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THE INFLUENCE OF IMPACT VELOCITY ON THE TENSILE CHARACTERISTICS OF SOME AIRCRAFT METALS AND ALLOYS

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SUMMARY

This report deals principally with the results of tension tests on sixteen metals and alloys, most of which are employed extensively in aircraft construction. The tension characteristics are discussed for static conditions and rates of deformation up to about 150 feet per second.

The equipment and procedure employed in these tests are described. Velocities are obtained by means of a heavy rotating disk. The forces acting during impact are determined by means of a strain-sensitive resistance dynamometer and are recorded with a cathode-ray oscillograph. The effective constant velocity of the rotating disk permits the development of stress-strain diagrams.

As a result of these tests, it has been shown that Dowmetal M and 18-percent chromium - 8-percent nickel stainless steel are adversely affected by an increasing rate of deformation. The other materials tested exhibit changes of yield stress, ultimate strength, and other tensile properties.

An investigation of the effect of decreasing the gage length of specimens below 1 inch is reported. The results indicate that there is no major effect until the ratio of gage length to diameter is reduced to unity.

I. STATEMENT OF THE PROBLEM

In a strict sense, impact testing refers to a study of the behavior of materials under the application of a suddenly applied load, or to a study of the rapid deformation of materials. Heretofore, the term "impact testing" has been most closely associated with those tests in which a notched specimen in bending was used. This, however, is more properly referred to as notched bar testing. There are, in general, three types of impact tests; that is, notched bar testing, torsion impact testing, and tension impact testing.

The notched bar tests have been found to be useful in the study of the susceptibility of materials to embrittlement by the presence of a notch. At the present time, it has been employed in a qualitative manner since it has not been possible to correlate the results in a quantitative manner with other tests or experience.

Torsion testing has been used most widely for the investigation of tool steels. Here, again, this test does not lend itself to quantitative analysis which can be directly applied to current practices.

The tension impact test involves the application of a load to a specimen such that it is pulled apart in tension. Many of the significant mechanical properties of a material are expressed in terms of the tensile and shear properties obtained from a tension test. In view of these circumstances, it may be logical to believe that more fundamental information pertaining to the behavior of engineering materials under different rates of deformation can be obtained by tension impact testing. However, it is of little avail to judge the influence of the rate of deformation and the properties of material from the value of the total amount of energy required to produce failure at a given rate of deformation. The problem is, then, to devise some means by which the stress-strain characteristics of any material may be recorded for different rates of deformation and to investigate the stress-strain characteristics of several different materials at different rates of deformation.

Many structural parts are subject to a high rate of strain and their performance under these conditions may be quite different from those under static conditions. Therefore, it is desirable to have some method of testing by which the influence of rate of deformation on properties of these materials may be determined prior to their application in a working structure. It was, therefore, the purpose of this investigation to determine the influence of rates of deformation on the tensile properties of some aircraft metals and alloys and some other common engineering metals and alloys. This report will describe the equipment, testing procedure, and the results of this investigation.

The report covers the effect of impact velocity on specimens subject to simple tension. The major portion of the results is given for 1-inch-gage length specimens, although the effect of smaller gage lengths on the dynamic tensile characteristics for one material is included. The effect of other variables or a combination of variables, such as notches of different forms, temperature, and combined stresses taken together with impact velocity, is probably highly significant in practical applications. The data given in this report should not be used as a basis for the adoption or exclusion of materials for application in parts subject to dynamic loading.

II. EQUIPMENT

A. IMPACT MACHINE

One of the most satisfactory methods of obtaining high impact velocity is by the use of a rotating disk, which can be made to possess sufficient energy so that the amount of energy absorbed in breaking a specimen is extremely small compared with the energy of the disk. In view of this requirement, a 750-horsepower hydraulic impulse turbine with an exciter generator was obtained on loan from the Southern California Edison Company. The water-wheel buckets were removed and the machine with suitable electric wiring for operation, either as a variable speed motor or generator, was installed in a pit below the floor level. (See fig. 1.)

The disk A has a diameter of 44 inches, turns on a horizontal shaft and, together with shaft and rotor, weighs approximately 2000 pounds. Suitable striking jaws B and counterweight C are connected firmly to the periphery of the wheel as shown in figures 1 and 2.

The normal operating speed of this machine is 750 rpm with a corresponding peripheral velocity of 150 feet per second. With a machine of this type, a reasonable overspeed for short intervals is permissible and impact velocities as high as 200 or, possibly, 250 feet per second may be obtained. Due to the inertia of the rotating mass, and because of the relatively small amount of energy required to rupture the specimens in tension impact, the velocity of the wheel is effectively constant during fracture at any operating speed.

Electrical connections to the machine are arranged so that the disk can be stopped from any operating speed within 20 seconds by operating the machine as a generator and dissipating the electrical energy through a suitable resistance. The operation of the machine is controlled from the panel shown at D in figure 3.

The force-measuring unit or dynamometer (E in fig. 4), into which the specimen screws, is firmly anchored at the end of a 715-pound anvil F machined from a 9- by 9- by 43-inch billet of steel, shown in figures 2 and 4. This anvil is bolted rigidly to a base (G, fig. 4) which slides horizontally on finished ways under the action of a gear crank and rack shown at H in figures 2 and 4. Thus, for the purpose of replacing specimens, the specimen holder is moved back from its usual operating position tangent to the under side of the disk, as shown in figure 5. One end of the specimen screws into the end of the holder, shown at L in figures 5 and 6, and on the other end of the specimen is screwed a tup (M in figs. 5 and 8) consisting of a piece of steel 1 inch square and 1/2 inch thick. The specimen is held firmly in the horizontal position, tangent to the under edge of the wheel in such a manner that the jaws of the disk under normal rotation clear the specimen and tup by a small amount. (See fig. 6.)

After bringing the wheel up to any desired speed, as shown by the speed indicator, at N on the control panel (fig. 3), a trigger mechanism is operated by a solenoid (O in fig. 7) synchronized with the disk rotation. Instantaneous tripping of the trigger is accomplished by a thyratron circuit. This trigger P releases a torsional spring which raises a flat yoke (Q, figs. 4 and 6) behind the tup into the path of the striking jaws. This yoke engages both the tup and striking jaws, after which the specimen is pulled off in tension. One end of the specimen, together with tup and yoke, flies off tangent to the wheel and is deposited in a container full of cotton waste at R (fig. 7).

B. DYNAMOMETER

The force-measuring device or dynamometer, shown at E in figures 4 and 5, consists of a hollow cylindrical bar of SAE 4130 steel 15/16 inch in outer diameter and 7/8 inch over-all length. It is threaded internally at the open end with 20 threads per inch into which one end of the specimen is screwed. The other end of the dynamometer fastens rigidly into the anvil F. The strain-gage winding is laid longitudinally along the outer surface of this cylinder and consists of approximately 30 feet of number 40 constantan wire formed into a mat in zigzag fashion, coated with glyptal as an insulating binder, and baked at 350° F. For purposes of protection, the wire is covered with scotch tape as shown at S (fig. 6). The constantan winding is referred to as the pickup resistor.

The leads from this pickup are connected to the electrical circuit shown in figure 9. This circuit consists of a 140-volt battery, a series resistor placed in series with the pickup, and a calibration resistor for purposes of calibrating the force measurements of the dynamometer as discussed later. The resistance of the series resistor is made very high compared to any change in the pickup resistor during impact, so that a constant current of approximately 100 milliamperes is maintained in the circuit.

When the tension impact force acts on the specimen, it is transmitted through the specimen to the dynamometer which elongates elastically in proportion to this force, according to Hooke's law. The wire covering the dynamometer bar follows this increase in length, changing its resistance in a linear manner proportionate to the force acting. The change in resistance varies linearly with the load over a range of forces exceeding that used in any of the tension tests. Typical calibration data are given in table I. With high-strength steel specimens, 6000 pounds is ordinarily the maximum force which will occur. By measuring the change in voltage produced by this change in resistance of the pickup circuit, forces can be determined as indicated later.

