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Evaluation of Tensile, Compressive, Torsional, Transverse, and Impact Tests and Correlation of Results for Brittle Cermets [1]

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Static tests were studied for the determination of mechanical properties of brittle materials. Specimens of brittle materials, represented by cermets having five different compositions, were subjected to tensile, compressive, torsional, transverse, and impact tests. The designs of specimens and apparatus, suitability of the tests to the materials, refinements in test procedures, and the variability of results and their correlation were studied. The elastic properties were obtained from tensile, compressive, and transverse tests, and the modulus of rigidity calculated from the results of these tests agreed with that from the torsional test. Tensile strength was obtained from the tensile, torsional, and transverse tests on specimens of comparable sizes in accordance with a limiting tensile strain. Shear strengths were obtained in the compressive tests. The correlation of impact values with mechanical properties was unsatisfactory.

1. Introduction

The unusual mechanical properties of refractory brittle materials, including cermets, intermetallics, and special ceramic bodies, have renewed the interest in test methods for determining these properties. Because of their heat and erosion resistance, these materials were suggested for many new engineering applications where high temperatures and stresses prevail. Divergent test methods and lack of control in the fabrication of the materials have resulted in confusing data for the mechanical properties. Consequently, the test methods for these brittle materials have been extensively studied in order to give better descriptions of the materials for engineering purposes.

The fabrication of cermet tensile specimens and their design have been studied by Blackburn [1].[3] Duckworth investigated the effects of specimen size [2] and bending [3] on the tensile strength. The causes of second fractures of tensile specimens were discussed by Miklowitz [4]. Stiefel [5] made photoelastic studies of stress distribution for several designs of tensile specimens. The tensile test has been extensively used for ductile materials, but, although tensile data for brittle materials have much theoretical interest, the test has rarely been employed for refractory ceramic materials [6,7].

The stress distribution in the compressive test of brittle materials and the effect of specimen size were studied by Salmassy [8, 9, 10]. The optimum shape for the compressive specimen was investigated by Duckworth [3] and Nadai [11, p. 328].

The torsional test for brittle materials has been studied by Duckworth [3] and Salmassy [9]; and torsion tests of refractory oxides were made by Stavrolakis [12]. Stress corrections for plasticity were presented by Nadai [13, p. 128].

The elastic properties of brittle materials have been obtained from the popular transverse test both by the deflection method [14] and by the surface-strain method [3], which also gave Poisson's ratio. The mathematics for the transverse specimen, with its accompanying anticlastic curvature, were presented by Timoshenko [15], who also reported Seewald's stress correction for the effect of concentrated loads [16, p. 99]. Photoelastic studies for different span-to-depth ratios were given by Frocht [17]. The altered stress distributions for short beams have been investigated by Timoshenko [16, p. 66], Caswell [18], Seewald [16, p. 99], and for short cylinders by Milligan [19]. Nadai [13, p. 164] evaluated the corrections in strength required when plastic flow occurs in the transverse specimens. The statistical theory relating specimen size to strength was discussed by Weibull [20], Griffith [21], and Salmassy [9, 10]. Barriage [22] discussed this theory and gave data indicating causes of heterogeneity of specimens.

The Charpy impact test has been standardized for metals [23] and organic plastics [24]. The types and characteristics of impact tests have been discussed by Sayre [25], and Soxman [26] has studied the drop test for cermets. A highly specialized impact test employing a fly wheel was reported by Maxwell [27]. The reproducibility of the Charpy test results was investigated by Driscoll [28], and the reduction in impact value by notching was studied by Quackenbos [29] who, with others [30], correlated impact values with flexure tests. There has been considerable difference in opinion as to the correct method of test and the interpretation of results for the impact test.

The research work, described in this incomplete list of references, has served to improve the methods of test and the reliability of the results.

These references indicated that brittle materials were characterized by small elongations and small plastic deformations, but that they had widely ranging strengths and moduli of elasticity. The five

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[3] Figures in brackets indicate the literature references at the end of this paper.

examples of refractory brittle materials tested in this investigation were selected (1) to emphasize the problems of measuring extremely high strengths on the one hand and of very small strains on the other; and (2) to obtain homogeneous material in order to minimize the complication of material variation in the comparison of the tests. These considerations led to the choice of four cermets and an intermetallic as specimen materials.

In the work reported here, additional refinements in the test methods were made. Each test was evaluated from the viewpoints of compliance with the mathematical assumptions, instrumentation, suitability to the materials, and the variability of the results. A study of the correlation of the results from the tensile, compressive, torsional, transverse, and impact tests was also made to check the over-all performance of each test and to further explain the behavior of the cermets.

2. Materials

The compositions, methods of fabrication, densities, and porosities of the cermet specimens are given in table 1. Manufacturers of cermets supplied the finish-ground specimens.

For each cermet, the same composition was specified for specimens for each of the tests. The manufacturer of cermet IV, however, made improvements in the fabrication of his product during the time interval when specimens were purchased. Transverse specimens were obtained first, followed by tensile, impact, and torsional specimens.

High-strength materials were represented by cermets I and II. Cermet III was an example of a material having considerable plasticity. Materials having small elongations were represented by cermets IV and V. The mechanical properties of cermet V, which was classified also as an intermetallic, were similar to those of some ceramic bodies having large percentages of refractory oxides.

TABLE 1. *Compositions, methods of fabrication, densities, and porosities of cermet specimens*

Cermet designation	Composition: Material	Composition: Percent by weight	Method of fabrication	Density [a]	Porosity [a] range
		%		g/cm^3	%
I	Tungsten carbide Cobalt	94 6	Cold press, sinter.	14.90	Nil.
II	Tungsten carbide Cobalt	87 13	Cold press, sinter.	14.15	Nil.
III	Titanium carbide Nickel	70 30	Cold press, sinter.	5.87	Nil.
IV	Alumina Chromium	30 70	Slip cast, sinter.	5.88	0.1 to 9.0.[b]
V	Zirconium boride Boron	>90 <10	Hot press	5.03	0.06 to 11.0.[b]

[a] ASTM Method C20-46 was used except that specimens were pressure saturated with heptane.
[b] Range is for different specimens.

3. Tensile Test

3.1. Evaluation of Specimen Designs

a. Specimens and Linkages

Five specimens each of the five designs shown in figures 1 and 2 (A, B, C, D1, D2) were made of cermet III. This material was selected because it was relatively uniform, had moderate strength, and could be readily fabricated. The dimensions of the pin-end, T-end, and shouldered-end specimens were proportioned in accordance with the information

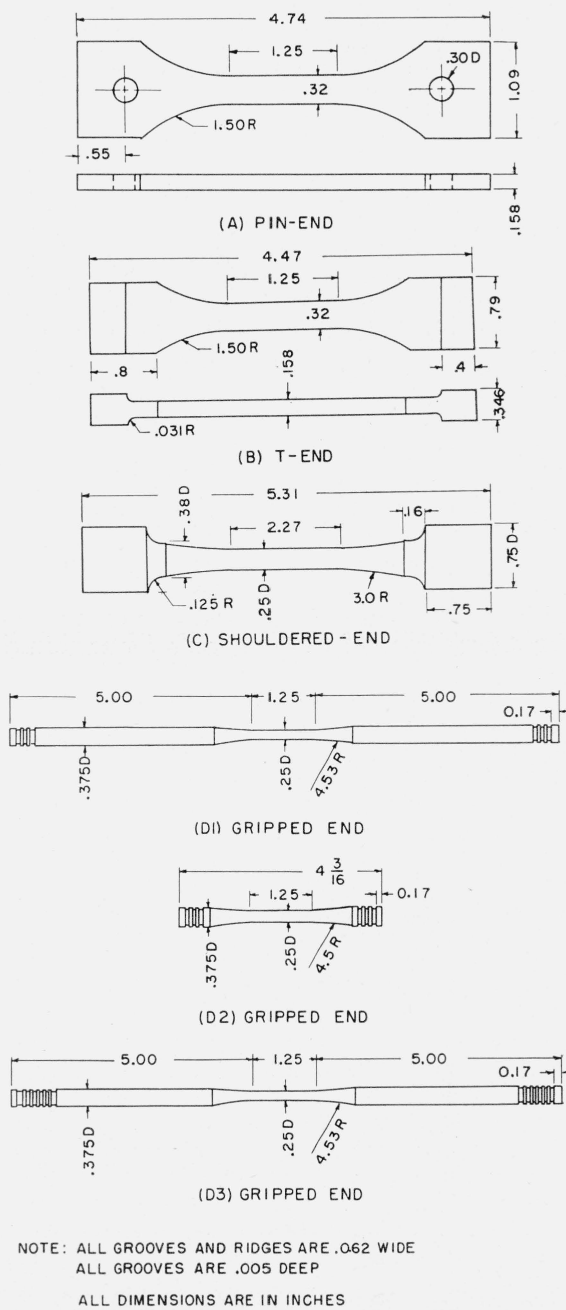

FIGURE 1. *Forms of tensile specimens.*

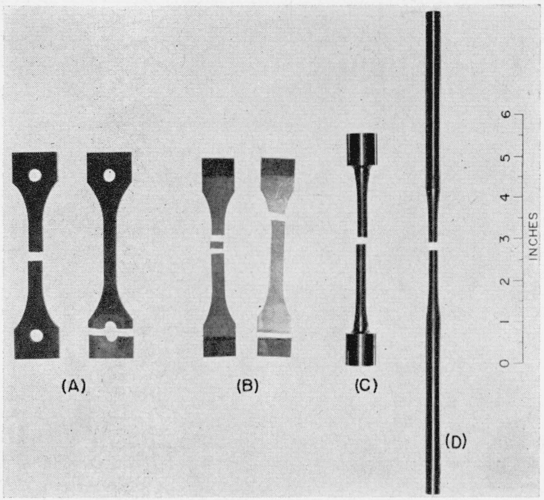

FIGURE 2. *Fractured tensile specimens made of cermet III.*

obtained from the photoelastic studies [5]. The basic design of the gripped-end specimens was developed at the Ohio State University [1]. All specimens had a reduced portion for making strain measurements. This portion was 1.25 in. long with a constant cross-sectional area of 0.05 sq. in.

The adaptors, or grips, for linking the corresponding specimens to the testing machine are shown in figure 3. Precautions were taken in machining to obtain axial loading.

The load was transmitted from the adaptors to the specimen by a pin for specimen A and by bearing surfaces for B and C, figures 1, 2, and 3. These designs gave specimen heads that were massive compared to the gage section.

The load was transmitted for specimens of types D1 and D2, figures 1, 2, and 3, from the grip to the specimen by means of a liner in shear. The grips were tightened sufficiently to force the mild steel liner material, 20 mils thick, into the grooves of the jaws and specimen. The grips were especially designed to obtain axial loading.

The long type of gripped-end specimen, D1 of figure 1, was originally designed to extend out of a furnace for high temperature tests and permit gripping at the colder end. A short type, D2, was machined from the end of each broken D1 form to give data indicating the value of this simpler specimen for room-temperature tests.

b. Apparatus and Procedure

A hydraulically operated universal testing machine was used for loading the specimens. All grips and adaptors were attached to the testing machine by means of conventional ball-and-socket joints, shown at the top of figure 3.

Figure 4 shows a long gripped-end specimen in position with Tuckerman gaged mounted. The specimen stress was increased in five equal steps, at a rate of 10,000 psi per miute, to a maximum of 10,000 psi, and then decreased in similar steps, to obtain the data for the modulus of elasticity. After determining the modulus of elasticity with the Tuckerman gages, the gages were removed, and SR-4 electric-resistance strain gages were applied to the specimens in positions noted in table 2. The loading procedure with the electric strain gages was the same as that used with the Tuckerman gages. The percent of bending was calculated as 100 times the difference between the maximum surface strain and the average strain divided by the average strain. The method of calculation reported

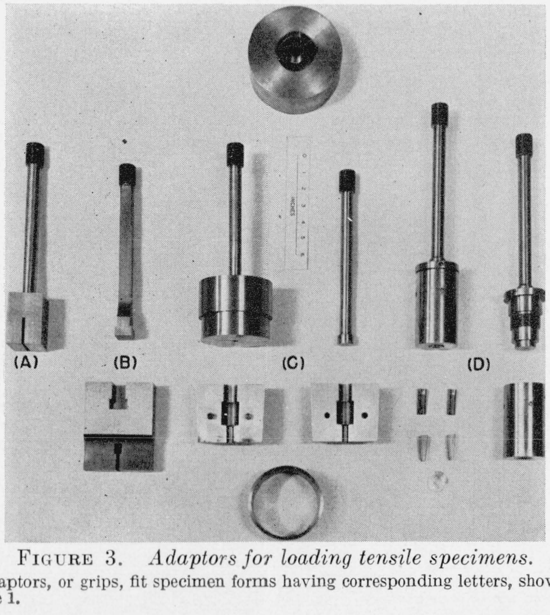

FIGURE 3. *Adaptors for loading tensile specimens.*

Adaptors, or grips, fit specimen forms having corresponding letters, shown in figure 1.

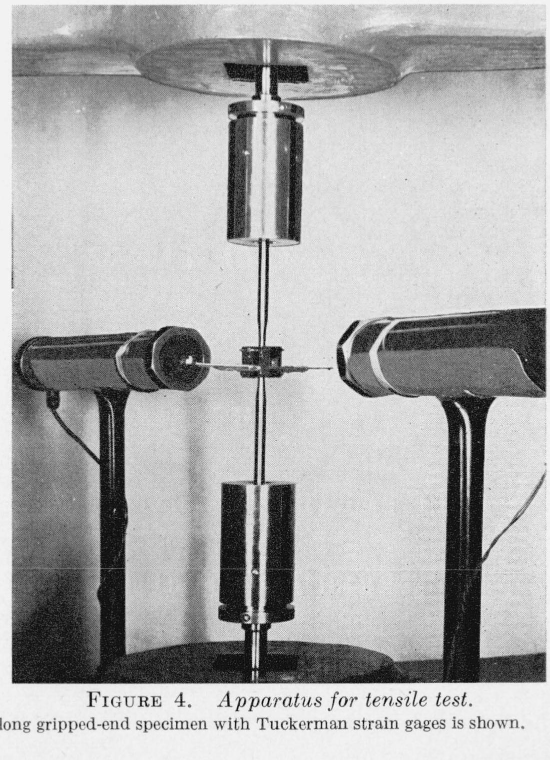

FIGURE 4. *Apparatus for tensile test.*

A long gripped-end specimen with Tuckerman strain gages is shown.

