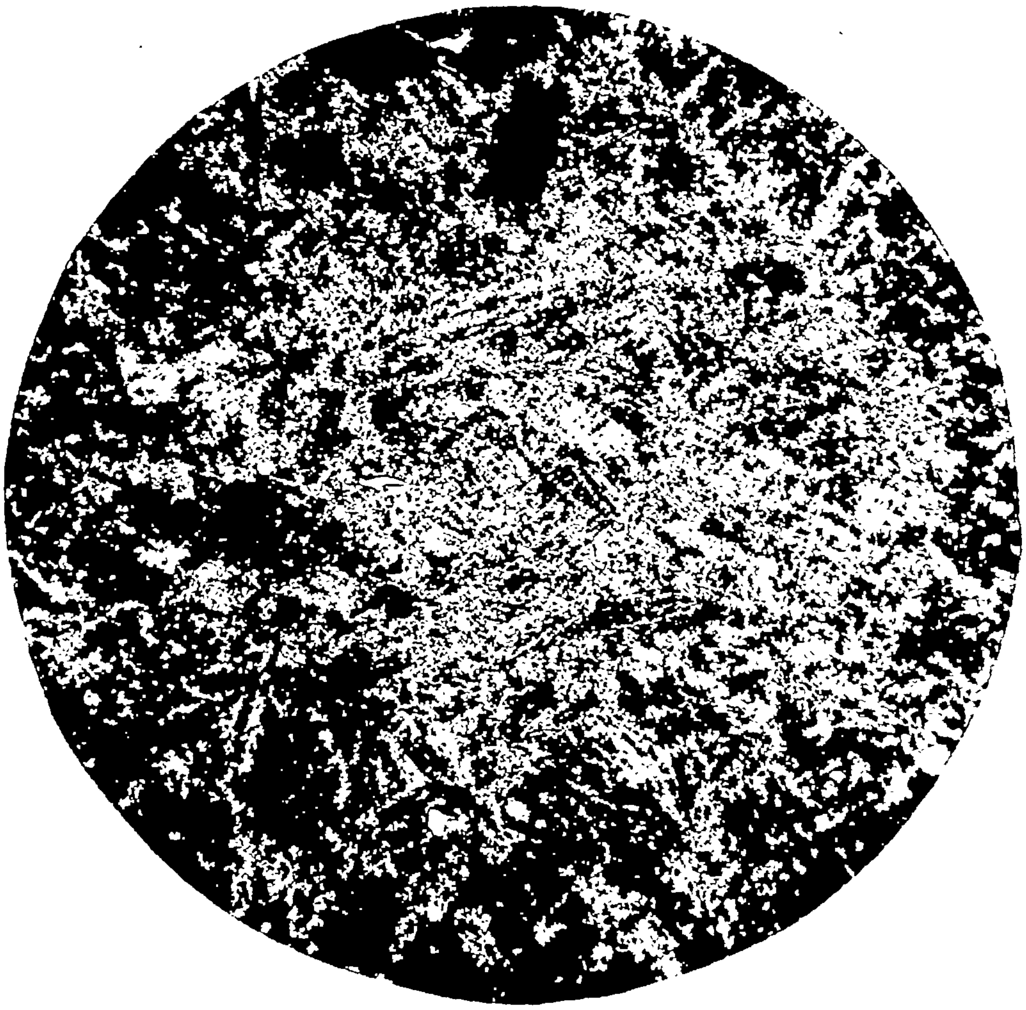
Figure 6. - Beryllium copper etched in ammonium persulphate and ammonium hydroxide. Magnification, 500X.



NACA
C-19725
10-7-47

(b) Unaged material.

Figure 6. - Continued. Beryllium copper etched in ammonium persulphate and ammonium hydroxide. Magnification, 500X.



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C-19724
10-7-47

(c) Over-aged material

Figure 6. - Concluded. Beryllium copper etched in ammonium persulphate and ammonium hydroxide. Magnification, 500X.

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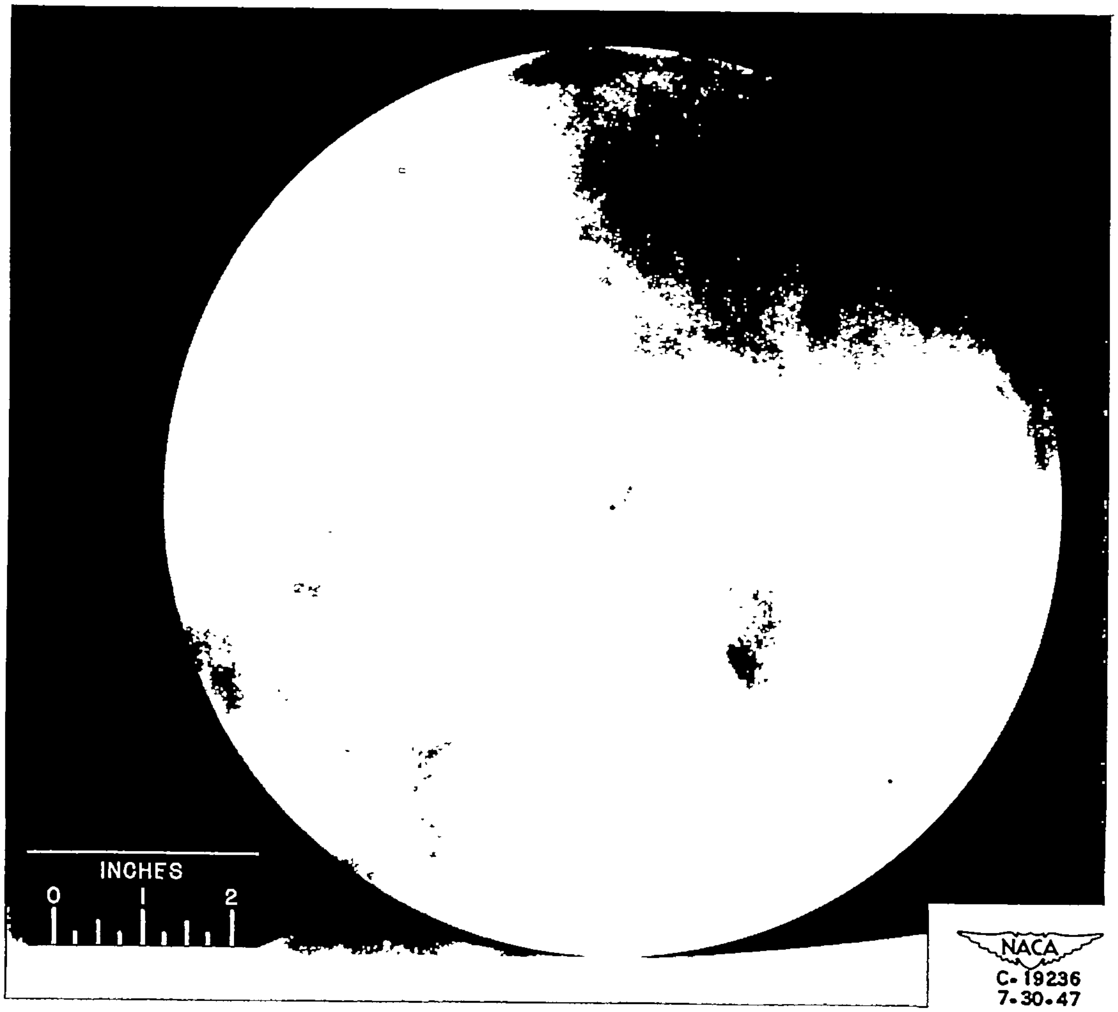