The linear relation between the impact forces and the dynamometer deformation is valid as long as the period of the natural vibration of the dynamometer bar is short compared with the duration of impact. The natural frequency of the dynamometer used in this work is 35,000 cycles per second, which gives a time for a half-period of 1/70000 second. This is practically the upper limit of frequency for this type of dynamometer bar, since further shortening of the bar is impractical. The natural frequency is determined by striking the end of the dynamometer and comparing the vibration set up on an oscillograph screen with a wave of known frequency. With this dynamometer, reliable force time records are available up to impact speeds of 200 feet per second.

C. RECORDING APPARATUS

The voltage changes in the circuit produced by the elastic deformation of the dynamometer are amplified by a two-stage alternating-current amplifier. From the amplifier, the signal is sent to an RCA TM-168-A cathode-ray oscillograph shown at J in figure 3. The connections are made such that the voltage changes will produce a vertical deflection of the electron beam. The scale for the vertical deflection in terms of resistance (ohms per in.) is determined by suddenly changing the resistance of the dynamometer circuit a known amount. For this purpose a calibration resistor, shown in figure 9, is used to produce a force calibration curve after each test. This change in resistance corresponds to a known force acting upon the dynamometer as determined by a static calibration of the type shown in table I.

The circuit of the oscillograph is arranged so that a single horizontal sweep of the electron beam can be obtained at any desired speed. The sweep speed is determined by connecting a known frequency to the oscillograph and producing a broken timing line across the screen after each test.

The force-time curve traced by the beam on the screen of the oscillograph is recorded photographically with the camera shown at T in figure 3. The camera is equipped with a Zeiss Biotar F:1.4 lens.

The horizontal single sweep of the oscillograph is started across the screen slightly in advance of the impact of the jaws on the tup by means of a small firing pin projecting beyond the front surface of the yoke. This pin is insulated from the yoke and connected through the wire, shown at U (fig. 7), to a condenser in the control panel shown at V in figure 3. The other side of the condenser is connected to ground. When the jaws of the disk strike the end of the pin the condenser is discharged, thereby starting the sweep of the electron beam. An instant later the hammers strike the tup producing a force-time diagram in the center of the oscillograph screen.

TABLE I

TYPICAL PICKUP CALIBRATION DATA

Total load (lb)	Total resistance (ohms)	Resistance change (ohms)
0	848.080	
		0.430
2,000	848.510	
		.434
4,000	848.944	
		.446
6,000	849.390	
		.458
8,000	849.848	
		.412
10,000	850.260	
		.428
12,000	850.688	
		.438
10,000	850.250	
		.442
8,000	849.808	
		.438
6,000	849.370	
		.435
4,000	849.935	
		.425
2,000	848.510	
		.417
0	848.093	

Up to 12,000 pounds and back to zero load, as fast as possible (within 10 sec), gives:

0 848.093

12,000, held for 10 minutes:

850.724 ohms, with no visible change.

6000, held 10 minutes: 849.410 ohms, with no visible change.

0 848.080

Results: Average resistance change: 2.180 ohms per 10,000 pounds, or 4585 pounds force per ohms change in resistance.

D. EXTENSOMETER

The record obtained from the oscillograph screen is essentially a force-time diagram with the ordinate proportional to force and the abscissa proportional to time. The constancy of wheel velocity during the impact was checked by means of a special extensometer. This extensometer provides a means by which units of elongation can be added to the force-time diagram discussed above.

The essential parts of the extensometer are shown in figure 8. It consists of a small cylinder 1/4 inch in diameter and 1 inch long, mounted on the end of the dynamometer parallel to and above the specimen gage length as shown in figures 5 and 6. This cylinder consists of 115 alternate layers of 0.009-inch celluloid and 0.001-inch aluminum foil pressed onto a central steel shaft in such a manner that the aluminum disks make electrical contact with the central shaft. The outer surface of the cylinder is turned smooth in a lathe. A narrow ribbon of clock-spring steel, carrying a needle point at one end, is fastened firmly to the tup prior to fracture of the specimen. This ribbon is held along an element of the cylinder by an elastic rubber tube. Figure 8 shows the parts which are assembled and placed as in figure 5. As the tup is drawn forward during deformation of a specimen, the needle point scratches the surface of the cylinder, alternately making and breaking an electric circuit after every 0.010 inch of elongation. This produces successive modulations on the force-time diagram corresponding to deformation units of 0.010 inch. Such modulations are shown in figure 10 for aluminum broken at 20 feet per second.

Investigation of these and similar diagrams indicate that the velocity of the wheel during impact is essentially constant since equal units of elongation are marked out at equal time intervals. In addition, elongation measurements obtained with the extensometer check sufficiently close with those based on the assumption that the rate of deformation during fracture is constant and equal to the velocity of the jaws. Consequently, this extensometer device is used only occasionally as a check on the operation of the dynamometer-oscillograph unit.

Table II shows a few typical values of elongation measured from specimens and compared with corresponding values recorded from the photographed curve. The time required for fracture is also given. It is interesting to point out that with 20-percent elongation or 2/10-inch deformation up to fracture, the time required to fracture at 150 feet per second is 0.00011 second or 1/9000 second. Also, 150 feet per second corresponds to an elongation of 180,000 percent per second.

TABLE II

ELONGATION-TIME RESULTS

Specimen	Velocity (ft/sec)	Measured elongation (in.)	Elongation taken from curves (in.)	Time for fracture (sec)
Cold-drawn steel No. 8	10	0.150	0.15	0.00125
Cold-drawn steel No. 17	10	.157	.155	.00130
Cold-drawn steel No. 10	30	.185	.165	.00049
Cold-drawn steel No. 16	50	.145	.15	.00025
Cold-drawn steel No. 1	75	.120	.12	.00013
Brass No. 1	20	.250	.24	.00104
17S-T duralumin	20	.250	.245	.00104

E. ANALYSIS OF TEST RECORDS

In general, the method of analyzing the force-time diagrams or, more specifically, the change in resistance-time diagrams of the type shown in figure 11 is simply by the method indicated in figure 12 and table III. The analysis of a force-time curve for a specimen of 17S-T duralumin broken at 51 feet per second is taken as an example. Typical photographs of the force-time curves, as photographed on the oscillograph screen, are shown in figure 11. The records are photographically enlarged and traced at a suitable size by drawing a mean line through the vibrations of the diagram, after which the force-time and elongation scales are determined. Successive force measurements and corresponding elongations are recorded in suitable units and the areas under the curves measured with a planimeter. Knowing the initial cross-sectional area and length of each specimen, stress-strain values are computed and the curve plotted. The energy required to rupture the specimen is obtained directly from the area of the force-elongation curve. For purposes of comparison, static tests were made with each material and corresponding data were obtained. Static tests were made by applying loads to the specimen in small increments and waiting for equilibrium conditions to be established before applying the next increment.

TABLE III

COMPLETE ANALYSIS OF STRESS-STRAIN CURVE OF FIGURE 13

17S-T duralumin
Specimen: 5
Film holder: 4
Timing wave: 10 kc

Time of break: 0.000416 sec
Velocity: 50.5 ft/sec

Force scale: 1 in.=2670 lb
Elongation scale: 1 in.=0.0727 ft
Energy scale: 1 sq in.=19.4 ft-lb

Original sectional area: $\frac{\pi}{100}$ sq in.
Percent elongation: 25.3
Percent reduction of area: 49.5

Planimeter reading: 1.94
Planimeter constant: 1.113
Area of diagram: 2.160 sq in.

Energy of rupture: 41.9 ft-lb
Yield stress: 59,400 lb/sq in.
Ultimate stress: 71,300 lb/sq in.
Breaking stress: 51,000 lb/sq in.