TABLE 2. *Average results for tensile tests on five specimens of each of five designs of specimens made from cermet III*

Specimen form	Modulus of elasticity— from Tuckerman gages—*E*	from electric gages: Assembly A — Gages	Assembly A — *E*	Assembly B — Gages	Assembly B — *E*	Poisson's ratio [a]	Tensile strength	Bending at rupture [b]	Extensibility — Measured	Extensibility — Calculated [c]	Fracture — Mode	Fracture — Number of specimens
	10^6*psi*		10^6*psi*		10^6*psi*		*psi*	*Percent*	*Percent*	*Percent*		
Pin-end	56.1 [d](0.8)	Two A-5 [e]	55.0 (1.2)	Four A-12 [f]	54.9 (2.0)	0.23 (6.6)	[g] 72,050 (14.4)	7.0 (37.5)	[g] 0.142 (14.3)	[g] 0.128 (14.0)	Single, in gage Across pin hole	2 3
T-end	55.2 (1.0)	Two A-5 [e]	54.8 (2.3)	Four A-12 [f]	55.4 (1.1)	0.22 (3.7)	[h] 131.000 (5.8)	3.2 (30.2)	[h] 0.278 (2.3)	[h] 0.235 (7.4)	Dougle, in gage Single, in gage At T fillet	2 1 2
Shouldered-end.	53.5 (0.6)	Three A-7 [i]	54.0 (0.1)	Three A-12 [j]	55.3 (2.5)	0.22 (nil)	112,940 (11.5)	2.3 (55.2)	0.241 (12.4)	0.204 (9.2)	Single, in gage Single through flaw in gage.	4 1
Long gripped-end.	54.8 (0.3)	Three A-7 [i]	57.4 (0.1)	Three A-12 [j]	55.1 (1.1)	0.22 (nil)	141,200 (8.0)	3.3 (65.3)	0.304 (11.6)	0.256 (4.5)	Single, in gage	5
Short gripped-end.	----------	Three A-7 [i]	54.5 (2.8)	Three A-12 [k]	54.0 (1.0)	0.22 (4.5)	[l] 127,700 (8.7)	5.2 (68.2)	[l] 0.251 (4.9)	[l] 0.236 (8.4)	Single, in gage Single, in enlarged end. Accidental	3 1 1

[a] Calculated from strains indicated by assembly A gages and an additional lateral A-7 gage.
[b] Average bending at rupture for five specimens calculated by the method given by Duckworth [3]; i. e., bending=100 (Max surface strain minus average strain)/average strain.
[c] Tensile strength ×100/modulus of elasticity=Percent calculated extensibility.
[d] Numbers in parentheses are coefficients of variation [32].
[e] Placed axially on the wide sides of three specimens.
[f] One gage placed axially on each side of five specimens.
[g] Average for two specimens fracturing in gage; stresses in gage section of remaining three were 82,000, 86,700, and 89,000 psi.
[h] Average for three specimens fracturing in gage; stresses in gage section of remaining two were 102,000 and 117,000 psi.
[i] Placed axially and spaced at 120° on two specimens.
[j] Placed axially and spaced at 120° on five specimens.
[k] Placed axially and spaced at 120° on three specimens.
[l] Average for three specimens fracturing in gage; stresses in gage sections of remaining two were 117,000 and 125,000 psi.

by Duckworth [3] was used to determine the maximum strain. Lateral strains from gages placed at right angles to the longitudinal axis of the specimen were obtained simultaneously with the axial strains for the determination of Poisson's ratio. The electric strain gage measurements were corrected for lateral strains [31].

Following the final determinations of the modulus of elasticity, the specimens were stressed, in steps of 10,000 psi with a rate of 10,000 psi per minute, to failure. Strain readings were taken at each stress increment to obtain the stress-strain curves to rupture.

The extensibility was the maximum tensile strain at fracture. The observed extensibility was the extrapolated strain at rupture from the stress-strain curve to rupture, reported in percent. It was also calculated as the ratio of tensile strength to modulus of elasticity and reported in percent.

Considering the possible errors to be additive, the rms error for the modulus of elasticity was 2.6 percent using the Tuckerman gage and 4.8 percent using the electric strain gages. The rms error in Poisson's ratio was 6.0 percent. These errors were probably less, for some compensation of errors could be expected. Bending introduced uncertainties in the strength determinations [3].

c. Results and Discussion

The results obtained for the five different specimen designs of cermet III are reported in table 2, and a typical stress-strain curve for a specimen having D1 form is shown in figure 5.

The modulus of elasticity values obtained by using the Tuckerman gages had lower coefficients of variation [32] than those obtained by electric strain gages. This difference can occur because: (1) a larger measurement error was possible with the electric strain gages, and (2) a different electric strain gage was used for each gage application whlie the same pair of Tuckerman gages was used throughout the tests.

The maximum percentage difference between the average moduli of elasticity for the five types of specimens made of cermet III was approximately the same as the experimental error. The average modulus of elasticity of the short gripped-end specimens was slightly less than for the long specimens from which they were cut. A lower value for the short

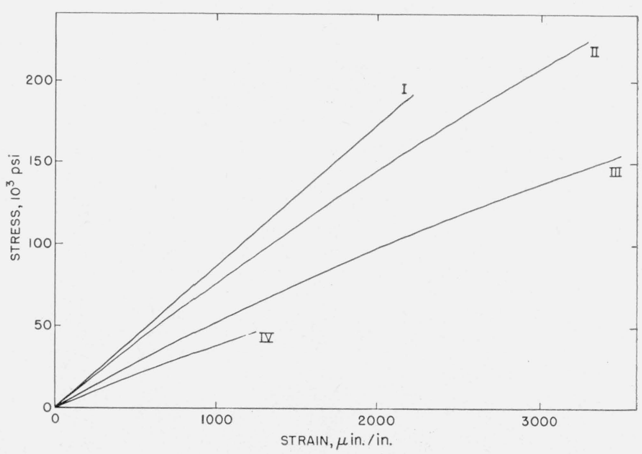

FIGURE 5. *Stress-strain curves for long gripped-end specimens of cermets tested in tension.*
The numbers refer to cermets given in table 1.

specimens was expected because they were prestressed beyond their elastic limit during the tensile tests on the long specimens, and they were subjected to shock when the latter specimens broke. All of the five designs were satisfactory, as expected from the photoelastic studies [5], for the determination of the modulus of elasticity of cermet III.

The Poisson's ratios for the different forms agreed rather well. It appears that electric strain gages are satisfactory for the determination of Poisson's ratio of a cermet in a tensile test.

The amount of bending varied during loading for many specimens, usually decreasing as the load increased. For comparative purposes, the bending at rupture was used. Bending was largest for the pin-end specimens and smallest for the shouldered-end specimens.

Table 2 gives the tensile strengths and the types of fracture for the five designs of specimens of cermet III. The types of fracture are illustrated in figure 2.

Three of the pin-end specimens broke across the pin hole. The two specimens that broke in the gage section had very low strengths when compared to those of other forms.

Two T-end specimens broke at the shoulder. The remaining three specimens broke in the gage section, two with double breaks [4]. The strengths of these three were comparatively high.

All of the shouldered-end specimens failed in the gage section. The average strength for these specimens was approximately 14 percent less than for the T-end form. The double length of the gage portion may have been expected to reduce the strength a small amount [2], but it is doubted that it was the only factor that lowered the strength so much. The modulus of elasticity was also slightly lower for this form, and it was possible that the heavy ends and comparatively slender gage portion contributed to overstressing during machining of this form with the accompanying generation of stress-raisers.

The long gripped-end specimens had the highest average strength of the five forms. All of the specimens fractured with a single break in the gage length.

The short gripped-end specimens had an average tensile strength 10 percent lower than the corresponding long specimens, from which they were cut. This difference may be due in part to the prestressing and shock in the tests on the original specimens. One specimen broke in the enlarged end and the remaining three broke in the gage length.

Both the experimental and the calculated extensibilities are reported in table 2. The ratios of these two values of extensibilities were substantially the same for the different forms because all specimens were made of the same cermet material. As the modulus of elasticity was essentially the same for all five, the extensibility values depended on the strength. The measured extensibility included the plastic strain and represented the behavior of the material more accurately, figure 5.

The pin-end and T-end forms were unsatisfactory for strength tests because breaks occurred outside the gage section. The pin-end specimen may be usable if the heads are made thicker in the direction of the holes. The T-end specimen needs a larger radius between the head and the gage section. This modification would necessitate a thicker head and would increase the fabrication difficulties. For both the shouldered-end and gripped-end designs, the fracture characteristics and the percent bending were reasonably satisfactory. Both designs require careful machining. The shouldered-end specimen requires that a large amount of material be removed to make the gage section. The long gripped-end specimen is slender but can be satisfactorily fabricated, if carefully done.

The long gripped-end design was chosen as the best design of the five for (1) it showed the highest strength, (2) the variation between specimens was relatively small, (3) the bending was reasonably low, and (4) the specimen can be used without further modification for tests at elevated temperatures. The short gripped-end specimen is probably satisfactory for use at room temperature and is relatively easy to fabricate.

3.2. Suitability of the Long Gripped-End Specimen for Different Cermets

a. Specimens, Apparatus, and Procedure

After the long gripped-end specimen design had been chosen as the best, five specimens each of this design of cermets I, II, and IV were obtained. As a precaution against slipping, the design was modified to include more grooves as shown in figure 1, D3. The apparatus and the procedure were the same as those described for testing the long gripped-end specimen, except that the strains were measured with electric strain gages only. All five specimens of cermet IV were improperly fabricated by the manufacturer, the enlarged ends being slightly out of line with the gage portion. The gripped portions of the enlarged ends were reground to aline with the gage portion before testing. The manufacturer of cermet V declined to furnish specimens.

b. Results and Discussion

The moduli of elasticity, strengths, extensibilities, Poisson's ratios, bending percentages, and types of fracture are given in table 3 for cermets I, II, III, and IV. Typical stress-strain diagrams for the cermets are shown in figure 5.

The plot of stress and strain for cermets II, III, and IV showed some curvature. The stress-strain diagram for cermet I was a straight line to rupture.

The cermets I, II, and III had comparatively low coefficients of variation for modulus of elasticity, but the coefficients for strength and extensibility were considerably higher. Nevertheless, these coefficients of variation for strength were considered to reflect material variability and were slightly lower than some reported values for a similar material [3]. The corresponding coefficients were considerably larger for cermet IV.

The specimens all ruptured in the gage length with

Table 3. *Average tensile properties of five long gripped-end specimens of each of cermets I, II, III, and IV*

Cermet	Modulus of elasticity [a]	Poisson's ratio [b]	Tensile strength	Bending at rupture [c]	Extensibility		Fracture	
					Measured	Calculated [d]	Mode	Number of specimens
	10^6 *psi*		*psi*	%	%	%		
I	89.9	0.21	176,000	3.4	0.201	0.196	Single, in gage	5
	[e] (0.9)	(2.3)	(6.0)	(70.8)	(6.0)	(6.0)		
II	78.6	0.23	[f] 204,000	0.6	[f] 0.292	[f] 0.259	Single, in gage	3
	(0.4)	(nil)	(5.0)	(38.6)	(6.1)	(4.9)	Single, in fillet	1
							Single, thru flaw in fillet	1
III	[g] 55.1	0.22	141,200	3.3	0.304	0.256	Single, in gage	5
	(1.1)	(nil)	(8.0)	(65.3)	(11.6)	(4.5)		
IV	43.1	0.22	38,100	6.9	0.100	0.089	Single, in gage	5
	(4.4)	(nil)	(13.6)	(40.1)	(16.2)	(15.9)		

[a] Average for electric strain gages from Assembly A consisting of three axial A–7 gages at 120° and one lateral A–7 gage on two specimens, and Assembly B consisting of three axial A–12 electric strain gages spaced at 120° on three specimens.
[b] Average for two specimens having gage Assembly A.
[c] Calculated by method given by Duckworth [3] for five specimens.
[d] Tensile strength x100/modulus of elasticity=percent calculated extensibility.
[e] Numbers in parentheses are coefficients of variation [32].
[f] Average for three specimens fracturing in gage; stresses in gage section of remaining two were 169,000 and 225,000 psi.
[g] Average for five specimens having Assembly A gages.

a single break except for two specimens that broke outside the reduced portion. One of these broke through a flaw in the fillet portion. No other flaws were noted.

The average percentage of bending was negligible for cermet II. The results for cermets I and III indicated reasonably low bending, but the bending of cermet IV was larger, due, in part, to the inaccurate shape of the specimens.

3.3. Evaluation of the Tensile Test

The essential requirements for a satisfactory tensile test on cermets are (1) a satisfactory specimen design, such as the long gripped-end of shouldered end specimen, (2) accurately shaped specimens and adaptors, (3) accurate alinement, checked by bending measurements of specimens, adaptors, and testing machine, and (4) sensitive strain gages such as electric-resistance or Tuckerman strain gages.

The tensile test gives reliable values of modulus of elasticity, Poisson's ratio, and tensile strength without complicated corrections.