(a) Reduction in strength, 30 percent.

Figure 7. - Grinding checks as shown by magnetic inspection. Hardness, Rockwell C-60.

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(b) Reduction in strength, 36 percent.

Figure 7. - Concluded. Grinding checks as shown by magnetic inspection. Hardness, Rockwell C-60.

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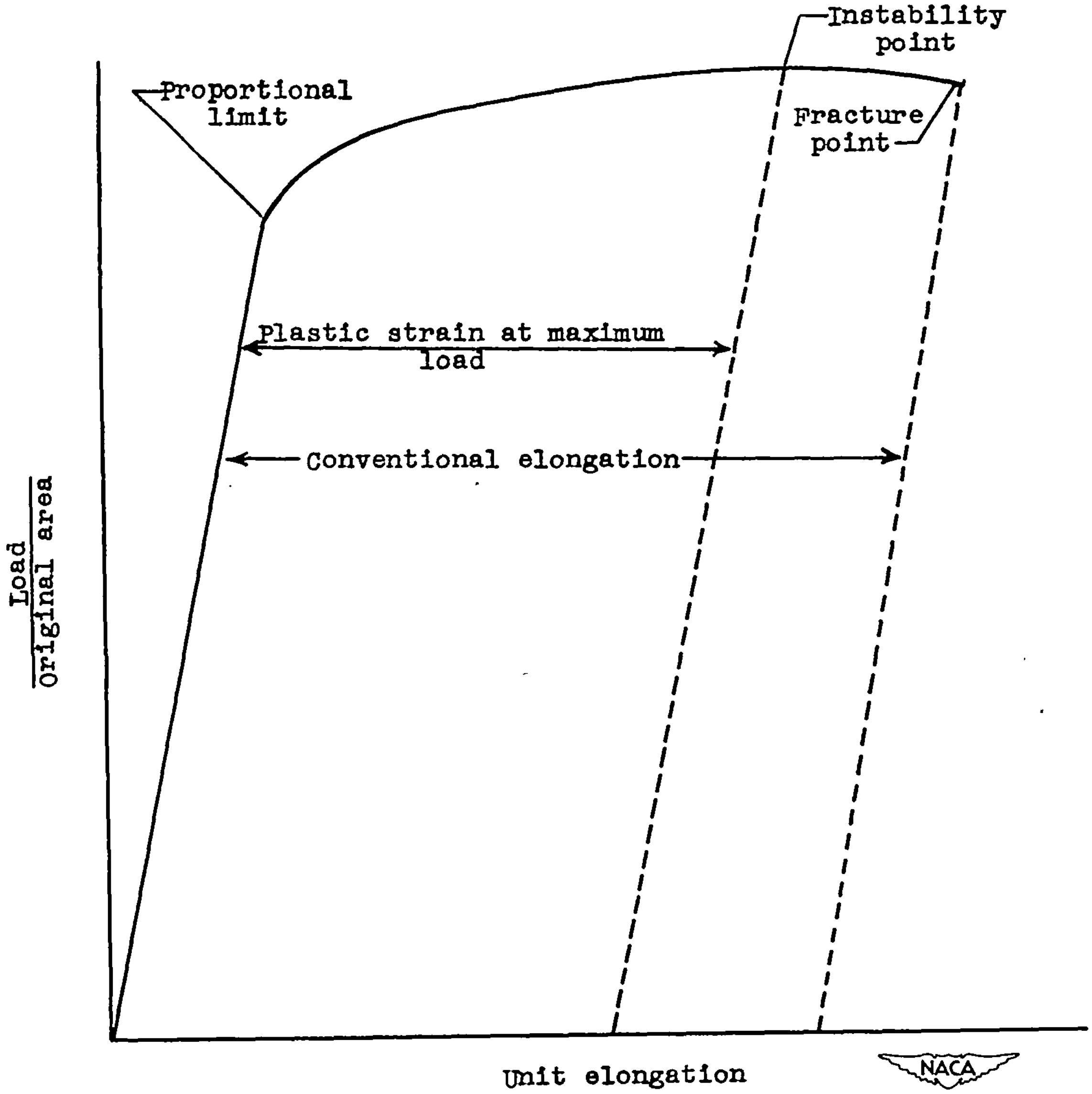

Figure 8. - Typical stress-strain curve of a ductile metal.