Elongation (in./in.)	Force units (50ths of an inch)	Force (lb)	Stress (lb/sq in.)
0.001	35	1870	59,400
.002	33	1760	56,000
.004	38	2030	64,500
.007	40	2135	68,000
.012	42	2240	71,300
.016	40	2135	68,000
.022	37	1975	62,700
.024	33	1760	56,000
.025	30	1600	51,000

III. TESTS ON 1-INCH-GAGE LENGTH SPECIMENS

A. MATERIALS TESTED

Using the procedure outlined above, twenty-one different engineering metals and alloys were prepared and broken in tension impact. These specimens were machined from 1/2-inch-diameter rod. They are threaded at each end and have a cylindrical gage length of 1.00 inch ± 0.005 inch and a gage diameter of 0.200 inch ± 0.001 inch, as shown in figure 13. The materials tested are listed below:

1. Light alloys

   a. Aluminum (2S), condition unknown (estimated ½ H)
   b. 17S-T aluminum alloy,
      nominal analysis - 4.0 percent Cu, 0.5 percent Mn, 0.5 percent Mg, balance Al
   c. 24S-T aluminum alloy,
      nominal analysis - 4.5 percent Cu, 0.6 percent Mn, 1.5 percent Mg, balance Al
   d. Dowmetal J magnesium alloy (extruded,
      nominal analysis - 6.5 percent Al, 0.2 percent Mn, 0.7 percent Zn, balance Mg
   e. Dowmetal M magnesium alloy (extruded),
      nominal analysis - 1.20 percent Mn, 0.3 percent Si, balance Mg
   f. Dowmetal X (extruded),
      nominal analysis - 3 percent Al, 0.2 percent Mn, 3 percent Zn, balance Mg

2. Copper alloys

   a. Copper (pure), condition unknown
   b. Machinery brass, condition unknown
   c. Silicon bronze (cold-drawn Herculoy No. 418 rod),
      nominal analysis - 96.25 percent Cu, 3.25 percent Si, 0.50 percent Sn

3. Steels

   a. SAE 1112 free cutting steel - cold drawn
   b. SAE 1020 hot-rolled steel
   c. SAE 1035 steel - annealed 1550° F
   d. SAE X4130 steel

3. Steels (continued)

d. SAE X4130 steel (continued)

1. Annealed 1575° F
2. Quenched in oil from 1575° F, tempered at 1000° F
3. Quenched in oil from 1575° F, tempered at 800° F
4. Quenched in oil from 1575° F, tempered at 600° F

e. SAE 6140 steel quenched in oil from 1575° F, tempered at 1020° F

4. Stainless steel

a. 16-percent chromium - 2-percent nickel M 286, oil-quenched from 1800° F

1. Tempered at 1200° F
2. Tempered at 900° F
3. Tempered at 700° F

b. 18-percent chromium - 8-percent nickel stainless steel, type 303 as received

B. TEST DATA AND RESULTS

Representative values of yield stress, breaking stress, ultimate stress are recorded in tables IV to XXIV for each material at various rates of deformation. Likewise, the percent elongation, reduction of area and energy required to rupture the specimen are recorded. Stress-strain diagrams are given at three velocities for each material in figures 15 to 35, inclusive. Curves showing the variation of the physical properties with rate of deformation are shown in figures 36 to 56, inclusive. The ratio of dynamic to static yield point, ultimate strength and energy are plotted as a function of velocity in figures 57 to 59, inclusive.

1. Light alloys

a. Aluminum. - The ultimate strength of aluminum increases slightly with an increasing rate of deformation.

The elongation and reduction of area increase appreciably with increasing velocity. It is also to be noted that the energy required for failure increases from about 6 foot-pounds in the static test to about 11 or 12 foot-pounds at a velocity of 20 feet per second.

b. <u>17S-T aluminum alloy</u>.- The ultimate strength, elongation, and reduction of area of this alloy increase slightly with velocity. It is evident that this material is not greatly affected by velocities in the range used in these tests and with this particular shape of specimen.

c. <u>24S-T aluminum alloy</u>.- As in the case of 17S-T, the ultimate strength, elongation, and reduction of area increase with velocity. However, the increase of ultimate strength is somewhat greater for 24S-T than for 17S-T and about the same as that of aluminum. This data indicates that 24S-T alloy is less velocity-sensitive than 17S-T.

d. <u>Dowmetal J, magnesium alloy</u>.- The ultimate strength of this material is adversely affected by increasing velocity as shown by a decrease of from 44,000 to about 39,000 pounds per square inch at 10 feet per second. The reduction of area increases from about 27 percent statically to about 38 percent at 10 feet per second. The elongation increases from about 16 percent to about 20 percent.

e. <u>Dowmetal M, magnesium alloy</u>.- There is an appreciable increase of ultimate strength from approximately 35,000 pounds per square inch statically to about 50,000 pounds per square inch at 10 feet per second with this alloy. The reduction of area and elongation decrease very markedly with increased velocity. The reduction of area decreased from about 25 percent to about 6 or 7 percent at 10 feet per second. The elongation of about 17 percent statically is reduced to a minimum of about 5 or 6 percent with increasing velocity. These effects occur below a velocity of 15 feet per second. As a result of the marked decrease in elongation, the energy required to rupture the material decreases in about the same manner, that is, from a value of about 14 foot-pounds to about 5 or 6 foot-pounds. One may conclude definitely that this material is velocity-sensitive.

f. <u>Dowmetal X, magnesium alloy</u>.- Dowmetal X does not seem to show any marked differences in tensile properties as the rate of deformation is increased. The results indicate a slight increase of the reduction of area and percent elongation with increasing velocity, but one should not attach too much significance to this, in view of the spread of the data.

2. Copper alloys

a. Copper.- The ultimate strength of copper increases from about 45,000 to about 50,000 pounds per square inch with increasing velocity. The reduction of area and elongation likewise increase, although the increase of reduction of area seems to be proportionately greater than the increase of elongation. Under the conditions of these tests, copper does not seem to be velocity-sensitive.

b. Brass.- The change of tensile properties of brass with velocity seems to follow the same tendency found with copper; however, the increase of energy absorbed by the alloy is greater than the increase shown by pure copper.

c. Silicon-bronze.- Here, again, the tension characteristics seem to vary in about the same way as with pure copper, that is, increase of ultimate strength, reduction of area, elongation and energy with increasing velocity. At first, the influence of velocity seems to be somewhat greater in the silicon-bronze than in pure copper, although this tendency is reduced at higher velocities.

3. Steels

a. SAE 1112 free-cutting steel, cold-drawn.- The yield stress of this material increases from 90,000 to 130,000 pounds per square inch with rise in rate of deformation from static to 20 feet per second. The energy required to rupture rises from 26 to 45 foot-pounds in the same range. In this material the yield stress was always higher than the ultimate strength except in the static test.

b. SAE 1020 hot-rolled steel.- The most effective influence of velocity on the properties of this steel occurs in the ultimate strength which increases from about 65,000 to about 80,000 pounds per square inch. The reduction of area remains approximately constant throughout the velocity range while the percent elongation is decreased slightly. Here, again, is a relatively ductile material and it is to be noted that the yield point in the low-velocity range increases very markedly.

c. <u>SAE 1035 steel fully annealed</u>.- This steel shows a marked increase of yield stress from 47,000 to 92,000 pounds per square inch. The ultimate strength increases from 75,000 to 100,000 pounds per square inch. The energy rises from 49 to 62 foot-pounds. These increases occur within a change in rate of deformation from static to 20 feet per second. At higher rates of deformation, the yield stress rises to 125,000 pounds per square inch at 140 feet per second, while the ultimate strength rises to a maximum of 115,000 pounds per square inch at 90 feet per second and then gradually decreases. The energy increases to about 78 foot-pounds at 140 feet per second. The reduction of area and percent elongation do not change appreciably with increasing velocity.