4. Compressive Test

4.1. Specimens

The compression specimens, 0.424 in. square by 1.27 in. long, were machined from the enlarged ends of fractured flexure specimens (B1 form) to be described later. Five specimens each of cermets I, II, III, and IV, and three specimens of cermet V were prepared.

4.2. Apparatus and Procedure

In the preliminary tests, the bearings for the specimens were blocks of cermet I either in direct contact with the specimen ends or separated by thin metal pads. Parallelism of the blocks was to be obtained either by a hemispheric bearing attachment or by casting a thin plaster of Paris layer between the bearing block and the head of a hydraulic testing machine having a capacity of 300,000 lb.

In the final improved method of test, the bearing blocks, or anvils, consisted of an insert of cermet I in a tool steel holder which was shrink-fitted. The cermet and opposite faces were made parallel by finish grinding. The cermet face of the anvil was reground before each test because the surface was roughened in the preceding test by the end of the specimen at the high stresses required for its fracture. The anvils made direct contact with the crosshead and table, which were accurately parallel, of an "electromatic" testing machine having a capacity of 200,000 lb.

Electric-resistance strain gages were attached at the middle of each of the four sides of the specimen for strain measurements. For axial strains, used to calculate the modulus of elasticity, A–7 gages, (SR–4), were used. AX–7 rosette gages were placed on two opposite sides of each of three specimens of each cermet for both lateral and axial strains, which were used to calculate Poisson's ratio. All strains were corrected for lateral strain [31]. The percent bending was calculated, as in the tensile test, by Duckworth's method [3].

Specimens were stressed in increments of 11,300 psi for modulus-of-elasticity measurements. The specimens were then loaded to rupture in increments of 28,300 psi. Strain and stress were read at each increment.

The root-mean-square errors introduced by the measuring devices were: 15.1 percent for modulus of elasticity, 4.5 percent for Poisson's ratio, and 1.5 percent for compressive strength. The additional error in strength due to bending was indeterminate [3].

4.3. Results and Discussion

In the preliminary tests employing the hemispherical attachment, bending was erratic and sometimes so large that a side of the specimen was in tension. Satisfactory values of bending were sometimes obtained when a layer of plaster of Paris was used, but the lowest values were obtained with the cermet I tool steel bearings and the well alined testing machine. The use of thin pads between the specimen and the bearings did not reduce bending.

The modulus of elasticity, compressive strength, Poisson's ratio, and the percent bending are presented in table 4. For cermets I, II, and III, the modulus of elasticity and the compressive strengths had low coefficients of variation, and the bending was small. The larger variability and bending noted in cermets IV and V were attributed to the materials and not to the test, for they also had large coefficients of variation in the other tests. The values for Poisson's ratio were in good agreement for specimens of a particular composition. The percent bending for all cermets showed a large coefficient of variation whether the actual bending was large or small. Since all conditions of the test were reproduced as nearly as possible, the large variation in bending seems to be an inherent characteristic of the compression test.

TABLE 4. *Average results from compression tests for each of five cermets*

Cermet [a]	Modulus of elasticity	Bending [b]	Poisson's ratio	Compressive strength	Calculated strain at rupture [c]
	10^6 *psi*	%		*psi*	%
I	91.3 [d] (3.4)	6.8 (60.3)	0.22 (nil)	588,000 (2.4)	0.646 (5.7)
II	78.8 (0.9)	5.4 (51.9)	0.23 (4.4)	555,800 (1.8)	0.705 (2.4)
III	50.9 (1.4)	6.1 (28.9)	0.24 (2.0)	374,000 (3.1)	0.735 (2.2)
IV	41.4 (6.5)	22.1 (52.5)	0.23 (5.2)	118,500 (11.2)	0.289 (16.6)
V	44.5 (11.9)	14.1 (57.4)	0.17 (3.5)	181,300 (27.0)	0.400 (18.8)

[a] Five specimens of each of cermets I, II, III, and IV, and three specimens of cermet V were tested. The specimens were 0.424 in. square in cross section by 1.27 in. long.
[b] Calculated according to Duckworth [3].
[c] Calculated strain at rupture=compressive strength x100/modulus of elasticity.
[d] Numbers in parentheses are coefficients of variation in percent [32].

Figure 6 shows a typical stress-strain curve for a specimen of each of the five cermet materials. The curves for cermets I, II, and III had considerable curvature, and the strains increased rapidly as their compressive strengths were approached making accurate measurements impossible with the portable strain indicator. Cermet IV had an almost straight line to the largest stress shown on the graph. Beyond this point the strain increased so rapidly that it could not be measured accurately. Cermet V was the only material that exhibited a linear stress-strain curve to rupture.

In general the specimens ruptured violently and were reduced to many small fragments, and detection of any flaws on the fracture surfaces was impossible. Specimens of cermet IV did not shatter completely, but broke into small fragments at the ends and left the middle intact. One specimen

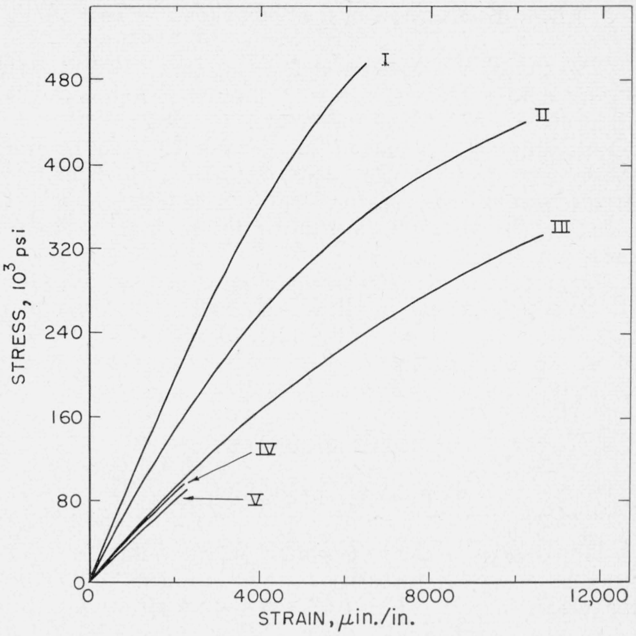

FIGURE 6. *Stress-strain curves of cermets tested in compression.* The numbers refer to cermets given in table 1.

formed a slip plane and did not shatter. This behavior was not surprising because cermet IV contained 70 percent metal.

Friction between the ends of the specimen and the anvils causes a distortion in the stress distribution, resulting in a stress concentration near the end of the specimen with a lowered average stress at fracture. Although this error has not been evaluated, its presence has led to the conclusion that the compression test is not reliable for brittle materials [8]. The results for cermets, table 4, indicate that the coefficients of variation are not appreciably greater than for the other mechanical tests, and that the error is consistent. Suggested means for reducing the error are, (1) lubricate the ends of the specimens, (2) make the ends of the specimen concave to match a cone-shaped anvil having the angle of friction, and (3) enlarge the end of the specimen, and fillet to the gage section [33].

The most common compression test specimens are right prisms or right cylinders, but other shapes are occasionally used [33]. The cylindrical shape is recommended often by the American Society for Testing Materials (ASTM) and also by Duckworth [3]. The shape factor seems to be minor, and the shape of the original stock often dictates the shape of the specimen.

The importance of uniform stress distribution and the effects of nonuniform distribution were discussed by Salmassy [8]. Stress distribution in this work was improved by (1) maintaining accurate alinement of specimen, bearings, and testing machine, and (2) the use of a testing machine having very little lateral movement of the crosshead relative to the table. Subpresses have also been employed to maintain alinement [34].

4.4. Evaluation of the Compressive Test

The major requirements for the compressive test on cermets are (1) accurately shaped specimens, (2) accurate alinement of specimens, bearings, and testing machine, (3) a testing machine with little lateral movement between the head and table, (4) bearings having sufficient hardness and strength, and (5) reducing bending to a minimum as indicated by multiple strain gages.

Prismatic or cylindrical specimens are suitable for the comparison of modulus of elasticity, Poisson's ratio, and compressive strength of cermets. Specimens having special shapes are required to obtain the true compressive strength.

5. Torsion Test

5.1. Specimens and Chucks

The design of the specimen was similar to that used in other laboratories for torsion tests of brittle materials [3, 12]. Figure 7 shows the specimen and gives its dimensions. The chucks consisted of a single piece and had 1.000-in. square sockets to fit the specimen as shown in figure 8.

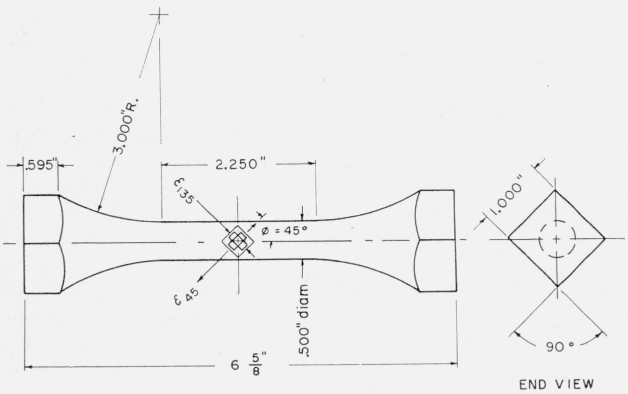

FIGURE 7. *Torsion specimen.*

The square indicates the position of a rosette strain gage, and the arrows indicate the directions of principal tensile and compressive strains.

5.2. Apparatus

A torsion machine having a capacity of 0 to 40,000 in.-lb, in four ranges, was designed especially for torsion testing of brittle materials, which are sensitive to bending. Bending of the specimen was reduced by making the main members of the frame of the testing machine symmetrical about the center line of the specimen, figure 8, as is done for conventional tensile-compressive testing machines. The conventional torsion-testing machine differs in that its frame is not symmetrical, and the applied torque may cause a bending moment to be applied to the specimen.

The angular deformation of the specimen was measured by means of the optical twist gages shown mounted on a specimen in figure 9. The optical systems for measuring twist using Tuckerman auto-

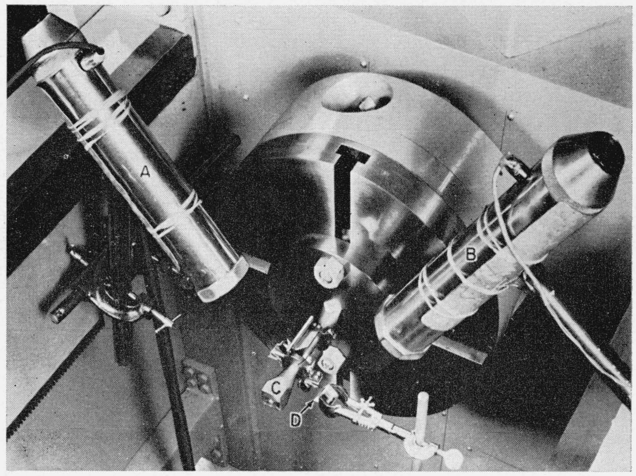

FIGURE 8. *Apparatus for torsional test.*

The torque head of the testing machine is withdrawn from the specimen C. Autocollimators A and B complete the optical system of the Tuckerman twist gage. D is a right angle prism to facilitate readings on B.

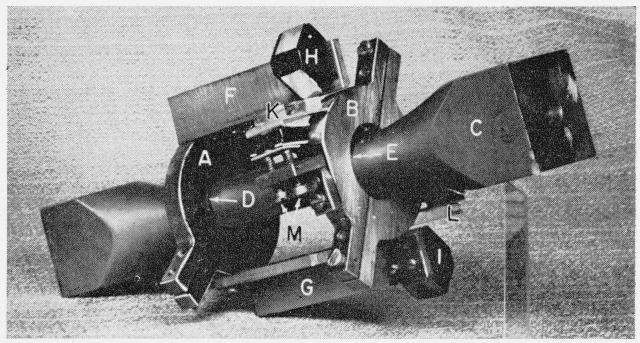

FIGURE 9. *Optical twist gage.*

Clamps A and B contact the gage marks, spaced 2 in., of the specimen C at knife edges, D and E, 1 mm wide. Twist from A is transmitted to Tuckerman prisms H and I by arms F and G. Twist from B is transmitted to first-surface mirrors K and L adjusted by screws M.

collimators [35], (A and B, figure 8) were established on opposite sides of the specimen when mirrors K and L were properly positioned before the roof prisms H and I. The gage was sensitive to 0.00001 radian.

AX–7 electric-resistance strain gages (SR–4) of the rosette type were used to measure surface strains, and were placed at 45° to the long axis at the middle, figure 7, and on opposite sides of the reduced section of the specimen.

All strain readings were corrected for lateral strain effects by the method described by Baumberger and Hines [31].

5.3. Procedure

The optical twist gages were mounted and the specimen placed in the torsion machine, as shown in figures 8 and 9. The torque was applied at a strain rate of 0.005 radian per minute in five increments of 80 in.-lb to a maximum torque of 400 in.-lb and reduced in five decrements to zero. Twist and torque were measured after each increment and decrement. The modulus of rigidity was calculated from these data using the following equation [15, p. 364]:

$$G=\frac{32ML}{\theta\pi d^4} \tag{1}$$

where

G=modulus of rigidity,
M=applied torque,
L=gage length (axial distance between knife edges),
Θ=total angular twist in radians for the gage length,
d=diameter of the reduced section.

The optical twist gages were removed after measurements with them were completed, and the electric strain gages placed in position. Data from these gages were used to calculate the modulus of rigidity by the following equations [15, p. 55] for the same loading procedure as that with the optical twist gages:

$$\gamma_{\max}=\epsilon_{45}-\epsilon_{135}=2\epsilon_{45}=-2\epsilon_{135} \tag{2}$$

and

$$G=\frac{\tau_{\max}}{\gamma_{\max}}=\frac{\tau_{\max}}{(\epsilon_{45}-\epsilon_{135})} \tag{3}$$

where

ϵ_{45}=principal tensile strain,
$-\epsilon_{135}$=principal compressive strain,
G=modulus of rigidity,
$\tau_{\max}$=shear stress,
$\gamma_{\max}$=shear strain.