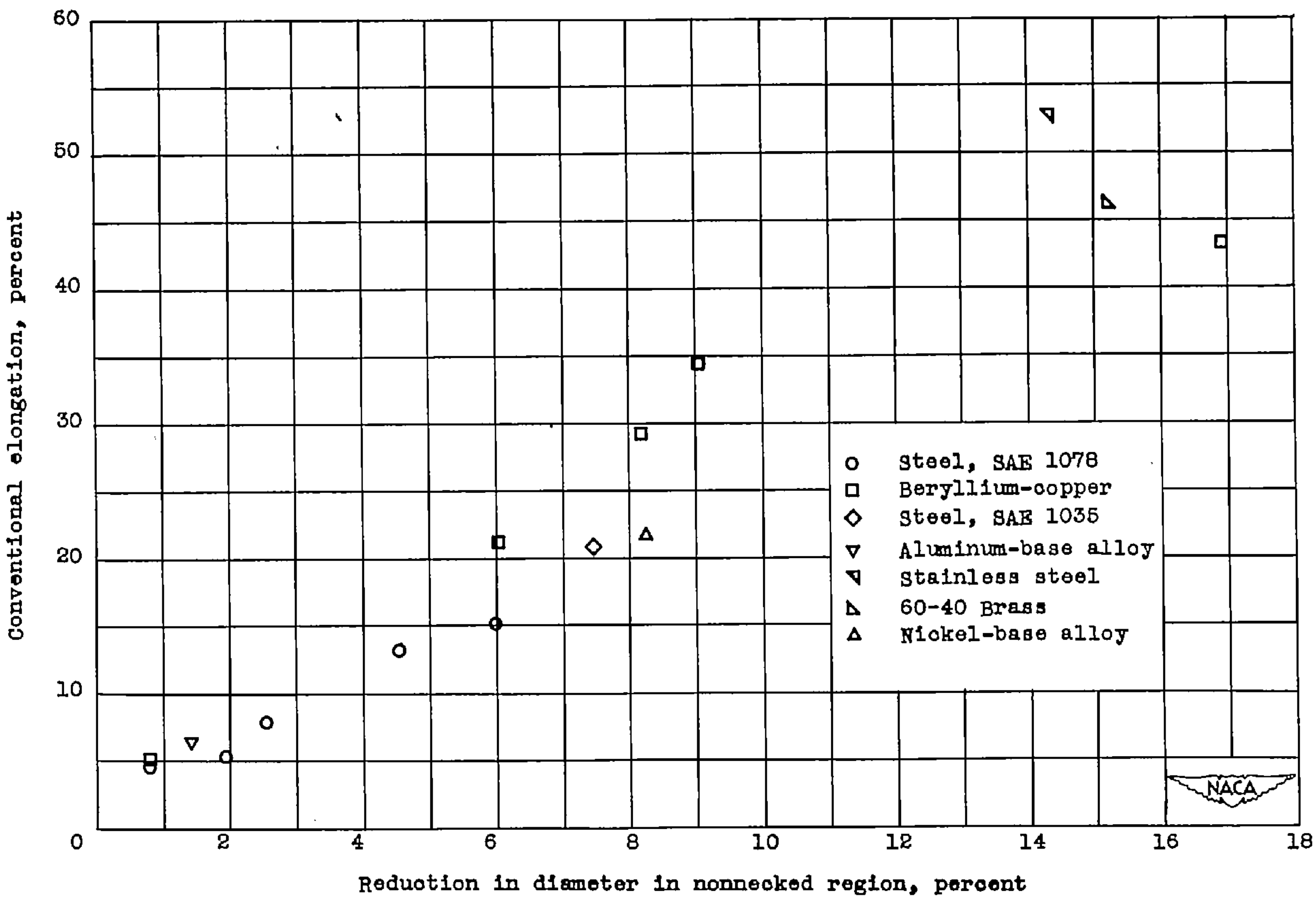

Figure 9. - Relation between ductility at fracture and ductility at instability point.