d. <u>SAE X4130 steel</u>.- This alloy steel is employed extensively in the aircraft industry for many purposes. Specimens were quenched from 1575° F into oil, some were tempered at 600° and 800° F, and others at 1000° F. Another group of specimens was annealed at 1575° F. The specimens tempered at 600° and 800° F show a decrease of ultimate strength with increase of velocity, while those tempered at 1000° F and the annealed specimens show no appreciable change of ultimate strength with increasing velocity. The ultimate strength of the specimens tempered at 800° F decreases more sharply than those tempered at 600° F. The so-called yield point of the specimens tempered at 600° and 800° F decreases with increasing velocity. This, coupled with the decrease of ultimate strength, is indicative of the poorer dynamic properties of this material when tempered at 600° and 800° F than when tempered at 1000° F. The specimens that were tempered at 1000° F show very little change of tensile properties with velocity. There seems to be a slight increase of energy absorbed. The annealed specimens show an increase of ultimate strength with increasing velocity. The other properties do not seem to be greatly affected. In the lower velocity range, the yield point of the annealed specimens increases very rapidly with increasing velocity, which is opposite to that found in the quenched and tempered specimens.

e. <u>SAE 6140 steel quenched and tempered at 1020° F</u>.- This steel does not show any appreciable change of ultimate strength with increasing velocity. The reduction of area and percent elongation tend to increase slightly.

There is an appreciable increase of the energy absorbed with increasing velocity. It is to be noted that in this material which has been tempered at a relatively high temperature, the yield point in the low-velocity range tends to increase as it does in the case of the SAE X4130 steel, tempered at 1000° F.

4. Stainless steel

a. 16-percent chromium, 2-percent nickel.- Specimens of 16-percent-chromium - 2-percent-nickel stainless steel, oil-quenched from 1800° F, were tempered at temperatures of 1200°, 900°, and 700° F. Owing to the few specimens available, these results are considered indicative only, though they are quite interesting. Values of percent elongation and reduction of area are almost identical for all three materials and remain constant over the velocity range; the stresses and absorbed energy, however, behave quite differently. There is moderate improvement in properties of the alloy tempered at 1200° F, with rapid loading up to 80 feet per second, with the absorbed energy rising from 58 to 96 foot-pounds. The material tempered at 900° F shows a decrease in ultimate strength, yield, and energy, with increasing speed up to 45 feet per second; but it is noted that the minimum values are not appreciably lower than the minimum values of the material tempered at 1200° F. The ultimate strength, yield strength, and energy values of the material drawn at 700° F do not change much up to speeds of 40 feet per second, after which the values increase appreciably. This might seem to indicate that the dynamic tensile properties of this steel are reasonably satisfactory for any of these heat treatments. Lower Izod impact values for the material tempered at 900° F have indicated a greater notch sensitivity than other heat treatments, but its dynamic tensile properties are quite good, though not as high as for the specimens tempered at 700° F. It may be noted that the curves for materials of higher tempering temperature appear to be of the same general shape as those of the lowest tempering temperature, but are displaced along the velocity axis.

b. 18-percent chromium, 8-percent nickel.- This material shows an appreciable decrease of reduction of area and elongation with increasing velocity and a gradual upward trend of ultimate strength. Here, again, it is to be noted that in the low-velocity range the yield point shows a marked increase with increase in velocity. In the low-velocity range, the energy decreases markedly, but in the higher velocity range, the energy is about the same as under static conditions.

C. TEST CONCLUSIONS AND SUMMARY

In examining the results of these tests, it is to be noted that there are no definite indications of the existence of a critical velocity for any of the materials investigated. If one examines the data in tables IV to XXIV, it will be noted that in most materials a large number of the specimens exhibited two reduced sections - one at which failure occurred near one end of the gage length and one at the other end of the gage length, as shown in figure 14. Such specimens are designated as having a double neck. This phenomenon has been observed before, but its cause has not been explained.

From the present investigation, it is apparent that the length of the specimen has a marked effect upon the results. If one considers the double-neck phenomenon from the standpoint of wave propagation, a more intelligent explanation of the behavior of these specimens may be obtained. The elastic wave is propagated at the velocity of sound in the material which is extremely high. Therefore, many reflections of the elastic wave may occur during the time involved from section discontinuities such as at the ends of the gage length. Furthermore, there is some evidence that the plastic strain is propagated at a much lower rate than the elastic strain. From this analysis, one may expect that the stress throughout the specimen may not be uniform at any specified instant. The stress distribution will depend upon the gage length and the applied velocity. Under certain conditions, maximums in the deformation pattern may occur at two points along the specimen, resulting in a double neck. The short specimen employed in these tests undoubtedly influences the results. Longer specimens would probably yield more fundamental information about the behavior of the material when subjected to suddenly applied loads. The results reported are true for the shape of specimen employed in this particular velocity range.

The values of yield point reported are probably most reliable in the range of velocities below about 20 feet per second. At higher velocities, the overshooting effect becomes more pronounced and, therefore, the values reported for yield point may be rightfully questioned. It seems to be significant, however, that in some materials the yield point decreases, while in others the yield point increases with increasing velocities.

In the light alloys, Dowmetal M is most affected by velocity. The other light alloys investigated do not suffer appreciable losses of ductility. The copper alloys seem to perform quite satisfactorily with increasing velocity. The SAE X4130 steel tempered at 1000° F appears to be less affected by an increasing rate of deformation than any other treatment employed. The results of the test on the SAE 6140 tempered at 1000° F indicate that there is no marked effect of velocity on the dynamic properties.

The results of the tests on 18-percent chromium, 8-percent nickel stainless steel are in general accord with the experience of those who have been concerned with cold-forming properties of this alloy. With increasing velocity, the reduction of area and percent elongation decrease, while the yield point and ultimate strength increase. At higher velocities, these results are somewhat complicated by the stress reflections referred to above. With this size of specimen, there does not seem to be any marked change in the ductility of the 18-percent chromium, 8-percent nickel stainless steel above approximately 20 feet per second.

The results of this investigation are in general agreement with other investigators such as Nadai and Manjoine (reference 1), de Forest, MacGregor, and Anderson (reference 2), and Parker and Ferguson (reference 3) with respect to trends for similar materials. The differences in absolute values may be attributed to differences in specimen, composition and structural condition of material, and testing equipment. Many authors have employed the term "strain rate" as a basis for reporting impact velocity. The curves in this report give both impact velocity and rate of deformation. Since the strain rate is not uniform along the specimen during a test, it would seem that the use of this term should be discouraged. It is probable that the actual velocity of the moving end of the specimen is a controlling factor in this type of work.

No definite critical velocity has been found in these tests such as reported by H. C. Mann (reference 4). The effect of velocity on the elongation of the annealed

SAE 1035 steel given in this report coincides reasonably well with that of Mann, but the decrease of energy observed by him is not found in the present investigation; nor have the other investigators referred to been able to observe this condition.

IV. EFFECT OF GAGE LENGTH

A series of tests was conducted for the purpose of studying the effect of gage length on dynamic tensile characteristics. For these tests, a cold-rolled steel was employed. The over-all length of the specimens was the same as that used for standard tests, namely, 2-3/16 inches. The gage diameter of the specimen was maintained at 0.20 inch, while the gage length was varied from 1 inch down to 0.025 inch. An attempt was made to maintain a fillet radius of 1/32 inch on specimens with a gage of more than 0.1 inch. With shorter gage lengths, the radius was negligible. The results of these tests have been plotted in figures 60 to 63, inclusive.

Figure 60 shows the relation of ultimate strength to the gage length as determined at velocities between 0 and 125 feet per second. There is no marked increase of ultimate strength of this material until the gage length is reduced to 0.2 inch, which corresponds to a l/d ratio of unity. Decreasing the gage length beyond this value effects an increase of ultimate strength, followed by a rather pronounced decrease when the gage length is less than 0.05 inch.