After the measurements for the determination of the modulus of rigidity were completed, torque was applied, at the strain rate of 0.005 radian per minute, in increments of 80 in.-lb, to failure. Torque and strain measurements were taken at each succeeding load increment until fracture occurred.

The shear stress at fracture, $\tau_{\max}$, was calculated from either [15, p. 264]:

$$\tau_{\max}=\frac{16M_{\max}}{\pi d^3} \tag{4}$$

or, for materials having nonlinear torque-twist relations to rupture, from Nadai's equation [13, p. 128]

$$\tau_{\max}=\frac{1}{2\pi r^3}\left(\Theta\frac{dM}{d\Theta}+3M_{\max}\right), \tag{5}$$

where $M_{\max}$=torque at fracture.

All fracture surfaces were examined for flaws using a binocular microscope.

Some errors were introduced in the measurement of load and strain by the limited sensitivity and accuracy of the measuring devices. The measurement of the applied torque could have introduced an error of 0.5 percent in the modulus of rigidity and of 2 percent in the torsional strength. The optical twist gages could have introduced an error of 0.5 percent in the modulus of rigidity due to the measurement of the span and an error of 0.2 percent due to the gage itself.

Bonded electric-resistance strain gages are subject to a thickness error when they are used for strain measurements in a torsion test. The gage wire used to measure strain at the outer surface of the specimen is actually removed from the outer surface by a distance equal to the thickness of the paper on which the wire is mounted, the cement layer, and half the thickness of the wire. The average distance from midwire to specimen surface was determined by measuring the thickness of several gages before and after mounting on a specimen, and this distance was used in a correction for the strain readings. The variation in this distance was sometimes appreciable and the resulting error in strain may have been as large as one percent of the observed value.

Each electric gage was placed as accurately as possible, and deviation from the proper alinement was undoubtedly small. The gage factor tolerance was 2 percent or less. The strain indicator could possibly introduce an error of 4 percent in the modulus-of-rigidity measurements. The calculated rms error for the torsional strength was 2 percent; for the modulus of rigidity determined by the modified Tuckerman strain gage, it was 0.74 percent; and for the modulus of rigidity determined by the bonded electric-resistance strain gages, it was 4.6 percent.

5.4. Results and Discussion

The modulus of rigidity, determined by both the optical twist gages and the electric strain gages, and the strength in torsion are given in table 5.

The coefficient of variation for the modulus of rigidity determined by the optical twist gages was low for all materials except cermet V. For all materials, the coefficient of variation for the modulus of rigidity was higher when determined from electric-strain-gage data than when determined from optical-twist-gage data.

TABLE 5. *Average results from torsional tests of each of five cermets*

Cermet [a]	Modulus of rigidity—		Torsional strength		Shear strain at rupture	
	From optical twist gages	From electric strain gages	Calculated by equation (4)	Calculated by equation (5)	Calculated [b]	Measured
	10^6 *psi*	10^6 *psi*	*psi*	*psi*	*Percent*	*Percent*
I	38.0 [c] (1.0)	36.0 (2.9)	156,800 (5.0)	156,800 (5.0)	0.436 (5.8)	0.435 (5.1)
II	32.7 (1.3)	33.0 (7.4)	195,100 (6.9)	180,200 (7.5)	0.547 (7.6)	0.724 (7.4)
III	22.9 (1.8)	22.8 (8.6)	[d] 116,600 (15.0)	[d] 109,400 (14.7)	[d] 0.500 (19.1)	[d] 0.668 (23.2)
IV	17.0 (1.6)	18.5 (7.2)	[e] 43,500 (3.8)	[e] 43,500 (3.8)	[e] 0.243 (5.2)	[e] 0.244 (6.5)
V	24.5 (10.7)	25.4 (11.0)	23,700 (9.3)	23,700 (9.3)	0.095 (15.4)	0.093 (16.8)

[a] Five specimens were tested for each cermet except cermet V for which there were four specimens.
[b] Torsional strength ×100/modulus of rigidity=calculated shear strain at rupture.
[c] Numbers in parentheses are coefficients of variation in percent [32].
[d] Defects noted on fracture surface of one specimen which broke at 95,600 psi, not included in the average, by eq (5).
[e] Defects noted on fracture surface of one specimen which broke at 36,600 psi, not included in the average, by eq (5).

For some specimens the modulus of rigidity determined by the electric strain gages did not agree well with the modulus of rigidity determined by the optical twist gages. Although less precise, the electric strain gages had advantages in that it was possible to measure strain to rupture and to detect bending from differences in measured strain. No appreciable differences indicating bending were observed in the strain readings among the four individual electric strain gages, and the specimens were considered to be in a state of simple torsion. The average electric-strain-gage readings were used in the calculations.

The coefficients of variation for strength were rather large, but this variation is common for brittle materials. The torsional strength calculated by the method of Nadai [13, p. 128] eq (5), was less for cermets II and III than that calculated by the elementary eq (4). The necessity of correcting for plastic deformation required the measurement of shear strain to rupture.

Two specimens, one each of cermets III and IV, had pinholes slightly below the surface of the specimen. These specimens had lower-than-average values of torsional strength. All specimens, including those that showed plastic flow, when ruptured exhibited the typical helical fracture of brittle materials caused by tensile stresses [15, p. 55].

Typical stress-strain curves in shear for each of the five cermets are shown in figure 10. The shear strains at rupture, both calculated by dividing the torsional strength by the modulus of rigidity, and measured, are given in table 5. The measured shear strains at rupture were obtained directly from the shear stress-strain curves to rupture and included the additional deformation due to plasticity. For the materials that did not exhibit any plasticity, the experimental shear strains at rupture were the same as the calculated shear strains. For the two "plastic" materials, cermets II and III, the experimental shear strains at rupture were about 24 percent greater than the calculated values.

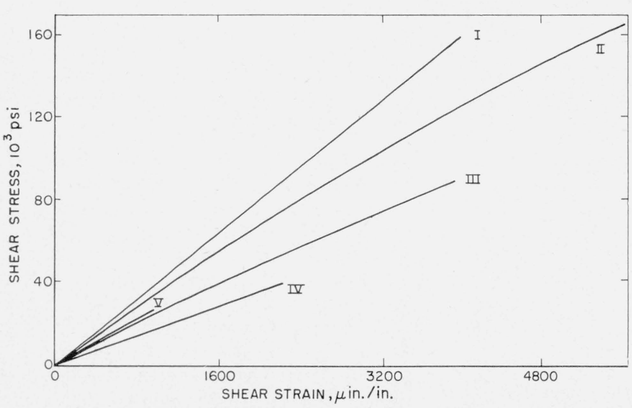

FIGURE 10. *Shear stress-strain curves of cermets tested in torsion.*

The numbers refer to cermets given in table 1.

5.5. Evaluation of the Torsional Test

The essential requirements for the torsional test are (1) specimens designed with adequate fillets and having accurate shaping, (2) accurate alinement of the specimen with a symmetric testing machine to avoid bending, (3) the use of strain gages to measure the principal tensile and compressive surface strains for the calculation of bending, modulus of rigidity, and plasticity, and (4) the correction of strength for errors due to plasticity.

The torsional test gives reliable values of modulus of rigidity and torsional strength of cermets. The torsional strength is related to the tensile strength as discussed in a later section.

6. Transverse Test

6.1. Specimens

Figure 11 shows the shapes, dimensions, and

Form	Dimension									
	D	T	B	R	L	S	O	X	F	E
A-1	0.150	0.212	0.450	0.300	1.100	1.366	3.833	0.450	0.667	0.250
A-2	.150	.212	.450	.300	2.100	1.700	5.500	.450	1.000	.250
A-3	.150	.212	.450	.300	3.100	2.033	7.167	.450	1.333	.250
B-1	.300	.424	.900	.600	1.100	2.117	5.334	.900	0.967	.250
C-1	.424	.600	1.272	.848	1.100	2.737	6.575	1.272	1.215	.250

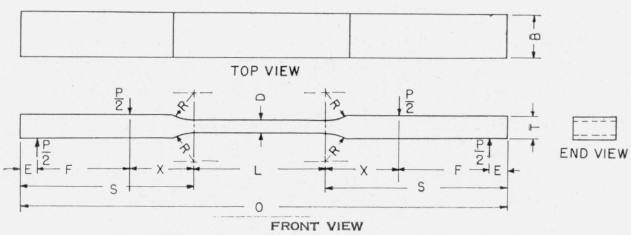

FIGURE 11. *Dimensions and loading points for enlarged end transverse specimens having fifth-point loading.*

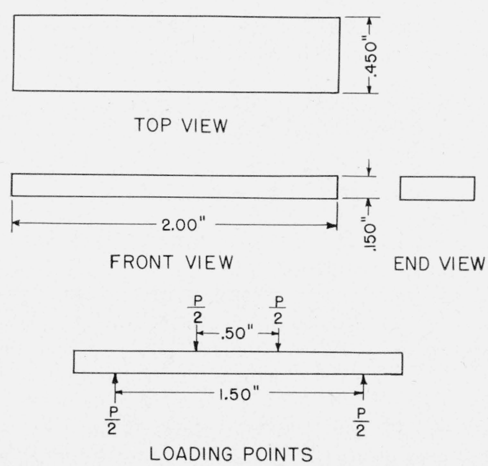

FIGURE 12. *Dimensions and loading points for form-D specimens.*

loading points for five sizes of enlarged-end specimens for the transverse tests. Dimensions of fillets, location of the loading points, and thickness of the enlarged ends were calculated from information given by Duckworth [36] and from data determined in this laboratory.

The shape and dimensions of the prismatic, form-D specimens are given in figure 12. The cross section of these specimens was similar to that used at other laboratories [37], and was the same as the cross section of the A forms.

Five specimens of each cermet in each of the six forms were obtained, with the exception of those for cermet V. The manufacturer of this cermet was unable to furnish the A3 and C1 forms, and only three specimens of each of the remaining forms were obtained.

6.2. Apparatus

Figure 13 shows the loading apparatus used in testing the specimens having enlarged ends. The cylindrical rollers that serve as knife edges are positioned by spring-held side plates. This arrangement allows for movement of the roller in the direction of the longitudinal axis of the specimen, relieving either compressive or tensile stresses due to changes in the length of span during loading.

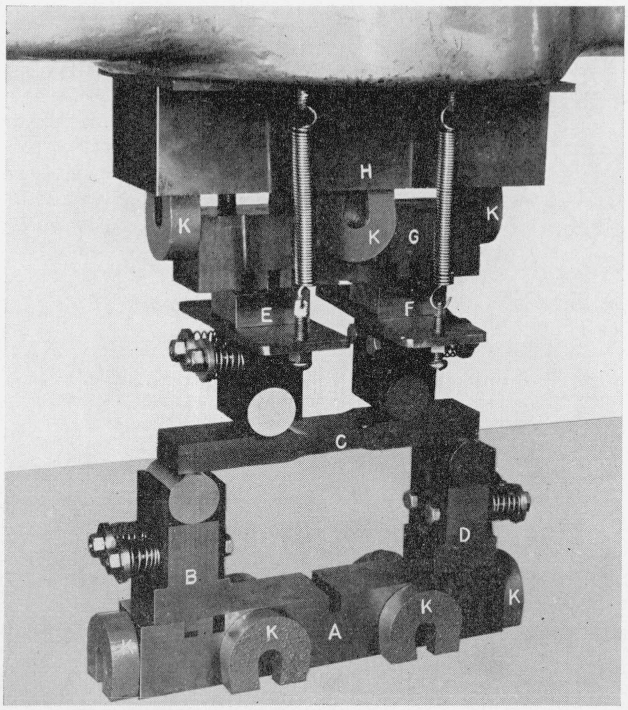

FIGURE 13. *Loading apparatus for enlarged-end specimens.*

Block A spaces the supports B and D, and beam G spaces the loaders E and F. Twist in the specimen C is compensated by rocker bases of D, E, and F, whose center of curvature is at the centerline of the specimen. The load applied by the crosshead is transmitted through H and divided equally by beam G, having a semicylindrical bearing (not visible) at its midpoint. Magnets K position the parts to the testing machine.

Because of the different sizes of specimen forms that were tested on this apparatus, it was necessarily complex. A smaller version of this apparatus was used in testing the form-D specimens.

A deflectometer similar in design to that described by Mong and Pendergast [38, p. 301] was used. When attached to the specimen, it made contact at the midpoint and at one end of the span on the centerline. At the other end of the span, there were two movable contacts located laterally from the centerline to give one of three lateral spans. The sensitivity of the deflectometer was 2 μ in.

Bonded wire-resistance electric strain gages (SR–4) were used to measure surface strains. The gage lengths were selected according to the application and ranged from ¼ to 1 in.

6.3. Procedure

Specimens were loaded and unloaded in five or more increments to obtain a maximum stress of approximately 20 percent of the strength. The rate of stressing between increments was approximately 60,000 psi per minute. At each increment, deflection and load were recorded, and the modulus of elasticity was calculated by the elementary beam formula [38, eq (7)]. The movable pair of contact points of the deflectometer were set to give the smallest lateral span.

The procedure was repeated for each of the other two settings of the lateral span on the deflectometer for eight specimens. The differences in the resulting moduli of elasticity were compared to the calculated differences [38, eq (8)] for each specimen.

After the deflection measurements were completed, wire-resistance strain gages were attached to the specimens on the tensile and compressive surfaces to determine axial and lateral strains, except for form D which had space for only one axial gage on the tensile side. The modulus of elasticity was calculated from longitudinal-strain measurements [38, eq (1) and (2)] obtained with the same loading procedure employed in the tests using the deflectometer. The strain-gage readings were corrected for lateral strain and thickness error as in the torsional test.