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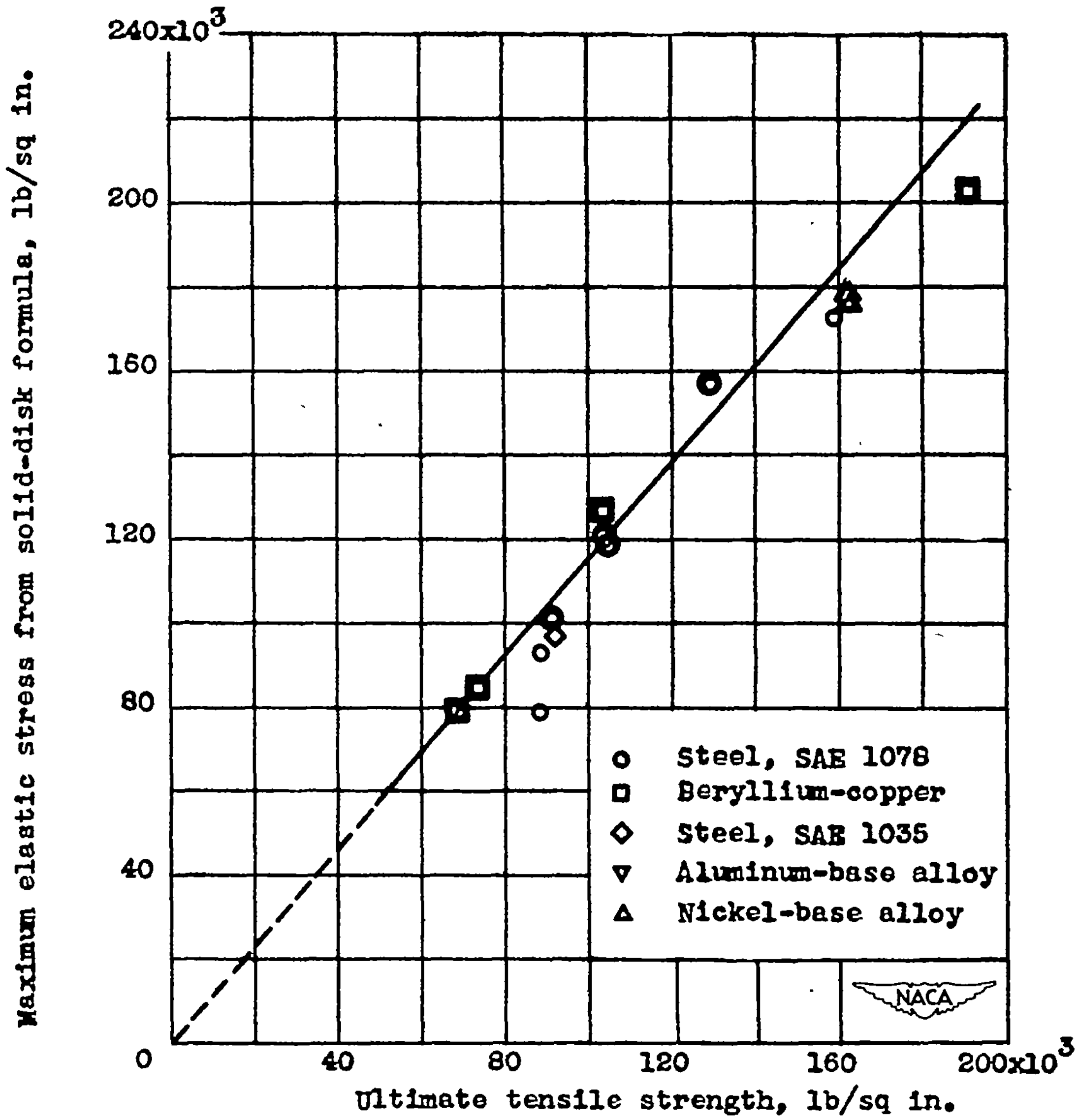
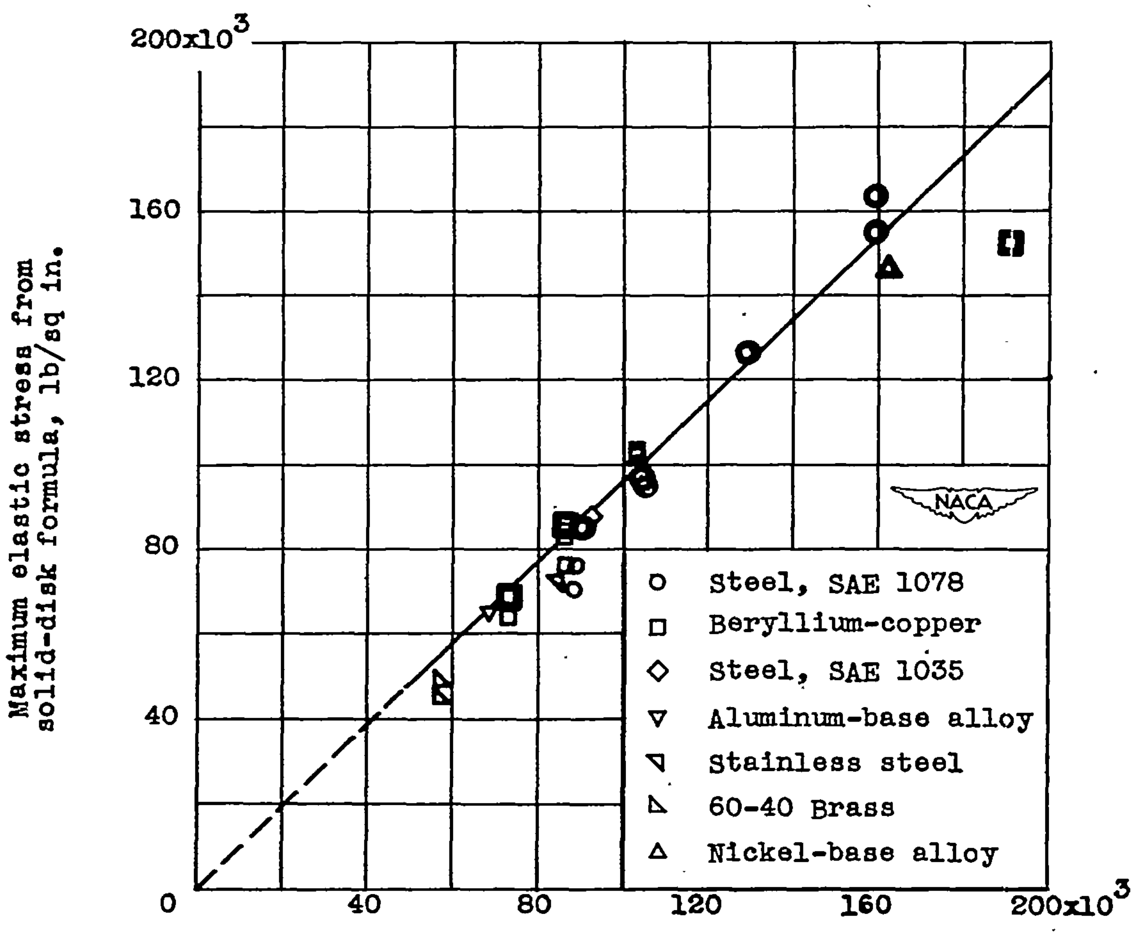


(a) Solid disks.

Figure 10. - Relation between elastic stress from solid-disk formula at burst and ultimate tensile strength. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.



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

Figure 10. - Continued. Relation between elastic stress from solid-disk formula at burst and ultimate tensile strength. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.