The change of percent elongation with gage length is shown in figure 61. It is interesting to note that the percentage elongation increases with decreasing notch length until a value of 0.2 inch is reached. With further decrease in gage length, the percent elongation decreases to a minimum at a gage length of about 0.075 inch, and then increases markedly.

Figure 62 shows the effect of gage length on the reduction of area. Here, again, there is no marked change until the gage length is about 0.20 inch, although there is a tendency for the reduction of area to decrease when the gage length is below a value of about 0.40 inch.

The variation of energy per unit volume is plotted against gage length in figure 63. This shows a gradual increase in energy down to a gage length of 0.20 inch. With smaller gage length, the energy per unit volume increases markedly. In general, a gage length of 0.2 inch ($l/d = 1$) seems to be a critical length.

CONCLUSIONS

The results given in this report indicate the relative velocity sensitivity of several engineering metals and alloys which are used directly or indirectly in the field of aircraft production. In considering the data, it is important to recognize that the results establish the properties of these materials at different rates of deformation for this particular size and shape of specimen. The presence of double necking indicates that serious stress reflections occur which definitely affect the results. It is to be expected that longer specimens would give somewhat different data.

In general, the results of this investigation indicate that for some materials a stress considerably above the static yield point can be applied for a very short duration without marked deformation. This could be stated in another way by saying that at higher rates of deformation the yield point is increased in some materials. All materials except Dowmetal M and 18-percent chromium - 8-percent nickel stainless steel, showed little change in percent elongation with increasing rate of deformation. Dowmetal M is very sensitive to velocity.

It is apparent that the effect of decreasing the gage length below 1 inch is only slight, provided the ratio of length to diameter is not below 1. The variation of properties with rate of deformation seems to remain approximately the same for different gage lengths below 1 inch.

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California Institute of Technology,
May 25, 1942.

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TABLE IV - ALUMINUM

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
Static	20,000	20,000	10,000	7.17	70.8	13.7	20	
Static	20,000	20,000	7,000	5.86	68.7	15.9	21	
15	16,800	21,500	12,000	10.2	76.0	21.6	2	
15	17,100	20,500	10,300	10.4	77.0	22.7	3	
35	21,200	22,400	11,200	9.8	78.8	23.6	6	*DN
35	13,400	20,700	9,700	11.8	77.4	28.2	5	DN
35	17,600	23,400	10,500	11.1	79.8	24.0	4	DN
60	15,200	22,800	11,400	11.7	----	----	7	DN
60	25,600	28,200	11,500	11.0	----	----	8	DN
60	26,500	26,500	15,100	10.3	81.1	25.3	9	DN
90	28,300	23,200	18,000	13.72	----	----	12	DN
90	25,700	20,600	15,400	8.6	81.9	24.9	11	DN
90	28,700	22,800	17,000	12.5	83.2	31.2	10	DN
120	29,300	23,900	16,000	10.6	81.5	23.2	15	DN
120	32,400	22,100	15,200	11.3	82.4	25.2	14	DN
120	25,300	20,000	13,300	9.6	82.8	24.6	13	DN
150	31,400	25,600	14,000	13.1	83.8	24.6	17	DN
150	27,900	20,700	11,600	11.9	83.2	28.0	16	DN

TABLE V - 17S-T ALUMINUM ALLOY

0	40,000	55,400	49,400	28.2	39.2	21.2	8	
15	46,200	55,400	-------	----	46.7	23.1	11	
15	43,000	54,500	-------	----	47.4	23.6	12	
15	42,700	56,000	43,900	33.3	46.6	22.7	16	
15	42,900	59,500	48,700	35.4	47.4	23.7	17	
45	34,000	57,900	44,200	27.2	46.6	25.1	18	
45	40,700	59,500	42,900	29.3	46.6	25.1	19	
45	36,600	63,600	47,100	29.4	47.4	25.2	20	
80	58,900	54,700	40,300	26.8	52.1	27.4	21	
80	67,500	54,400	40,100	28.5	52.4	28.5	22	
80	71,600	51,600	36,200	30.2	53.0	27.6	23	
120	71,600	55,000	32,800	30.6	54.4	29.6	24	
120	66,200	52,500	33,100	32.2	53.0	27.5	26	
120	79,400	65,000	47,200	40.5	54.0	30.6	25	*DN
150	59,500	57,900	41,400	38.5	53.8	28.8	27	DN
150	57,000	54,100	34,400	36.4	53.1	30.4	28	DN
150	67,500	61,800	42,300	40.2	51.7	28.5	29	DN

Average hardness - 59 R_B

*DN = double neck

TABLE VI - TENSILE PROPERTIES

24S-T ALUMINUM ALLOY

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %
Static	46,000	65,600	64,000	32.0	33.0	20.0
10	56,000	73,000	63,000	35.7	32.7	20.2
37	67,100	77,800	65,400	43.0	40.6	22.3
64	75,000	81,800	70,000	46.0	36.8	23.5
89	71,300	76,100	63,400	40.4	40.0	22.0
117	79,600	78,000	61,500	46.0	41.5	24.8
148	84,800	78,000	61,500	46.6	41.0	25.0

TABLE VII - DOWMETAL J, MAGNESIUM ALLOY

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	30,000	44,500	41,000	16.7	27.8	15.7	18	
10	38,800	38,800	32,100	15.5	37.5	16.3	2	
1 10	39,800	39,800	29,300	16.9	37.5	16.7	3	
30	40,700	40,700	32,500	17.4	39.1	16.8	4	
30	42,300	40,100	30,600	18.2	38.4	17.4	5	
30	47,100	38,800	30,600	17.3	36.9	17.0	6	
50	51,600	43,000	38,200	14.7	39.1	19.3	7	
50	53,200	46,800	36,900	18.1	40.1	19.6	8	
50	46,800	39,500	28,700	16.3	39.1	19.0	9	
75	58,000	41,700	32,800	24.6	39.1	21.8	10	*DN
75	62,000	44,600	32,200	18.1	39.1	20.8	11	DN
75	69,400	39,800	29,800	18.3	40.0	22.7	12	DN
100	73,200	41,000	33,400	18.9	39.1	22.5	13	DN
100	61,700	42,300	29,600	18.5	39.1	19.1	15	DN
120	70,300	42,300	37,200	20.6	40.0	22.4	16	DN
120	50,000	41,100	33,700	20.3	40.1	22.1	17	DN

Average hardness - 55 R_F

TABLE VIII - DOWMETAL X, MAGNESIUM ALLOY

0	31,500	44,600	44,600	12.5	29.4	14.5	20	
15	42,300	46,000	35,000	17.6	27.7	14.2	1	
15	42,600	44,900	36,600	15.7	29.5	13.1	2	
15	35,000	42,300	35,000	17.0	28.7	14.5	3	
48,35	48,400	47,100	41,700	16.3	25.2	15.3	4	
35	51,600	45,500	35,300	18.8	40.0	16.2	5	
35	46,700	44,000	36,100	17.4	39.1	17.4	6	
60	41,700	41,700	33,700	14.2	39.2	19.3	7	Slight *DN
60	46,100	42,400	32,200	14.2	38.4	18.8	8	
60	42,700	41,500	32,400	12.9	29.6	18.7	9	DN
90	55,000	------	------	----	41.5	22.2	10	DN
90	44,500	43,200	39,400	19.3	40.4	23.5	11	DN
90	52,000	45,300	38,800	18.8	39.4	21.3	12	DN
90	48,100	45,200	35,300	23.4	40.8	21.0	19	DN
120	53,700	50,800	------	----	38.6	20.3	13	DN
120	38,800	38,800	32,200	20.1	40.8	23.4	14	DN
120	38,500	45,200	39,800	19.5	37.6	19.7	15	DN
150	47,100	48,400	45,500	25.3	40.8	20.1	16	DN
150	47,900	50,800	45,000	22.3	----	----	17	DN
150	49,400	43,600	42,400	22.7	40.8	18.5	18	DN