When the tests for modulus of elasticity were completed, the specimens were loaded in increments similar to those for modulus of elasticity, to obtain stress-strain curves to rupture and the transverse strength. The strength was calculated by the elementary beam formula, [38, eq. (1)] for cermets having linear stress-strain curves, but for those cermets having plasticity, indicated by nonlinear curves, Nadai's formula [13, p. 164] was used. Seewald's method, [16, p. 99], was used to calculate the strength of the form-D specimens for which concentrated load was a factor.

The rms error for the modulus of elasticity for the deflectometer was 3.3 percent and 5.5 percent for the wire-resistance gages. The error due to the apparatus in the determination of strength was 3.5 percent.

6.4. Results and Discussion

Table 6 gives the differences between moduli of elasticity of specimens of four cermets determined with three different lateral spans on the deflectometer. The calculated values, [38, eq. (8)] of anticlastic curvature were larger than the observed. The disagreement indicated that the anticlastic curvature at the end of the span was less than would be expected. This stiffening by the enlarged ends and loader reaction was also indicated by wire-resistance strain gages placed laterally at the middle and at the ends of the axial span. Anticlastic curvature agreed with the calculated values only at the middle of the A2 and A3 forms as indicated by values of Poisson's ratio, reported subsequently.

Typical stress-strain curves for one specimen of each of the five brands of cermets are shown in figure 14.

The moduli of elasticity of the cermet specimens from both the wire-resistance strain gages and the deflectometer are presented in table 7. The differences between the moduli of elasticity determined by the deflectometer and surface-strain methods were usually insignificant. The coefficients of variation for the moduli of elasticity obtained from surface-strain and deflection measurements were practically the same for all lots of specimens.

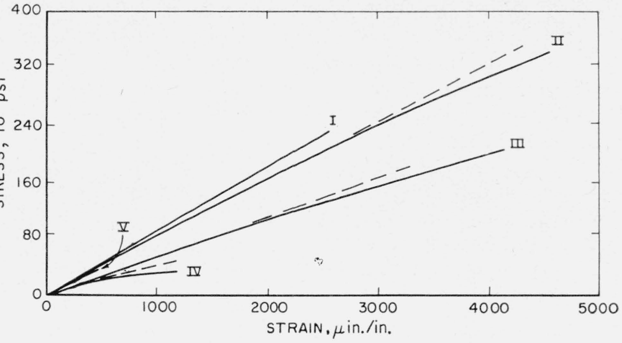

FIGURE 14. *Typical stress-strain curves for one specimen having form A1 of each of five cermets.*

TABLE 6. *Differences in modulus of elasticity resulting from anticlastic curvature and different lateral spans of the deflectometer for specimens having form C1*

Cermet [a]	Differences				
	Small span	Medium span		Large span	
	Increase from zero span, calculated [b]	Increase from small span		Increase from small span	
		Calculated [b]	Observed	Calculated [b]	Observed
	%	%	%	%	%
I	1.1	6.2	5.0	14.4	10.3
II	1.1	6.2	3.9	14.4	12.7
III	1.1	6.2	3.9	14.4	10.9
IV	1.0	5.7	3.3	13.1	12.5

[a] Results are averages for two form C1 specimens of each cermet.
[b] These values were calculated according to [38].

An analysis of the surface-strain data indicated that 48 percent of all specimens had a higher strain on the tensile side of the specimen, 48 percent had a higher strain on the compressive side, and 4 percent had the same strain on both sides. The differences were generally within the error of the gages. The equality of tensile and compressive moduli of elasticity, for transverse specimens in tests where axial restraint of the knife edges was canceled, has been discussed by Duckworth [3]. The strains on the tensile and compressive sides frequently diverged after the elastic limit was exceeded.

Average moduli of rupture for the six forms of the cermets are given in table 8. The value of this tensile stress of the outer fibres, which grades to zero at the neutral axis, was less by 4 to 22 percent when calculated by the method of Nadai for cermets II,

TABLE 7. *Average moduli of elasticity from transverse tests for five cermets calculated from surface-strain and deflection measurements*

Specimen form	Cermet I [a]			Cermet II [a]			Cermet III [a]			Cermet IV [a]			Cermet V [b]		
	Surface strain		Deflection [c]	Surface strain		Deflection [c]	Surface strain		Deflection [c]	Surface strain		Deflection [c]	Surface strain		Deflection [c]
	T [d]	C [e]		T [d]	C [e]		T [d]	C [e]		T [d]	C [e]		T [d]	C [e]	
	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*
A1	92.3 [f](0.7)	91.1 (1.6)	95.9 (3.9)	79.9 (1.9)	77.9 (1.5)	83.4 (1.7)	52.1 (1.6)	52.5 (2.6)	51.6 (2.9)	34.1 (19.6)	34.8 (20.7)	37.1 (17.2)	60.4 (2.4)	60.4 (2.8)	64.6 (3.7)
A2	93.1 (0.8)	93.5 (1.0)	91.2 (0.9)	83.3 (0.8)	83.0 (1.0)	81.0 (0.9)	55.8 (0.8)	55.8 (1.1)	54.4 (0.6)	[g]42.8	[g]42.2	43.6 (3.1)	63.2 (1.6)	63.2 (2.8)	64.1 (0.7)
A3	91.1 (0.5)	91.1 (1.2)	91.2 (1.2)	81.6 (1.7)	81.1 (1.9)	80.0 (1.1)	55.6 (1.5)	55.0 (1.8)	54.4 (1.4)	41.0 (11.4)	40.7 (12.4)	41.6 (12.7)	-------	-------	-------
B1	94.1 (0.8)	93.7 (0.6)	94.7 (1.4)	81.7 (0.4)	81.6 (0.4)	82.1 (1.1)	55.7 (2.1)	55.2 (1.8)	55.4 (3.3)	42.0 (10.9)	42.6 (9.5)	42.7 (12.3)	51.8 (6.1)	52.6 (5.4)	53.7 (6.8)
C1	92.2 (1.4)	92.7 (1.4)	94.4 (2.3)	80.7 (0.4)	80.4 (0.4)	81.1 (2.2)	53.7 (1.4)	53.8 (1.5)	53.9 (3.6)	42.1 (1.0)	42.3 (1.2)	44.4 (2.9)	-------	-------	-------
D	90.1 (0.9)	-------	90.3 (0.9)	78.8 (1.0)	-------	79.5 (0.8)	55.0 (0.6)	-------	54.9 (1.0)	41.7 (3.5)	--------	41.5 (3.3)	49.3 (5.3)	-------	50.8 (2.6)

[a] Except where noted five specimens were tested.
[b] Average for three specimens except for form A3 and C1 which were not furnished.
[c] Calculated from deflection measurements [38].
[d] Calculated from strain measurements on the tensile side of the specimen [38].
[e] Calculated from strain measurements on the compressive side of the specimen [38].
[f] Numbers in parentheses are coefficients of variation in percent.
[g] Average for two specimens.

TABLE 8. *Average moduli of rupture for five cermets*

Specimen form	Cermet I [a]	Cermet II [a]			Cermet III [a]			Cermet IV [a]				Cermet V [b]
	A [c]	A [c]	B [d]	$\frac{A-B}{A}$	A [c]	B [d]	$\frac{A-B}{A}$	A [c]	B [e] Tensile	B [e] Compression	$\frac{A-B}{A}$ [f]	A [c]
	psi	*psi*	*psi*	%	*psi*	*psi*	%	*psi*	*psi*	*psi*	%	*psi*
A1	198,000 [g](11.3)	304,000 (8.9)	293,000 (8.4)	3.8	162,000 (12.3)	154,000 (12.3)	5.1	32,500 (12.6)	26,100 (24.5)	32,200 (17.7)	20.5	27,800 (7.6)
A2	208,000 (9.0)	282,000 (6.5)	271,000 (6.6)	4.1	131,000 (36.0)	122,000 (33.1)	4.8	[h] 43,100	[h] 35,900	[h] 46,100	[h] 16.4	31,800 (11.3)
A3	183,000 (11.5)	286,000 (4.6)	275,000 (4.3)	3.8	179,000 (3.9)	171,000 (5.1)	4.5	39,700 (11.8)	38,100 (11.0)	40,500 (10.1)	8.1	--------
B1	208,000 (5.5)	226,000 (6.2)	217,000 (6.5)	3.9	156,000 (12.7)	149,000 (13.3)	4.7	32,300 (5.3)	30,000 (17.0)	33,100 (2.7)	7.8	24,900 (12.9)
C1	183,000 (10.5)	230,000 (10.8)	218,000 (10.0)	5.0	145,000 (11.8)	137,000 (12.0)	5.2	35,600 (11.0)	27,200 (10.3)	37,300 (22.0)	22.3	--------
D	[i] 223,000 (5.9)	[i] 318,000 (3.5)	[j] 297,000 (2.7)	6.5	[i] 173,000 (5.3)	[j] 162,000 (7.4)	6.5	[i] 40,800 (12.0)	[j] 39,100 (11.8)	--------	4.2	[i] 32,500 (5.5)

[a] Except where noted, five specimens were tested.
[b] Average for three specimens except for forms A3 and C1 which were not furnished.
[c] Calculated by the elementary beam theory [38].
[d] Calculated by the method of Nadai for specimens having equal tensile and compressive strains [13, p. 164].
[e] Calculated by the method of Nadai for specimens having unequal tensile and compressive strains [13, p. 164].
[f] Based on the tensile value.
[g] Numbers in parentheses are coefficients of variation in percent.
[h] Average for two specimens.
[i] Calculated by the method of Seewald for concentrated loads [16, p. 99].
[j] Calculated using the method of Seewald and the method of Nadai based on strains for tensile surface only.

III, and IV which had plastic flow. This correction was not required for cermets I and V which had little plastic flow, as shown by figure 14.

The correction for concentrated loads was approximately 1.0 percent for the form-D specimens. Although this correction is small, it may be considerable for other specimen designs [38, p. 301]. The enlarged-end specimens were designed to eliminate this correction.

The deviations from a suggested curve [22] representing the dependence of strength on the size of specimen were quite large. Significant differences of the average values of different forms due to differences in size were found for cermets II and IV only. The smallest specimens of each cermet, however, had a higher strength than that of the largest specimens. The rate of change of strength with size is presumed different for different materials [22], and may not be evident unless there is a many fold change in size.

The coefficients of variation for modulus of rupture were quite variable with values comparable to those obtained in the three preceding tests. The coefficients for strength were considerably larger than for modulus of elasticity and had no correlation with specimen size [22].

The specimens broke with irregular fractures, similar to those for the tensile specimens, in the tensile half. For cermets IV and V, this fracture continued at right angles to the span direction in the compressive half, but for cermets I, II, and III the fractured surface curved in the compressive half to an angle of about 45° to the span direction at the compressive surface. Single fractures were common for specimens of cermets IV and V and for all form-D specimens. Multiple breaks, as many as five, were prevalent for enlarged-end specimens of cermets I, II, and III. The phenomena of multiple breaks has been studied by Miklowitz [4, b].

The average calculated and measured extensibilities of the cermets are given in table 9. The extensibilities paralleled strength in that they were characteristic to each cermet, had similar coefficients of variation, and had a similar dependence on specimen size.

6.5. Evaluation of the Transverse Test

The essential requirements for a satisfactory transverse test for cermets are (1) accurately shaped specimens having large length-to-depth and length-to-width ratios, (2) measurement of strains by deflection or preferably by surface-strain gages, (3) the relief of axial stresses due to change in span length during loading by means of roller knife-edges, (4) the correction of strength for effects of plasticity and concentrated loads when required, (5) the restriction of the test to small deflections where the mathematical assumptions are not exceeded.

The transverse test gives satisfactory values of modulus of elasticity and estimates of Poisson's ratio for cermets. Tensile strength and extensibility may be obtained provided creep is small and necessary corrections for the effects of plasticity and concentrated loads are made. Special shapes of specimens are not appreciably superior to the simple prismatic specimen having sufficient size to accommodate strain gages.

7. Impact Test

7.1. Specimens

The specimens were made in accordance with ASTM Designation (E23–47T) [23]. They were rectangular parallelepipeds 10 mm square by 55 mm long. Five notched and five unnotched specimens

TABLE 9. *Comparison of the average calculated and measured extensibilities from transverse tests on five cermets*

Specimen form	Cermet I [a]			Cermet II [a]			Cermet III [a]			Cermet IV [a]			Cermet V [b]		
	Calculated [c]	Measured [d]	Difference	Calculated [c]	Measured [d]	Difference	Calculated [c]	Measured [d]	Difference	Calculated [c]	Measured [d]	Difference	Calculated [c]	Measured [d]	Difference
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
A1	0.217	0.218 [e](9.6)	0.5	0.386	0.424 (10.5)	8.9	0.310	0.353 (12.4)	12.2	0.095	0.136 (27.9)	30.1	0.046	0.047 (5.6)	2 1
A2	0.223	0.227 (10.0)	1.8	0.339	0.377 (7.1)	10.1	0.235	0.303 (33.6)	22.4	0.102	[f] 0.121	15.7	0.051	0.053 (4.0)	3.8
A3	0.201	0.228 (9.4)	11.8	0.351	0.388 (6.2)	9.5	0.324	0.388 (3.7)	16.5	0.095	0.115 (16.8)	17.4	-----	------	----
B1	0.221	0.226 (5.2)	2.2	0.277	0.305 (6.7)	9.2	0.282	0.327 (20.4)	13.7	0.077	0.087 (18.5)	11.5	0.048	0.048 (12.2)	0.0
C1	0.194	0.202 (11.2)	4.0	0.286	0.310 (11.9)	7.7	0.270	0.310 (11.9)	12.9	0.085	0.104 (24.1)	18.3	-----	------	----
D	0.248	0.260 (6.1)	4.6	0.404	0.481 (4.5)	16.0	0.315	0.390 (6.1)	19.2	0.098	0.109 (32.5)	10.1	0.065	0.068 (28.9)	4.4

[a] Except where noted, five specimens were tested.
[b] Average for three specimens except for A3 and C1 forms which were not furnished.
[c] Extensibility $=100\sigma/E$ in percent, where σ is the average modulus of rupture by the elementary beam formula and E is the average modulus of elasticity from surface strain.
[d] From stress-strain curves similar to those shown on figure 14.
[e] Numbers in parentheses are coefficients of variations in percent.
[f] Average for two specimens.

were obtained for each cermet. The notch had a depth of 2 mm, an angle of 45°, and a fillet radius of 0.25 mm.