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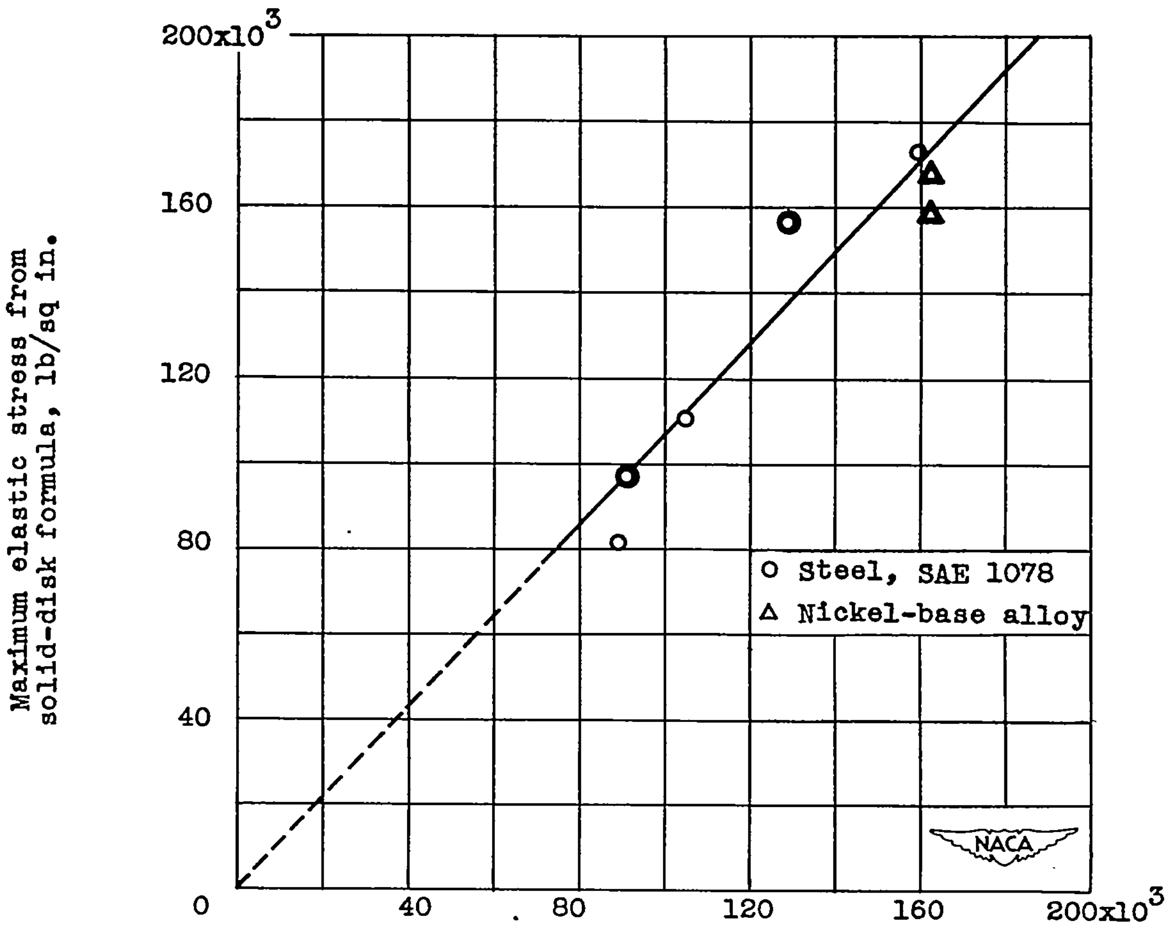
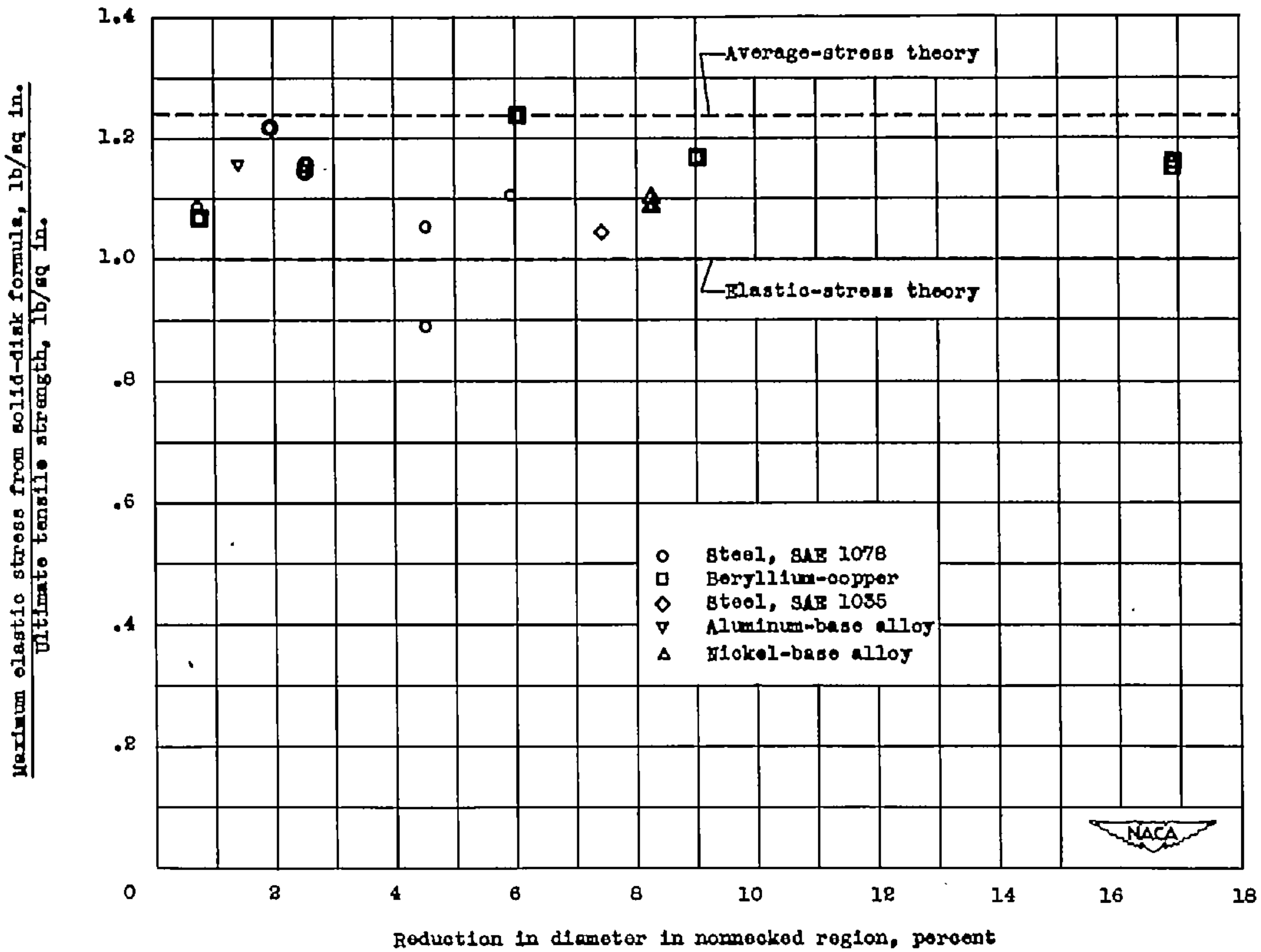