Average hardness 58 R_F

*DN = double neck

TABLE IX - DOWMETAL M, MAGNESIUM ALLOY

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number
0	31,800	35,500	32,500	7.40	15.4	8.75	38
0	31,800	33,000	30,000	13.96	26.1	16.9	39
0	33,800	34,500	31,000	14.14	26.9	16.4	40
10	47,400	47,400	43,900	5.22	5.9	2.6	1
10	46,500	46,500	41,700	6.37	8.8	4.8	2
10	44,900	44,900	42,300	3.84	5.0	2.9	3
20	49,600	49,600	43,600	7.33	9.8	4.7	5
20	46,200	46,200	41,100	6.05	8.8	4.7	6
30	53,200	55,600	50,600	6.40	9.8	5.0	7
30	43,000	44,200	36,600	4.58	6.9	3.8	8
30	38,800	49,300	44,200	6.01	---	---	9
40	------	48,000	35,400	5.37	6.0	3.5	10
40	------	64,000	44,900	4.59	6.0	4.0	11
40	------	59,500	40,100	5.55	5.0	3.3	12
50	------	55,000	38,500	5.34	6.9	5.2	13
50	------	50,900	30,000	4.78	10.6	6.8	14
50	------	51,200	30,700	3.83	6.9	3.9	15
60	------	45,500	36,000	4.72	8.8	5.6	16
60	57,900	57,900	49,000	5.19	8.8	6.1	18
60	59,200	59,200	36,000	6.36	8.9	5.5	19
70	41,700	41,700	37,600	5.14	9.7	7.2	20
70	42,300	42,300	35,400	5.44	6.9	4.3	21
70	46,800	46,800	34,800	4.23	7.9	7.4	22
80	44,200	44,200	37,600	6.89	6.9	4.9	23
80	41,100	41,100	30,400	6.65	6.9	4.7	24
80	49,600	49,600	35,300	5.33	6.0	3.4	25
90	49,300	49,300	43,000	6.95	5.0	4.0	26
90	48,100	48,100	43,000	7.99	---	---	27
90	39,600	50,000	37,200	6.33	8.8	6.1	28
100	54,100	54,100	40,400	7.70	8.8	5.8	29
100	38,000	43,000	30,400	6.29	8.8	6.1	30
100	49,300	49,300	26,000	5.87	9.7	6.9	31
120	32,100	46,800	26,000	7.09	9.7	7.8	32
120	31,200	44,900	39,800	6.99	7.0	4.5	33
120	44,200	44,200	40,400	7.00	7.9	4.4	34
150	------	45,500	6,500	5.08	8.9	5.0	35
150	55,400	55,400	36,000	8.93	8.9	5.6	37

TABLE X - COPPER

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number
0	46,000	46,000	24,700	17.3	56.8	16.2	19
15	50,600	50,600	31,200	27.6	62.8	22.2	1
15	55,400	56,600	38,500	28.5	61.5	20.0	2
15	47,700	54,400	38,200	28.4	61.5	20.3	3
35	55,400	58,000	37,900	29.2	63.4	22.0	4
35	52,200	50,900	32,200	30.1	61.5	24.2	5
35	49,000	54,400	33,100	28.8	62.2	23.0	6
60	64,900	51,200	32,500	30.2	64.6	27.2	7
60	62,700	52,200	32,200	30.0	63.4	27.3	8
60	54,800	54,700	35,300	32.2	62.2	26.7	9
90	67,200	49,300	48,000	23.3	66.4	23.9	10
90	71,300	58,500	53,500	28.1	----	----	11
90	69,700	52,200	41,100	23.5	66.4	22.1	12
120	70,700	53,800	43,900	24.1	69.2	21.8	13
120	61,800	49,400	45,200	24.2	68.0	21.5	14
120	68,700	52,500	47,100	24.6	70.3	21.9	15
150	68,100	52,800	39,800	26.8	70.8	21.4	16
150	68,100	54,100	47,400	25.8	68.6	21.2	17
150	73,500	54,400	49,300	26.1	68.6	21.0	18

Average hardness 79 R_F

TABLE XI - MACHINERY BRASS

0	56,000	64,000	55,000	27.7	43.0	17.4	21	
0	56,000	64,000	55,000	26.0	42.3	16.4	22	
15	69,400	73,200	54,100	49.3	54.5	25.4	1	
15	60,500	64,300	44,900	37.4	63.4	23.4	2	
15	63,000	69,400	47,400	39.2	62.8	24.0	3	
35	59,200	63,000	49,000	44.8	56.4	27.0	4	
35	64,000	66,500	48,700	47.2	56.5	27.5	5	
35	71,300	71,300	51,900	46.0	55.8	27.5	6	
60	74,500	77,000	60,800	48.5	57.8	27.9	8	
60	59,500	71,900	57,000	44.1	56.5	27.1	9	
60	64,600	68,500	60,800	50.1	54.5	28.6	10	*DN
90	61,400	72,900	50,000	50.1	65.8	31.3	11	DN
90	62,000	70,600	49,700	50.4	56.9	30.7	12	DN
90	70,400	73,000	50,000	54.6	58.5	31.2	13	DN
120	72,900	66,800	58,200	52.5	60.2	34.8	15	DN
120	74,500	62,700	56,000	41.5	57.8	28.7	17	DN
120	76,000	65,600	60,200	48.5	58.4	30.2	20	DN
150	------	------	------	----	59.5	28.7	18	DN
150	------	------	------	-----	58.3	26.8	19	DN

Average hardness 71 R_B *DN = double neck

TABLE XII - SILICON BRONZE

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	65,000	73,000	40,000	41.4	79.3	24.3	14	
25	84,800	90,500	------	----	74.7	27.8	1	
25	83,000	81,500	40,800	53.7	76.5	28.2	2	
25	92,000	89,400	46,100	63.4	77.4	30.3	3	
50	76,500	80,300	43,700	53.1	77.2	30.9	4	
50	70,700	80,200	40,700	51.9	78.4	31.3	5	*DN
50	79,600	81,000	34,100	54.4	76.8	31.7	6	DN
100	89,100	77,700	28,800	60.6	77.4	32.3	7	DN
100	90,000	84,200	38,600	71.3	77.2	36.3	8	DN
100	66,200	83,100	------	----	77.4	40.0	9	DN
150	103,000	87,300	78,600	65.3	78.2	33.2	10	DN
150	106,200	81,500	69,000	57.4	----	----	11	DN
150	107,000	82,100	76,700	52.2	79.3	26.4	12	

Average hardness 76 R_B
*DN = double neck

TABLE XIII - SAE 1112 FREE-CUTTING STEEL COLD DRAWN

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %
Static	90,600	105,000	84,300	26.3	37.8	10.5
10	123,400	------	85,000	46.5	40.6	16.0
24	135,200	------	81,500	43.4	48.1	15.2
37	136,000	------	86,500	44.5	47.5	15.2
53	143,500	------	90,000	53.0	52.4	18.2
80	150,000	------	75,000	36.3	45.0	13.0
93	155,000	------	91,000	47.1	43.8	14.5
145	160,000	------	110,000	37.0	47.5	11.2
155	163,000	------	114,000	42.8	44.0	13.0