7.2. Apparatus and Procedure

A Baldwin-Bell Telephone Laboratory pendulum impact machine was used. It was fitted for Charpy tests and had a capacity of 0 to 2 ft-lb, extended to 16 ft-lb by using heavier hammers. The velocity at impact was 11 fps. The impact tester was designed according to specifications outlined in ASTM Method D256–47T (for plastic materials) [24]. The anvils and striking edge were modified to fit the smaller specimens tested in this work, and these modifications met the conditions set forth in ASTM E23–47T (for metallic materials) [23]. The apparatus was mounted on a firm base.

The standard procedure recommended by ASTM (E23–47T) [23] was used. The friction and windage correction was determined and applied.

By reading the scale to the nearest half division (0.005 ft-lb) a maximum error of 4.2 percent occurred for the notched specimens made from cermet V. Specimen dimensions were within the prescribed tolerances, and errors due to difference in size were considered to be negligible.

7.3. Results and Discussion

The impact values are given in table 10. The results of tests on the unnotched specimens indicated a wide range of impact values for the five cermets.

The notched specimens ranked the cermets in the same order as the unnotched specimens, but the values obtained were much lower. The impact values of the cermets I, II, and III were reduced about 90 percent while the impact values of cermet IV and cermet V were reduced about 72 percent. These results point out the notch sensitivity of cermets. Quackenbos [29] noted a similar reduction of the impact values of some organic plastics.

The coefficient of variation for impact value of the unnotched specimens of each of the cermets was over 10 percent, and was generally larger than that for strength from the tensile, compressive, torsional, and transverse tests.

TABLE 10. *Impact values for cermet specimens*

Cermet	Unnotched [a]		Notched [b]	
	Hammer weight [c]	Impact value	Hammer weight [c]	Impact value
	lb	*ft-lb*	*lb*	*ft-lb*
I	8	6.30 [d] (13.9)	2	0.59 (25.4)
II	16	9.23 (20.34)	2	0.95 (9.5)
III	8	4.33 (10.16)	1	0.48 (2.1)
IV	2	0.57 (14.0)	1	0.16 (nil)
V	1	0.44 (11.4)	1	0.12 (nil)

[a] Five specimens 10mm×10mm×55mm (ASTM E23-47T) standard Charpy specimen, except unnotched.
[b] Five standard Charpy specimens (ASTM E23-47T).
[c] The linear velocity of the hammer was 11 fps.
[d] Numbers in parentheses are coefficients of variation in percent.

With the exception of cermet I, all notched specimens had lower coefficients of variation than the unnotched specimens. It should be noted that the limited sensitivity of the impact tester masked the variation in cermets IV and V.

It is well known that the impact value is much less than the stored energy in an identical static simple beam just before fracture. It is also recognized that stress concentrations in the impact specimens are very large, and consequently only a small portion of the specimen has stresses approaching failure. The large coefficients of variation would be expected because, according to the flaw theory, the variability increases as the size decreases [22].

In any impact test, there are many variables, of which some are maintained constant. The various tests are classified by Sayre and Werring as (1) proof tests, (2) increment drop tests, (3) single blow tests, and (4) pendulum tests. The methods of test have been discussed [25, 26, 29], and there is considerable disagreement as to the measurement and significance of the impact resistance of a material.

The Charpy test was selected for this investigation because (1) it is a standard ASTM test for metallic materials [23], (2) the specimen is broken in a single blow without introducing plasticity, creep, and fatigue as factors, (3) the impact hammer strikes accurately at the desired location, (4) the test is made simply and quickly, (5) when properly made, test results are reproducible [28], (6) the specimen is tested as a simple beam and the error due to gripping is eliminated, and (7) both unnotched and notched specimens can be tested satisfactorily.

7.4. Evaluation of the Impact Test

The requirements of a satisfactory impact test are (1) accurately shaped specimens with a suitable finish, either notched or unnotched, (2) a well constructed Charpy tester, and (3) an adequate number of specimens to give the desired confidence limit.

Cermets are satisfactorily classified by the Charpy impact test according to impact resistance and notch sensitivity. Impact values are not satisfactorily correlated with other properties of the material, and the values for other sizes of specimens cannot be predicted.

8. Correlation of Mechanical Properties

8.1. Elastic Properties

Table 11 gives the average elastic properties for the tests listed.

The average moduli of elasticity of cermets I, II, and III agreed within approximately 10 percen regardless of the method of test. As previously shown, the tensile and compressive moduli for a single cermet were equal within experimental error, and the modulus did not depend on specimen size for th series of transverse specimens. The average moduli of elasticity determined by the different tests varied as much as 17 percent for cermet IV which had the largest coefficients of variation. The variation of the average moduli determined by the different tests for cermet V was even larger, being 37 percent.

The compressive moduli of specimens cut from form B1 transverse specimens were lower than the transverse moduli for this form. These consistently lower values indicated that the material in the ends of the B1 specimens may have been different from that in the thinner midportion, or there may have been systematic errors in the test methods. The differences were within the experimental error except for cermet V.

The correlation of the elastic properties obtained in tension and also in shear, expressed by the eq [15, p. 57],

$$E=2G(1+\mu) \qquad (6)$$

is illustrated by the agreement of the modulus of rigidity calculated from the tensile data and that obtained from the torsion test, table 11. This agreement and similarity of the transverse and compressive moduli of elasticity, for specimens having axes at 90°, indicate that these materials, with the possible exception of cermet V, are isotropic.

8.2. Evaluation of the Stresses and Strains in the Cermet Specimen at Fracture

a. Stress and Strain Analyses

(1) *Tensile Specimens.* In the tensile test, the axial strain, ϵ, and lateral strain, ϵ_1 were measured

TABLE 11. *Average values of elastic properties of cermets obtained from tensile, compressive, transverse, and torsional tests*

Cermet	Modulus of elasticity						Poisson's ratio				Modulus of rigidity	
	Tensile test	Compressive test	Transverse test: Form B1	Transverse test: Min [a]	Transverse test: Avg [a]	Transverse test: Max [a]	Tensile test	Compressive test	Transverse test [b]: Min	Transverse test [b]: Max	Torsion test	Calculated [c]
	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*	10^6 *psi*					10^6 *psi*	10^6 *psi*
I	89.9 [d](0.9)	91.3 (3.4)	94.7 (1.4)	90.3 (0.9)	93.0 (1.7)	95.9 (3.9)	0.21 (2.3)	0.22 (Nil)	0.14 (14.5)	0.23 (1.3)	36.0 (2.9)	37.1
II	78.6 (0.4)	78.8 (0.9)	82.1 (1.1)	79.5 (0.8)	81.2 (1.3)	83.4 (1.7)	0.23 (Nil)	0.23 (4.4)	0.16 (1.3)	0.24 (2.5)	33.0 (7.4)	32.0
III	55.1 (1.1)	50.9 (1.4)	55.4 (3.0)	53.9 (3.6)	54.1 (2.0)	55.4 (3.3)	0.22 (Nil)	0.24 (2.0)	0.15 (1.9)	0.23 (2.6)	22.8 (8.6)	22.6
IV	43.1 (4.4)	41.4 (6.5)	42.7 (12.3)	37.1 (17.2)	41.8 (8.4)	44.4 (2.9)	0.22 (Nil)	0.23 (5.2)	0.14 (2.1)	0.22	18.5 (7.2)	17.7
V	([e])	44.5 (11.9)	53.7 (6.8)	[f] 50.8 (2.6)	[f] 58.0 (3.7)	[f] 64.6 (3.7)	([e])	0.17 (3.5)	[g] 0.11 (5.7)	[g] 0.14 (2.8)	25.4 (11.0)	[h] 25.

[a] For six forms of transverse specimens.
[b] For five forms of transverse specimens.
[c] Calculated from $E/2G=1+\mu$ using data from the tensile test.
[d] Figures in parentheses are coefficients of variation in percent.
[e] Specimens were not furnished for this material.
[f] For four forms of transverse specimens.
[g] For three forms of transverse specimens.
[h] Data from average of transverse specimens were used because tensile specimens were not furnished.

and the relation expressed as

$$-\epsilon_1=\mu\epsilon, \tag{7}$$

where μ=Poisson's ratio.
The axial stress corresponding to ϵ is

$$\sigma=E\epsilon=\frac{P}{A} \tag{8}$$

where
E=Young's modulus of elasticity,
P=total load,
A=area of cross section of specimen,
ϵ=extensibility when σ=strength.

The maximum shear stress is for uniaxial loading [39, p. 15],

$$\tau_{\max}=\frac{\sigma}{2} \tag{9}$$

and the maximum shear strain

$$\gamma_{\max}=\epsilon(1+\mu). \tag{10}$$

(2) *Compressive Specimens.* In the compressive tests, the applied load was axial, and the axial strains, ϵ, and lateral strains, ϵ_1, were measured. Equations (7), (8), (9), and (10), modified for stress direction, apply. In accordance with Nadai [11, p. 208]

$$\text{"equivalent stress"}=E\,\epsilon_1=-\mu E\epsilon=-\mu\sigma, \tag{11}$$

where "equivalent stress", in the sense of the maximum strain hypothesis of failure, is the value of σ when ϵ_1 is substituted for ϵ in eq (8) and ϵ and σ are the values at fracture in the compressive tests, and are, of course, negative.

(3) *Torsion Specimens.* In the torsional test, compressive and tensile principal strains were recorded to failure in addition to shear strains within the elastic limit. The maximum shear stress was obtained from the applied torque. The maximum induced tensile and compressive strains were equal; therefore, eq (2) and (3) apply.

Also, [39, p. 15]:

$$\sigma_{45}=\tau_{\max}=-\sigma_{135}. \tag{12}$$

Since, for the tensile test, the maximum tensile strain from eq (8) is:

$$\epsilon=\frac{\sigma}{E}$$

and for the torsional test, the corresponding maximum tensile strain [11, p. 208] or [39, p. 15], is:

$$\epsilon_{45}=\frac{\sigma_{45}-\mu\sigma_{135}}{E}=\frac{\sigma_{45}(1+\mu)}{E}.$$

Then from [11, p. 208]

$$\text{"equivalent stress"}=\sigma_{45}(1+\mu). \tag{13}$$

(4) *Transverse Specimens.* The stress analysis of the tensile half of the transverse specimen resembles the analysis for the tensile specimen, except that the stress grades from zero at the neutral axis to a maximum at the outer tensile fibres. Similar also to the tensile specimen, the lateral and shear stresses are of minor significance. The compressive half of the transverse specimens resembles the compressive specimen except that the maximum stress can exceed the tensile stress on the tensile side by only small amounts which are due to plasticity and concentrated loads, and the induced lateral tensile strain and shear stress are also limited. The maximum shear due to loads and reactions on transverse specimens is too small, even for spans of 9/16 in., used in some tests, where this stress is approximately 13 percent of the tensile, to be a source of failure.

b. Stress-Strain Relation and Fracture of Cermets

The stress-strain curves to rupture previously reported indicated that the stress-strain relation was linear for specimens of cermets I and V in all tests except for cermet I in compression. The relation for cermet IV also was linear in the torsional and compressive tests. In the remaining tests, curvature of the stress-strain lines was apparent. Porous materials or those with inclusions of a relatively soft or weak substance having stress-strain curves of a similar shape were discussed by Nadai [11, p. 26] under the heading of hysteresis and after effects. Such materials fractured at *strains* low in comparison to those attained by ductile materials [11, p. 3] and, in these respects, resembled the cermets.

The calculation by eq (1) to (13) of stresses and strains present in specimens as the strength is approached depends on the assumption that the material remains elastic until failure.

The fracture surfaces of the tensile, transverse, and torsional specimens indicated that failure of the specimens as a whole occurred in tensile fracture. The compressive specimens broke into fragments from which the mode of failure could not be determined. According to Nadai [11, p. 182] the actual mechanism of failure, however, may be quite different from that apparent from the fracture surface of the specimen.

Several criteria for failure have been proposed, such as a limiting maximum principal stress, a limiting maximum strain, various energy considerations, etc. [11, p. 175]. The criteria for failure given in most theories have been advanced to explain the performance of ductile materials as well as of brittle materials having bi- or triaxial loading. For the cermets reported here, and also for many brittle materials, the criteria usually considered are a limiting tensile stress, a limiting maximum shear stress, and a limiting maximum elastic tensile strain (theory of the so-called equivalent stress, St. Venant) [11, p. 208]. The last criterion would not be expected to apply, however, to these same materials at elevated temperatures for reasons discussed by Nadai [11, p. 175, 208].