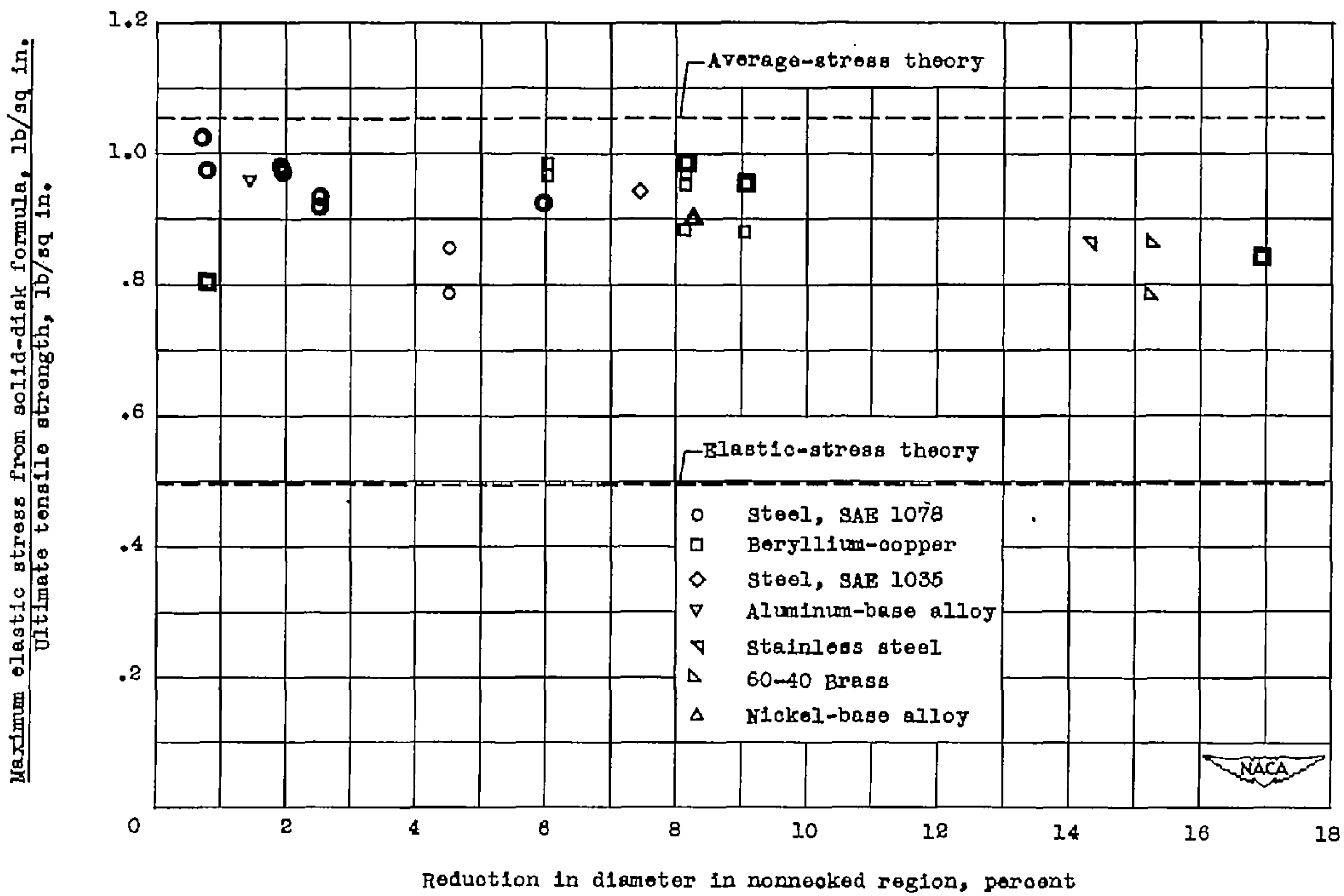
(c) Disks with $\frac{1}{16}$-inch-diameter central holes.

Figure 10. - Concluded. Relation between elastic stress from solid-disk formula at burst and ultimate tensile strength. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.