TABLE XIV - SAE 1020 HOT-ROLLED STEEL

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	38,500	67,000	47,500	50.2	65.2	35.0	19	
0	38,500	60,000	47,500	52.2	65.2	33.4	20	
15	102,200	95,100	------	----	64.7	37.2	1	*DN
15	75,400	80,800	------	----	66.3	39.7	2	
15	73,000	81,200	52,000	74.2	64.1	34.7	3	DN
15	74,500	71,900	43,600	65.6	65.8	36.1	15	DN
35	77,400	76,100	48,400	48.6	64.6	31.3	4	DN
35	84,500	77,900	48,500	56.4	64.7	31.6	5	DN
35	97,000	98,600	66,200	67.5	65.1	30.1	6	DN
60	64,000	65,300	43,600	41.4	64.6	26.9	7	DN
60	92,200	79,700	48,200	57.6	66.0	35.4	8	DN
60	82,500	72,900	51,300	53.4	64.6	30.2	9	DN
90	75,800	78,400	33,000	79.0	65.6	33.8	10	DN
90	93,200	79,000	56,600	60.0	65.7	32.4	11	DN
90	80,100	76,100	55,200	67.5	65.0	36.5	12	DN
120	98,500	76,300	64,000	60.3	65.3	30.2	13	DN
120	93,900	81,500	70,400	63.7	65.2	30.8	14	DN
150	126,300	87,200	81,500	80.6	66.9	36.9	16	DN
150	121,200	87,200	69,400	58.8	66.3	25.2	17	DN
150	117,000	77,600	68,800	57.7	66.7	29.2	18	DN

Average hardness 40 R_A

*DN = double neck

TABLE XV - SAE 1035 STEEL

Fully Annealed

Static	47,700	76,500	63,600	49.0	51.0	26.5	
10	87,500	95,500	69,500	59.9	52.5	26.0	
39	92,800	99,000	68,000	62.1	53.7	26.5	
47	105,500	108,500	75,800	72.0	53.7	28.0	
57	102,300	105,400	78,000	62.2	53.7	27.0	
67	107,500	109,000	70,000	60.2	51.7	25.0	
88	118,000	114,000	73,800	71.6	55.1	26.9	
120	120,000	112,000	64,000	69.9	55.7	27.5	
130	125,000	107,000	57,000	79.1	56.5	30.5	
140	121,000	97,000	55,000	75.8	56.7	32.0	

TABLE XVI - SAE X4130 STEEL
Annealed - 1575° F

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	56,000	76,000	50,000	62.2	71.1	33.9	19	
15	88,900	81,900	70,700	62.0	69.6	33.6	1	*DN
15	86,000	91,400	54,400	67.2	68.6	30.3	2	
15	84,700	84,700	48,300	68.3	68.5	31.4	3	DN
35	99,900	86,900	51,900	57.2	69.2	27.8	4	DN
35	104,000	87,300	49,500	65.0	68.5	32.1	5	DN
35	102,500	94,800	55,700	70.6	68.6	32.5	6	DN
60	74,500	96,700	53,500	61.4	69.2	29.0	7	DN
60	74,500	81,800	54,100	55.4	68.7	32.2	8	DN
60	70,000	81,100	43,600	52.7	68.1	30.3	9	DN
90	105,000	86,500	46,500	60.1	69.4	33.4	10	DN
90	103,500	81,800	44,900	52.5	----	-----	11	DN
90	96,500	80,500	44,300	51.2	69.9	29.3	12	DN
120	110,000	86,000	35,000	55.4	70.3	27.4	14	DN
120	126,000	98,500	56,300	65.0	68.5	27.8	15	DN
150	103,700	79,300	26,900	59.1	71.8	28.5	16	DN
150	124,600	90,400	41,100	68.0	71.9	29.6	17	DN
150	120,000	89,700	87,200	52.3	71.4	25.3	18	DN

Average hardness 45 R_A *DN = double neck

TABLE XVII - SAE X4130 STEEL
Oil-quenched - 1575° F; tempered - 1000° F

0	133,000	146,000	94,000	48.9	64.6	14.4	19	
0	133,000	147,000	93,000	48.5	63.4	14.2	20	
15	-------	146,000	-------	----	63.4	17.9	1	
15	139,000	156,000	88,800	62.8	61.6	16.9	2	
15	141,000	151,000	91,000	63.7	63.4	17.3	3	
35	163,000	160,000	95,700	60.7	62.8	17.5	4	*DN
35	155,000	147,000	85,000	57.1	64.0	19.9	5	DN
35	139,000	149,000	89,600	59.2	63.4	17.4	6	DN
60	148,000	155,000	87,800	53.9	63.4	18.3	7	DN
60	137,000	149,000	90,600	55.9	63.4	18.5	8	DN
60	139,000	143,000	74,900	45.2	64.6	17.9	9	DN
90	177,000	166,000	94,200	60.0	59.7	17.1	10	DN
90	162,000	152,000	87,200	55.5	64.0	17.3	11	DN
90	132,500	155,000	85,000	59.9	64.6	17.9	12	DN
120	159,000	150,000	77,700	56.8	65.2	15.4	13	DN
120	164,300	150,000	77,000	62.5	66.4	18.4	14	DN
120	142,300	149,000	73,200	60.1	64.6	17.6	15	
150	221,000	154,000	79,500	65.1	63.4	16.4	16	
150	192,000	151,000	76,700	65.2	66.9	16.6	17	DN
150	170,000	143,000	75,400	57.2	----	----	18	

Average hardness 28 R_C *DN = double neck

TABLE XVIII - SAE X4130 STEEL

Oil-quenched - 1575° F; tempered - 800° F

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	175,000	186,000	128,000	41.9	52.4	9.9	19	
0	175,000	189,000	125,000	47.8	54.5	10.8	20	
15	138,000	153,000	85,700	45.6	55.4	13.3	1	*DN
15	152,000	162,000	97,000	46.1	52.2	12.2	2	DN
15	145,000	153,000	91,000	45.0	51.7	12.4	3	DN
35	192,000	171,000	104,300	49.5	53.5	14.0	4	DN
35	185,000	166,000	99,300	48.0	55.8	12.6	5	DN
35	197,000	157,000	84,600	41.5	55.1	12.3	6	
60	201,000	171,000	108,500	46.5	54.3	13.6	7	DN
60	177,000	159,000	95,800	40.8	55.8	13.6	9	DN
90	175,000	156,000	92,600	40.1	----	----	10	DN
90	194,000	156,000	93,000	49.2	57.8	14.9	12	DN
120	173,000	155,000	88,500	43.7	52.4	12.1	13	DN
120	221,000	150,000	90,000	57.3	59.7	15.6	14	DN
120	210,000	170,000	108,000	58.9	60.3	13.7	15	DN
150	233,000	162,000	62,700	54.3	57.1	14.2	16	DN
150	232,000	149,000	51,600	48.1	55.1	12.0	17	DN
150	163,700	143,500	62,100	48.1	----	----	18	

Average hardness 30 R_C

TABLE XIX - SAE X4130 STEEL

Oil-quenched - 1575° F; tempered - 600° F

0	194,000	210,000	140,000	50.5	54.5	10.4	10	
50	209,000	184,000	109,000	53.7	56.5	13.8	1	*DN
50	200,000	196,000	120,500	59.4	57.5	15.0	2	DN
50	211,000	182,000	119,300	49.2	52.2	13.2	3	DN
100	200,000	191,000	99,300	58.8	57.1	14.5	4	DN
100	198,000	179,000	92,600	58.5	58.2	14.5	5	DN
100	197,000	163,000	99,800	57.4	54.2	15.1	6	DN
150	206,000	178,000	94,900	58.0	57.1	12.0	7	DN
150	168,400	149,500	70,400	51.2	56.0	12.8	8	DN
150	214,000	187,000	105,400	62.7	59.9	12.7	9	DN