Table 12 lists, in a given column, the critical quantities of stress or strain that are equal in the

Table 12. *Equal values of maximum stress or maximum strain for different criteria of fracture in the tensile, transverse, compressive, and torsional tests*

Test	Criterion of fracture					
	Max tensile stress		Max tensile strain or equivalent stress		Max shear stress or max shear strain	
	Equal stress	Equal strain	Equal stress	Equal strain	Equal stress	Equal strain
Tensile	σ_t [a]	ϵ_t	σ_t	ϵ_t	$\frac{\sigma_t}{2}$	$\epsilon_t(1+\mu)$
Transverse	σ_{tr}	ϵ_{tr}	σ_{tr}	ϵ_{tr}	$\frac{\sigma_{tr}}{2}$	$\epsilon_{tr}(1+\mu)$
Compressive	---	$-\mu\epsilon_c$	$-\mu\sigma_c$	$-\mu\epsilon_c$	$\frac{-\sigma_c}{2}$	$-\epsilon_c(1+\mu)$
Torsional	σ_{45},	$\epsilon_{45}(1+\mu)$,	$\sigma_{45}(1+\mu)$,	ϵ_{45},	σ_{45},	$2\epsilon_{45}$,
	τ_{max}	$\frac{\gamma_{max}(1+\mu)}{2}$	$\tau_{max}(1+\mu)$	$\frac{\gamma_{max}}{2}$	τ_{max}	γ_{max}

[a] Symbols defined in eq (1) to (13), subscripts *t*, *tr*, and *c* refer to tensile, transverse and compressive tests respectively. For a particular criterion, the values of all of the quantities in a given column should be equal.

four tests when a particular criterion of fracture prevails. An interpretation of the significance of a strength from a given test requires some knowledge of the criterion of fracture. In the torsional test, for example, it might be expected that the shear strength would be obtained, but the torsional strength may be simply the shear stress at fracture as limited by the attainment of a maximum value according to one of the other criteria of fracture given in table 12. If the criteria of fracture can be determined, then the strength from the torsional test can be correlated with the corresponding shear strength, tensile strength, or "equivalent" strength. In a similar manner, the compressive stress present in the compressive test at fracture may be a function of either the shear strength or tensile strength.

Considering the maximum tensile stress and the maximum tensile strain criteria, the prevailing criterion is not evident from the values from the tensile, compressive, and transverse tests because the principal stress relations are similar. These relations are different, however, in the torsional test. A comparison of the experimental values of stress and strain from the torsional test to those from the other tests make possible a distinction between these two criteria of fracture. For example, the tensile strength, from the tensile test, is equal to σ_{45} if the maximum tensile stress is the criterion, but is equal to $\sigma_{45}(1+\mu)$ if the maximum tensile strain criterion is effective. If the maximum shear criteria are applicable, then the strength from the tensile test is equal to 2 σ_{45} from the torsional test.

The brittle materials have shear strengths that are larger than their tensile strengths, as suggested by Preston [41]. The shear stress in the tensile specimen, although less than σ, is appreciable and may be the source of failure as it is for some ductile materials, but tensile fracture would be expected for cermets.

In the compressive test, the compressive stress, σ, is comparatively large, and exceeding either the induced lateral strain [11, p. 208] or the shear strength [42] may be the cause of failure. This analysis assumes uniform stressing in the specimen. Even when bending is absent, the friction at the ends of the specimen restrains the lateral strain [8]. Thus the stress distribution at the ends is not simple and can be a determining factor in the compressive test.

The maximum shear stress recorded as the torsional strength should indicate a tensile strength for brittle materials according to Preston [41]. This explanation is also mentioned by Kingery [42], who reported that the tensile strength is obtained from the torsional test on brittle materials.

8.3. Comparison of Data for Cermets

a. Data from Tests

Table 13 gives average values of the measured stresses and strains present in specimens at the moment of failure, and also those calculated by formulas (1) to (13). Table 14 lists the percentage differences between values of pairs of stresses or strains, that are significant in the behavior of the cermets and in the evaluation of the tests.

The manufacturer of cermet IV reported improvements in the product during the time interval that specimens were procured in the order transverse-tensile-torsional. The strengths given in table 13 indicate the improvement, but no correlations of results from these three lots of specimens were made because the materials were admittedly different.

b. Comparison of Measured and Calculated Extensibilities

The differences, in percent, of the average measured extensibilities for the tensile, transverse, and torsional tests from the calculated values, assuming elastic behavior, are given in table 14, line A. The differences indicated that the stress-strain lines were linear for cermets I and V, but the measured extensibilities were appreciably larger for cermets II, III, and IV.

c. Dependence of Strength on the Size of the Specimen

The form-D transverse specimens had only about six percent of the volume of the form-C1 specimens, and the smaller specimens were stronger by from 18.2 to 43.7 percent, as given in line B, table 14. The results indicated that the rate of change in strength with the change in size was different for the five cermets, and that their "material constants" [22], that govern the variation of strength with size, were probably different.

Because the strengths of tensile, compressive, torsional, and transverse specimens may decrease as the size of the specimen is increased [22], the comparison of strengths would preferably be made on specimens having the same, or nearly the same, size. As indicated for transverse specimens, the dependence is approximate only, and a many-fold change in size may be required to produce a significant change in strength. The strengths for cermets I and III, from table 13, are higher than those given by Johnson [43], who used considerably larger specimens. For the tensile and compressive tests,

TABLE 13. *Average stresses and strains for cermet specimens at fracture in tensile, compressive, torsional, and transverse tests*

Cermet E	Tensile test: Stress: Axial σ [b]	Tensile test: Stress: Shear τ_{max}	Tensile test: Strain: Extensibility: Measured ϵ	Tensile test: Strain: Extensibility: Calculated σ/E	Compressive test: Stress: Axial σ	Compressive test: Stress: Shear τ_{max}	Compressive test: Strain: Lateral ϵ_l	Compressive test: Strain: Axial σ/E	Compressive test: Strain: Shear γ_{max}	Torsional test: Stress: Shear tensile σ_{45}, τ_{max}	Torsional test: Stress: Equivalent $\sigma_{45}(1+\mu)$	Torsional test: Extensibility: Measured ϵ_{45}	Torsional test: Extensibility: Calculated $\frac{\tau_{max}}{2G}$	Torsional test: Shear strain $\frac{\tau_{max}}{G}$	Transverse test: Stress for form: C1 σ	Transverse test: Stress for form: B1 σ	Transverse test: Stress for form: D σ	Transverse test: Extensibility: C1: Measured ϵ	Transverse test: Extensibility: C1: Calculated σ/E	Transverse test: Extensibility: B1: Measured ϵ	Transverse test: Extensibility: B1: Calculated σ/E	Ratio [a] $\frac{\tau_{max}}{\sigma}$
	10^3 *psi*	10^3 *psi*	%	%	10^3 *psi*	10^3 *psi*	%	%	%	10^3 *psi*	10^3 *psi*	%	%	%	10^3 *psi*	10^3 *psi*	10^3 *psi*	%	%	%	%	
I	176 [c](6.0)	88	0.201 (6.0)	0.196 (6.0)	588 (2.4)	294	0.142	0.646 (5.7)	0.788	156.8 (5.0)	189	0.217 (5.1)	0.218	0.436	183 (10.5)	208 (5.5)	223 (5.9)	0.202 (11.2)	0.194	0.226 (5.2)	0.221	1.41
II	204 (5.0)	102	0.292 (6.1)	0.259 (4.9)	555.8 (1.8)	277.9	0.162	0.705 (2.4)	0.867	180.2 (7.5)	221	0.362 (7.4)	0.273	0.547	218 (10.0)	217 (6.5)	297 (2.7)	0.310 (12.0)	0.286	0.305 (6.7)	0.277	1.28
III	141.2 (8.0)	70.6	0.304 (11.6)	0.256 (4.5)	374 (3.1)	187	0.176	0.735 (2.2)	0.911	109.4 (14.7)	133	0.334 (23.2)	0.250	0.500	137 (12.0)	149 (13.3)	162 (7.4)	0.310 (11.9)	0.270	0.327 (20.4)	0.282	1.26
IV	38.1 (13.6)	19.5	0.101 (16.2)	0.089 (15.9)	118.5 (11.2)	59.2	0.065	0.289 (16.6)	0.350	43.5 (3.7)	53.1	0.122 (6.5)	0.121	0.243	27.2 (10.3)	30.0 (17.0)	39.1 (11.8)	0.104 (24.1)	0.085	0.087 (18.5)	0.077	1.97
V	(d)	(d)	(d)	(d)	181.3 (27.0)	90.6	0.069	0.400 (18.8)	0.468	23.7 (9.3)	27.0	0.046 (16.8)	0.047	0.095	(d)	24.9 (12.9)	32.5 (5.5)	(d)	(d)	0.048 (12.2)	0.048	3.64

[a] τ_{max} is taken from the compressive tests, while σ is the B1 transverse value.
[b] Symbols are given in eq (1) to (13).
[c] Numbers in parentheses are coefficients of variation in percent.
[d] No tensile or C1 specimens furnished.

TABLE 14. *Differences for pairs of properties of cermets*

Line	Comparison [b]	Differences [a]: Cermet I	II	III	IV	V
		%	%	%	%	%
A	ϵ Avg measured from calculated.	2.0	17.8	22.2	10.9	0
B	σ_{tr}, Form D from C1	21.8	36.2	18.2	43.7	[c] 30.5
C	ϵ_{tr} from ϵ_t, measured	0.5	6.2	2.0	(d)	(e)
D	ϵ_{tr} from ϵ_t, calculated	−1.0	10.4	5.5	(d)	(e)
E	ϵ_{to} from ϵ_t, measured	7.9	23.4	9.9	(d)	[c] −4.3
F	ϵ_{to} from ϵ_t, calculated	11.2	5.4	−2.3	(d)	[c] −2.0
G	ϵ_{cl} from ϵ_{tr}, calculated	−35.7	−41.5	−37.6	−15.6	43.7
H	σ_{tr} from σ_t	4.0	6.9	−3.0	(d)	(e)
I	σ_{to} from σ_t	−10.9	−11.7	−22.5	(d)	[c] −4.8
J	σ_{to} (equi) from σ_t	7.4	8.3	−5.8	(d)	[c] 8.4
K	σ_c (equi) from σ_{tr}	−38.0	−41.0	−39.7	−9.3	23.7
L	τ_{tr} from τ_c	−64.6	−61.1	−60.4	−74.3	−86.3
M	τ_{to} from τ_c	−46.7	−35.1	−41.5	−26.5	−73.8

[a] Calculated from values given in table 13. Excess of first over second quantity.
[b] Symbols used are: ϵ=average extensibility for tensile, torsional, and transverse tests; ϵ_t, ϵ_{tr}, ϵ_{to}=extensibilities from tensile, transverse, and torsional tests, respectively; ϵ_{cl}=lateral strain from compressive test; σ_t, σ_{tr}, and σ_{to}=tensile stresses in tensile, transverse, and torsional tests, respectively; σ_{to} (equi) and σ_c (equi)="equivalent" stresses from torsional and compressive tests, respectively; τ_{tr}, τ_{to}, and τ_c=shear stresses in tension, torsional, and compressive tests, respectively.
[c] Tensile properties of B1 transverse specimens were used because no tensile or C1 specimens were furnished.
[d] Comparison not made because of changes in material.
[e] Tensile specimens not furnished.

the size comparison is easily made on the basis of the volume within the gage portion of the specimen. The torsional and transverse specimens, however, have only a surface at maximum stress, and, on the basis of volume, an infinitely large specimen would be required to equal a small tensile specimen. Failure may be initiated, however, at stress concentration points below the surface where the calculated average stress is less than at the surface, and, solely for size comparison, it was assumed that the volume having stresses ranging from 90 to 100 percent of the outer fibre stress might contain stress raisers causing fracture. The volumes of specimens used in this investigation for the various tests are given in table 15, and, excepting the volume for form D, were considered sufficiently alike to permit comparisons of strengths.

TABLE 15. *Gage sections of cermet specimens and volumes subjected to test stresses*

Test	Section	Volume [a]
	in.	*in.*^{3}
Tensile	0.250 diameter×1.25	0.061
Compressive	.424×0.424×1.27	.228
Torsional	.500 diameter×2.25	.084
Transverse	Form D, third point	.0017
Do	Form B1, constant moment	.0148
Do	Form C1, constant moment	.0296

[a] Transverse and torsional specimens had surfaces only, i. e., zero volume, at maximum stress. For comparison of specimen sizes only, the volume of that portion stressed from 90 to 100% of the maximum stress was considered the volume of these specimens.

d. Criteria of Fracture

The differences of stresses or strains of pairs assumed equal according to the maximum tensile strain criterion [11, p. 208], table 12, are given in table 14, lines E, F, G, J, and K. The comparisons in lines E, F, and J refer to specimens that had tensile fractures and to the torsional and tensile tests with their distinct principal stress patterns. These comparisons, with the exception of the value for cermet II, line E, indicated that the application of the maximum elastic tensile strain criterion gave values that agreed within 11.2 percent. The lateral strains and "equivalent" stresses calculated from the data from the compressive test according to the maximum tensile strain criterion, lines G, and K, however, were much less than the corresponding extensibilities and transverse strengths for cermets I, II, III, and IV. These differences suggested that some other criterion of fracture, such as a limiting maximum shear stress, was effective in the compressive test before the lateral strain exceeded the extensibility. On the other hand, cermet V was exceptional in that it probably fractured according to the maximum strain criterion in the compressive test, but the lateral strain and "equivalent" stress were higher than expected.

The particularly close agreement of transverse and tensile results, for specimens of comparable size, lines C, D, and H, was expected because the stress patterns were similar. This agreement confirmed, but did not prove, the applicability of either the maximum tensile strain or the maximum tensile stress criteria. The latter criterion seemed less applicable in the comparison of the torsional to the tensile test, in which the stress patterns were different, because the tensile stress in the torsional test was definitely less than in the tensile test, line I. Although the maximum tensile strain criterion overcompensated these stress differences, line J, this criterion gave the better agreement.

The widely different values of shear stress at fracture in the various tests, table 13 and table 14, lines L and M, led to the conclusion that a common maximum shear stress was not a criterion for correlating strength in the four tests. The largest values of shear stress were obtained, for each of the five cermets, in the compressive test. The maximum shear strains were also largest in the compressive test, and ranged from 3.03 to 9.9 times the extensibilities from the transverse test.