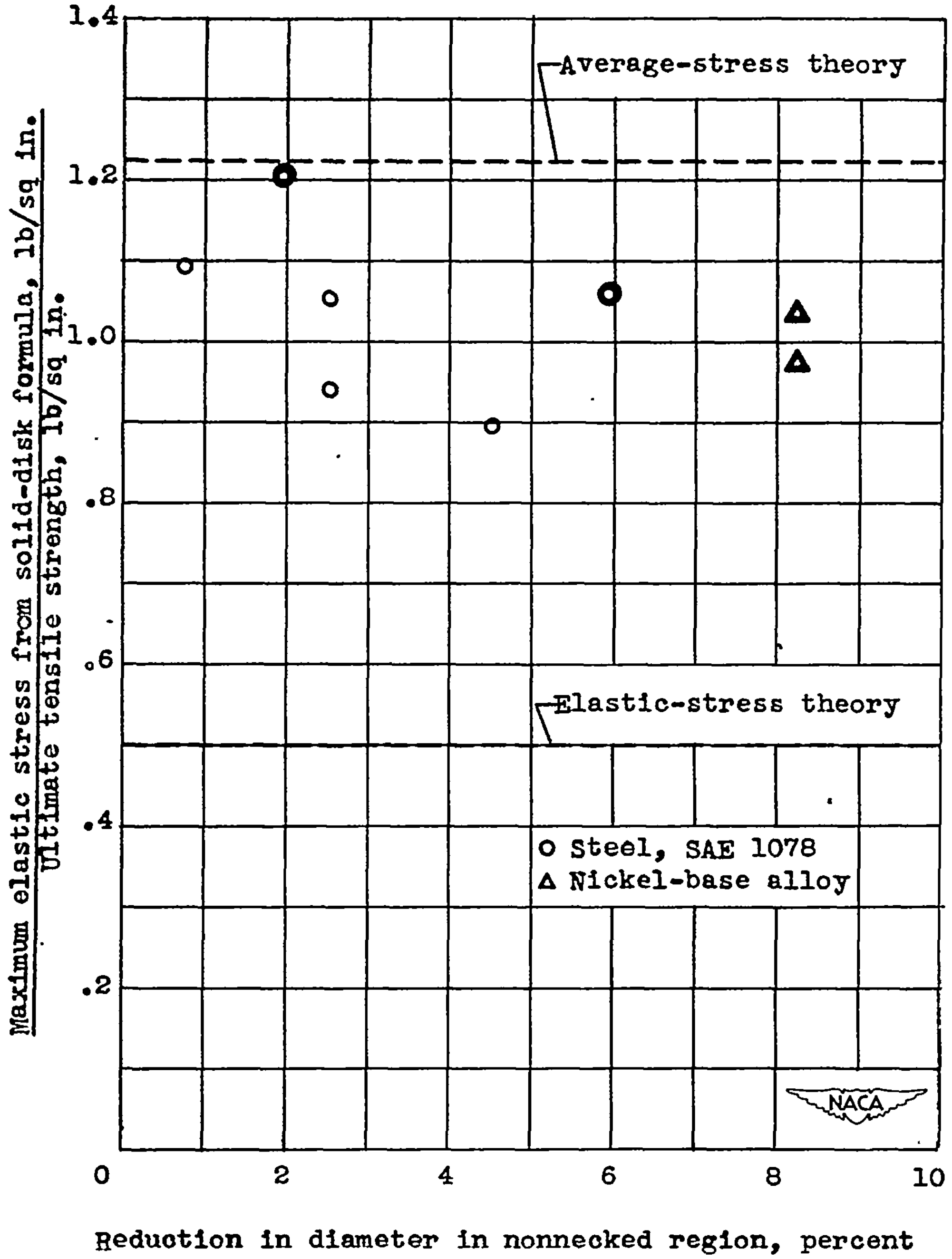
(a) Solid disks.

Figure 11. - Relation between ductility and utilization of tensile strength. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.



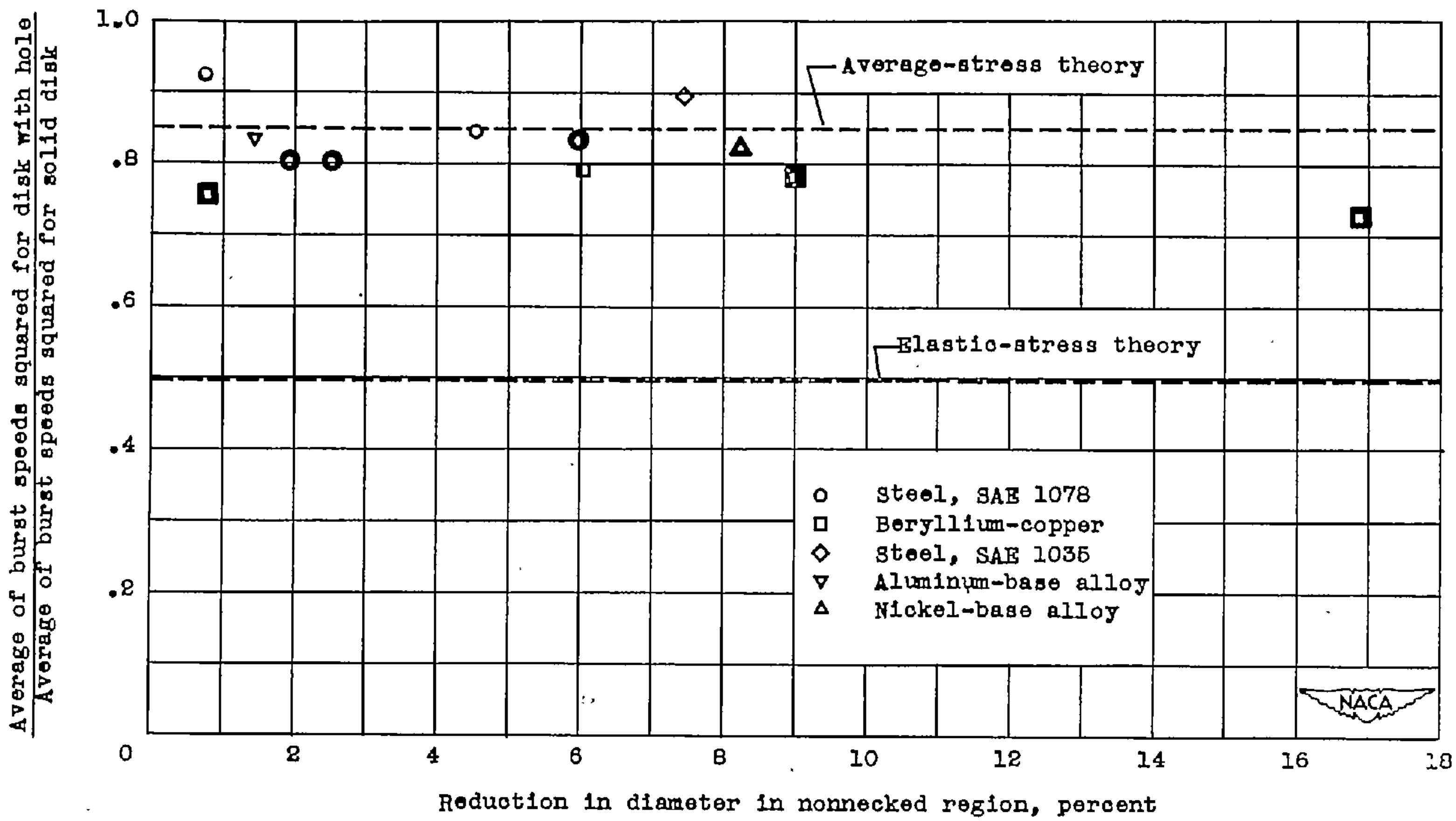
(b) Disks with $1\frac{1}{2}$-inch-diameter central holes.