No single criterion for failure was evident for the compressive test. In this test, cermet V may have failed as predicted by the maximum strain theory. According to Kingery [42], brittle materials fail in shear in the compressive test. The extensive deformation of compressive specimens at a stress just below the strength is suggestive of failure in shear. That a maximum shear stress or a maximum shear strain is a second criterion of failure cannot be proved or contradicted from the data because sufficiently large shear stresses were not developed in the other tests. Although tests to develop the shear stress to these high levels may yet be devised, especially to evaluate such a shear strength, it seems common practice to accept the maximum shear stress as a criterion and the shear stress in the compressive test as the approximate shear strength [42]. The error in this assumption may not be serious for design purposes, because of the similarity in stress patterns for the compressive specimen and for parts such as cutting tools, punches, and stubby beams.

e. Brittleness

The brittle materials, including cermets, glass, ceramics, etc., are characterized by a texture or structure in which resistance to shearing is well developed, but the tensile strength, or cohesion, is limited by the presence of zones or planes of weakness. The degree of brittleness for these cermets may be expressed as the inverse of extensibility. Preston's requirement that, for a substance to be classified as being brittle, failure occur in tension when the specimen is tested in shear [41] provokes the suggestion that the ratio of $\tau_{\max}/\sigma$ could be an index of brittleness. Because $\tau_{\max}$ is usually derived from compressive tests, it follows that the ratio of compressive to tensile strengths should also be an index. Table 13 gives the values for $\tau_{\max}/\sigma$ and there is some correlation since a plot of $\tau_{\max}/\sigma$ and extensibility gives a fairly smooth curve. The value of this ratio seems to be a characteristic of the cermet.

8.4. Correlation of Impact Values and Mechanical Properties

Figure 15 gives plots of impact values with three factors derived from mechanical properties.

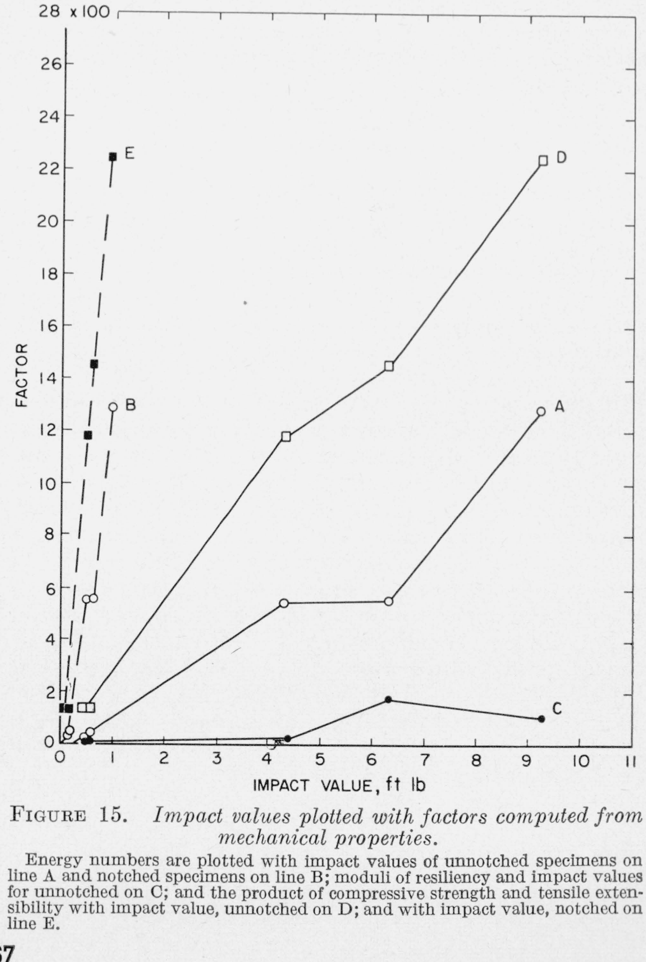

FIGURE 15. *Impact values plotted with factors computed from mechanical properties.*

Energy numbers are plotted with impact values of unnotched specimens on line A and notched specimens on line B; moduli of resiliency and impact values for unnotched on C; and the product of compressive strength and tensile extensibility with impact value, unnotched on D; and with impact value, notched on line E.

The modulus of resiliency [15, p. 282] is given by

$$F_1=\frac{\sigma_y^2}{E} \tag{14}$$

where σ_y is the yield stress. This modulus gives a measure of the energy absorbed elastically by the impact specimen. The correlation of this factor with impact value was unsatisfactory, line C, figure 15.

The energy number [30] is given by

$$F_2=\frac{\sigma^2}{E} \tag{15}$$

where σ is the tensile strength from form-D specimens. This number gives a considerably better correlation with impact values, lines A and B.

Concentrated compressive stresses as well as tensile properties are involved in impact tests. It would seem that a factor derived from results from both tensile and compressive tests would give a better correlation; such a factor is

$$F_3=-\sigma\epsilon \tag{16}$$

where σ is the compressive strength and ϵ is the calculated extensibility from the form-D specimens. This factor gives the best correlation with impact value, lines D and E. None of these correlations is satisfactory for predicting the impact value from the mechanical properties.

9. Summary

Tensile, compressive, torsional, transverse, and impact tests were made on specimens of cermets having five distinct compositions. The tests were evaluated according to the design requirements of the specimens and apparatus, refinements in test procedure, suitability to the cermets, and the variability of the results. The tensile, compressive, and transverse tests gave comparable moduli of elasticity and Poisson's ratios, and the modulus of rigidity calculated from these values agreed with the modulus of rigidity from the torsional test. The stresses and strains present at fracture in the tensile, compressive, torsional, and transverse tests on specimens of comparable sizes indicated that these brittle materials broke either at a limiting tensile strain or at a limiting shear stress. Brittleness was expressed as the ratio of shear to tensile strength and was related to maximum tensile strain. The combination of tensile and compressive tests gave the essential elastic properties and strengths of the materials. The degree of correlation of impact values with mechanical properties was considered too low for the prediction of impact values.

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10. References

[1] A. R. Blackburn, T. S. Shevlin, and H. R. Lowers, Fundamental study, and equipment for sintering and testing of cermet bodies: III, equipment for cross-bending stress and tensile at high temperature, J. Am. Ceram. Soc. **32,** 93 (1949).

[2] W. H. Duckworth, A. D. Schwope, O. K. Salmassy, R. L. Carlson, and H. Z. Schofield, Mechanical-property tests on ceramic bodies, U. S. Airforce, Air Research and Development Command, WADC Tech. Rept. No. 52–67, 17 (March 1952).

[3] W. H. Duckworth, et al., Mechanical property tests on ceramic bodies, AF Tech. Rept. No. 6512 (April 1951).

[4a] Julius Miklowitz, Elastic waves created during tensile fracture: The phenomenon of a second fracture, Naval Ordnance Test Station Rept. 1961 (1952).

[4b] Julius Miklowitz, Flexural waves in beams according to the more exact theory of bending, Naval Ordnance Test Station Rept. 2049, NOTS 741 (Sept. 1, 1953).

[5] M. B. Stiefel, Application of photoelasticity to the design of tensile specimens for ceramic-metal materials, Am. Ceram. Soc. Bul., **34,** 133 (1955).

[6] R. A. Heindl and L. E. Mong, Young's modulus of elasticity, strength, and extensibility of refractories in tension, J. Research NBS, **17,** 46 (1936) RP923; Ceram. Abstr. **16,** 24 (1937).

[7] R. F. Geller and M. D. Burdick, Strength and creep of special ceramic bodies in tension at elevated temperatures, NACA, ARR 6D–24.

[8] O. K. Salmassy, et. al., Behavior of brittle state materials, Battelle Memorial Institute, WADC Tech. Rept. 53–50, Part II (June 1955).

[9] O. K. Salmassy, W. H. Duckworth, and A. D. Schwope, Mechanical-property tests on ceramic bodies, Battelle Memorial Institute, WADC Tech. Rept. 53–50 (March 1953).

[10] O. K. Salmassy, et. al., material-property tests on ceramic bodies, Battelle Memorial Institute Rept. 19 (Aug. 22, 1953).

[11] Arpad Nadai, Theory of flow and fracture of solids, vol. I, 2d. ed. p. 328 (McGraw-Hill Book Co., New York, N. Y., 1950).

[12] J. A. Stavrolakis and F. H. Norton, Measurement of torsion properties of alumina and zirconia at elevated temperatures, J. Am. Ceram. Soc. **33,** 263 (1950).

[13] A. Nadai, Plasticity (English Translation by A. M. Whal), p. 128 (McGraw-Hill Book Co., Inc., New York, N. Y., 1931).

[14] R. A. Heindl and W. L. Pendergast, Progress report on investigation of fire-clay bricks and clays used in their preparation, J. Research NBS **3,** 691 (1929), RP114; Ceram. Abstr. **9,** 39 (1930).

[15] S. Timoshenko, Strength of materials: Part I, Elementary theory and problems, 2d ed., 13th printing (D. Van Nostrand Co., New York, N. Y., 1951).

[16] S. Timoshenko, Theory of elasticity, 1st ed., p. 99 (McGraw-Hill Book Co., Inc., New York, N. Y., 1934).

[17] M. M. Frocht, Photoelasticity, vol. II, p. 112 (John Wiley & Sons, Inc., New York, N. Y., 1948).

[18] J. S. Caswell, Stress analysis in short beams: II, Theoretical analysis and conclusions, engineering **178,** 656 (Nov. 19, 1954).

[19] L. H. Milligan, Note on modulus of rupture of cylindrical ceramic rods when tested on a short span, J. Am. Ceram. Soc. **36,** 159 (1953).

[20] W. Weibull, Phenomenon of rupture in solids, Ing. Vetenskaps Akad., Handl., **153,** 55 (1939), Ceram. Abstr., **20,** 250 (1941).

[21] A. A. Griffiith, Phenomena of rupture and flow in solids, Trans. Roy. Soc. (London). [A] **221,** 163 (1920); abstracted in J. Am. Ceram. Soc., **4,** 513 (1921).

[22] M. J. Barriage and R. H. Jacobsen, Development and application of brittle material method of stress analysis and study of brittle failure problems (Armour Research Foundation, Chicago, Ill., July 1952).

[23] Impact testing of metallic materials, Am. Soc. Testing Materials Designation: E23–47T, Am. Soc. Testing Materials Standards, Part I, p. 1451 (1952).

[24] Impact resistance of plastic and electrical insulating materials, Am. Soc. Testing Materials Designation: D256–47T, Am. Soc. Testing Materials Standards, Part 6, p. 1025 (1952).

[25] M. F. Sayre and Walter F. Werring, Introduction to symposium on impact testing, Proc. Am. Soc. Testing Materials **38,** Part 2, p. 21 (1938).

[26] E. J. Soxman, J. R. Tinklepaugh, and M. T. Curran, An impact test for use with cermets, J. Am. Ceram. Soc., **39,** 261 (1956).

[27] B. Maxwell and L. F. Rohn, Impact testing of plastics: Elimination of the toss factor, Am. Soc. Testing Materials Bul. No. 161, p. 44 (1949).

[28] D. E. Driscoll, Reproducibility of charpy impact test Symposium on Impact Testing, Am. Soc. Testing Materials Spec. Tech. Publ. No. 176, p. 70 (1955).

[29] H. M. Quackenbos, Jr., J. M. Hill, Jr., and C. E. Staff, The significance of the charpy and flexure tests in evaluating the impact resistance of plastics, Am. Soc. Testing Materials Bul. No. 159, p. 56 (July 1949).

[30] Properties of carboloy cemented carbides, Eng. Bul. HM–100A (Carboloy Co., Detroit, Mich., April 2, 1951).

[31] R. Baumberger and F. Hines, Practical reduction formulas for use in bonded wire strain gages in two dimensional strain fields, Proc. Soc. Exp. Stress Anal. II, No. 1, 113 (1944).

[32] Manual on quality control of materials, p. 14, STP 15–C, part I, Am. Soc. Testing Materials (Philadelphia, Pa., 1951).

[33] L. A. Yerkovich and G. J. Guarnieri, Compression-creep properties of several metallic and cermet materials at high temperatures, Proc. Am. Soc. Testing Materials **55,** 732 (1955).

[34] C. S. Aitchison and J. A. Miller, A subpress for compressive tests, NACA Tech. Note No. 912 (Dec. 1943).

[35] Instructions for the Tuckerman strain gage, Am. Instr. Co. (April 1950).

[36] W. H. Duckworth, Precise tensile properties of ceramic bodies, J. Am. Ceram. Soc., **34,** 1 (1951).

[37] A. M. Burghardt and A. S. Elder, Mechanical tests, development of a standard bend test for cemented carbides Lab. Rept. No. WAL 110/16 (Watertown Arsenal, Watertown, Mass., Feb. 15, 1950).

[38] L. E. Mong and W. L. Pendergast, Dynamic and static tests for mechanical properties of fired plastic refractories and other more resilient materials, J. Am. Ceram. Soc. **39,** 301 (1956).

[39] Stephen Timoshenko and J. N. Goodier, Theory of elasticity, 2d ed., p. 15 (McGraw-Hill Book Co., Inc., New York, N. Y., 1951).

[40] N. M. Parikh, Modes of fracture and slip in cemented carbides, J. Am. Ceram. Soc., **40,** 335 (1957).

[41] F. W. Preston, A note on the concept of brittleness, J. Am. Ceram. Soc., **15,** 176 (1932).

[42] W. D. Kingery, Factors affecting thermal stress resistance of ceramic materials, J. Am. Ceram. Soc., **38,** 3 (1955).

[43] A. E. Johnson, Mechanical properties at room temperatures of four cermets of tungsten carbide with cobalt binder, NACA Tech. Note 3309 (December 1954); Mechanical properties at room temperatures of four cermets of titanium carbide with nickel binder, NACA Tech. Note 3197 (Aug. 1954).

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