Figure 11. - Continued. Relation between ductility and utilization of tensile strength. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.



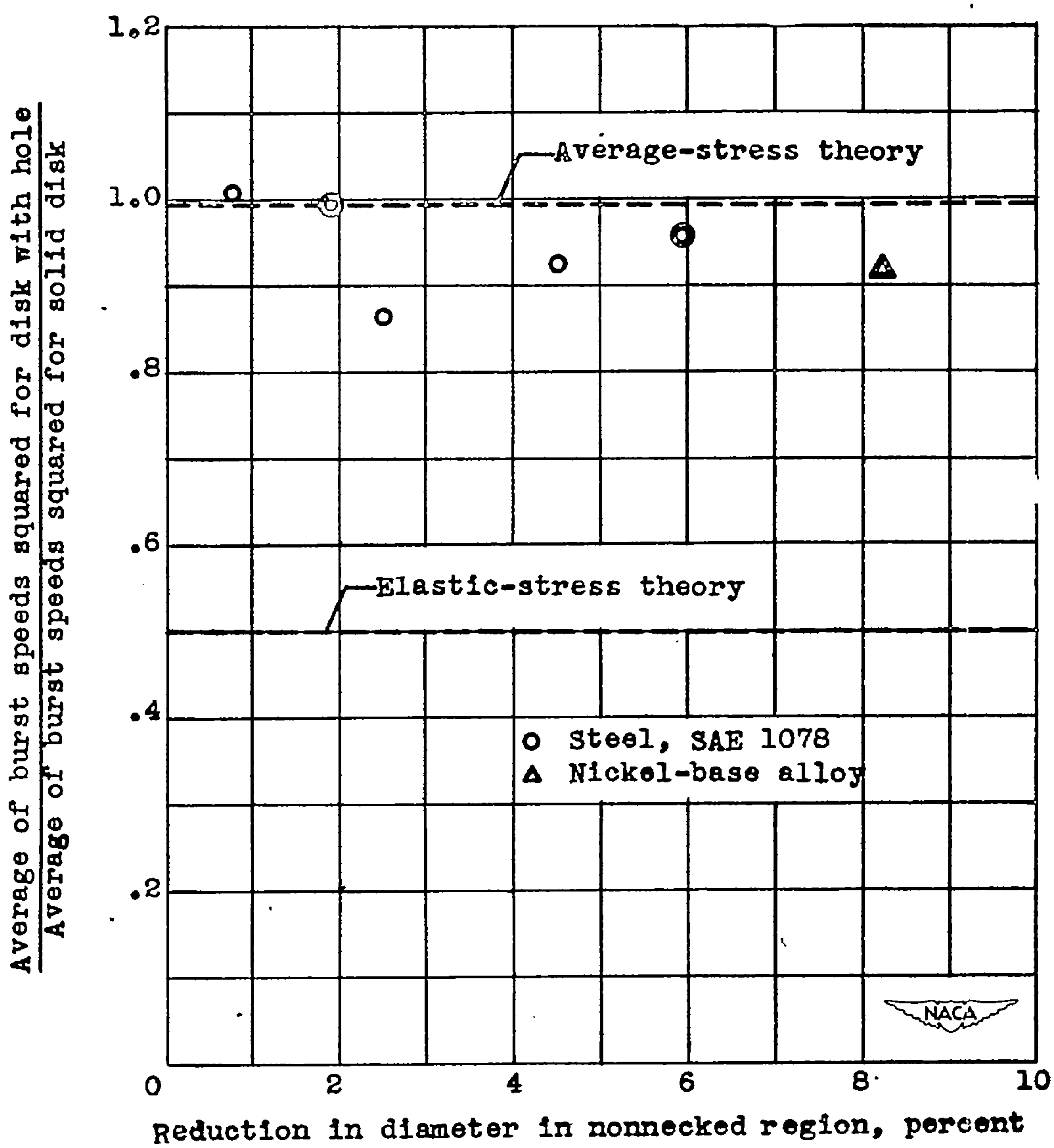
(c) Disks with $\frac{1}{16}$-inch-diameter central holes.

Figure 11. - Concluded. Relation between ductility and utilization of tensile strength. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.



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

Figure 12. - Relation between ductility and strength reduction caused by holes. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.



(b) Disks with $\frac{1}{16}$-inch-diameter central holes.

Figure 12. - Concluded. Relation between ductility and strength reduction caused by holes. Large points represent disks that showed no imperfections upon X-ray and surface inspection. Small points represent disks with trivial defects.