Average hardness 37 R_C

*DN = double neck

TABLE XX - SAE 6140 STEEL

Oil-quenched - 1620° F; tempered - 1020° F

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	170,000	193,000	152,000	53.2	43.0	11.2	19	
0	166,000	187,000	161,000	48.8	44.5	11.4	20	
15	189,200	208,300	146,300	79.0	47.7	13.8	1	
15	182,000	199,000	144,200	72.7	47.4	14.1	2	
15	185,300	198,300	135,300	84.4	49.6	15.1	3	
35	185,000	196,500	141,300	67.0	48.9	13.7	4	*DN
35	227,000	234,000	163,200	94.5	48.9	14.3	5	
35	200,300	191,000	133,000	71.6	49.6	15.3	6	DN
60	188,000	199,000	131,000	65.4	50.3	14.6	7	DN
60	196,000	190,000	128,000	68.5	50.3	15.9	8	DN
60	174,000	192,000	136,000	64.8	51.0	15.4	9	DN
90	195,000	191,000	135,000	73.1	49.6	15.0	10	DN
90	188,000	193,000	132,000	73.7	46.7	14.9	11	DN
90	139,000	188,000	124,000	71.5	50.3	14.6	12	
120	204,000	188,000	115,000	70.6	49.6	13.7	13	DN
120	129,700	198,000	132,500	78.0	53.0	14.5	14	DN
120	127,000	186,000	120,000	83.1	50.3	14.3	15	DN
150	196,300	194,000	125,000	81.4	53.1	13.9	16	DN
150	216,000	182,300	111,000	73.0	51.0	13.8	17	DN
150	210,300	173,000	108,800	74.5	53.8	14.5	18	DN

Average hardness 35 R_C

*DN = double neck

TABLE XXI - STAINLESS STEEL

16 Percent Cr - 2 Percent Ni Tempered at 1200° F

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %
Static	99,000	126,000	84,000	57.1	61.5	18.5
37	158,000	158,000	85,000	70.9	64.0	20.0
75	166,500	173,000	85,000	94.3	65.8	21.5
107	192,000	168,000	85,000	86.4	66.3	23.5

TABLE XXII - STAINLESS STEEL

16 Percent Cr - 2 Percent Ni Tempered at 900° F

Static	204,000	215,000	143,000	110.0	63.5	21.0
33	196,000	176,000	89,500	54.9	60.3	14.6
65.3	267,000	215,000	116,000	82.1	60.3	16.6
83.3	225,000	195,000	113,000	72.0	60.3	16.3
105	214,000	170,000	68,000	66.4	61.2	17.5

TABLE XXIII - STAINLESS STEEL

16 Percent Cr - 2 Percent Ni Tempered at 700° F

Static	194,000	204,000	154,000	73.1	53.0	15.0
33.3	204,500	197,500	88,500	59.2	60.3	14.1
60.5	256,000	232,000	100,000	84.6	60.3	16.2
81.4	216,000	185,000	97,000	64.3	60.3	16.0
127	294,000	225,000	127,000	66.4	61.2	20.0

TABLE XXIV - STAINLESS STEEL

18 Percent Chromium - 8 Percent Nickel

Velocity (ft/sec)	Yield (lb/sq in.)	Ultimate (lb/sq in.)	Break (lb/sq in.)	Energy (ft-lb)	Reduction of area %	Elongation %	Specimen number	
0	------	96,800	96,800	169.5	74.0	75.0	31	
0	------	96,800	96,800	149.3	75.0	66.5	32	
15	64,000	101,200	------	-----	64.0	50.8	13	
15	75,400	100,300	74,200	131.0	63.4	50.6	14	
15	79,300	107,300	------	-----	64.0	56.2	15	*DN
35	79,900	--------	------	-----	63.4	56.0	16	DN
35	68,500	106,000	------	-----	62.2	55.4	17	
35	75,500	103,000	78,300	130.0	63.4	59.0	18	DN
35	70,000	104,000	79,500	136.0	64.0	54.0	30	DN
60	55,400	112,000	------	-----	62.8	60.5	19	
60	59,900	107,300	73,900	137.0	63.4	56.2	20	
60	58,500	111,500	80,900	147.0	62.8	54.8	21	
90	69,700	106,000	78,000	143.0	62.8	59.4	23	DN
90	76,100	111,000	80,200	150.0	63.4	55.6	25	
120	79,500	111,000	82,500	160.0	63.4	58.1	26	DN
120	83,400	119,000	83,300	168.0	63.4	57.5	27	
150	112,500	117,000	85,500	173.0	63.6	59.0	28	DN
150	102,800	111,700	80,500	154.0	63.6	55.6	29	

Average hardness 82 R_B

*DN = double neck

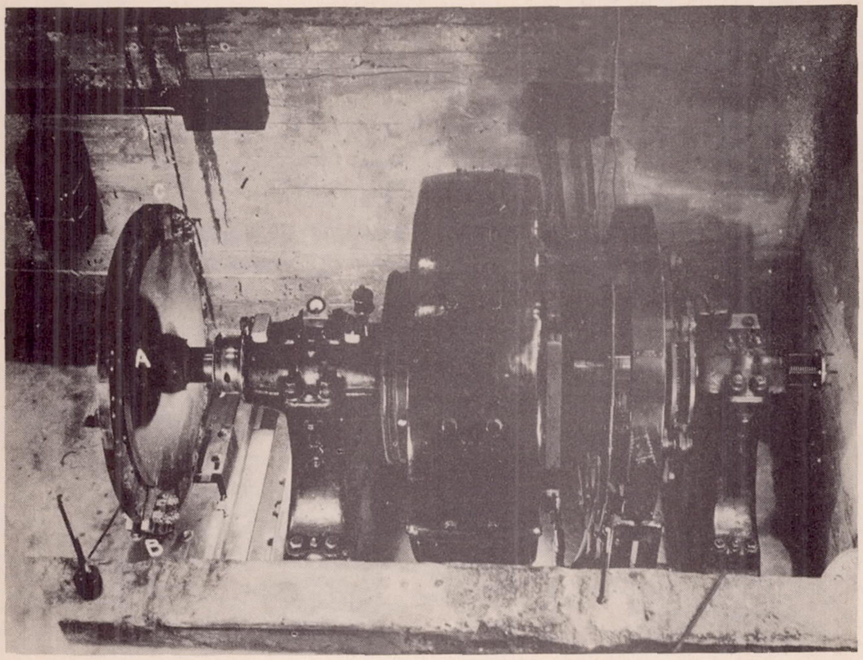

Figure 1.- Rotary impact tester in pit.

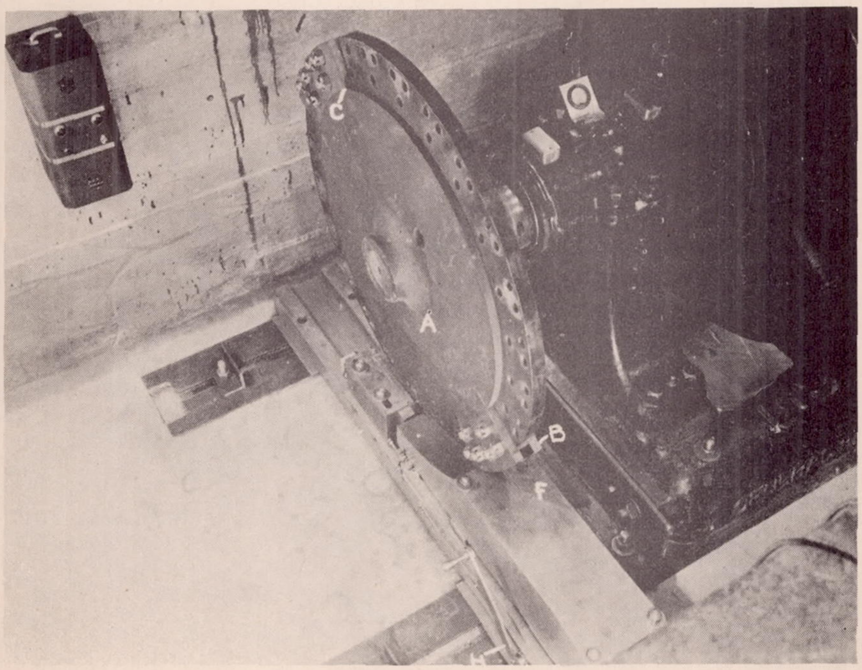

Figure 2.- Disc showing jaws and counter-weights.

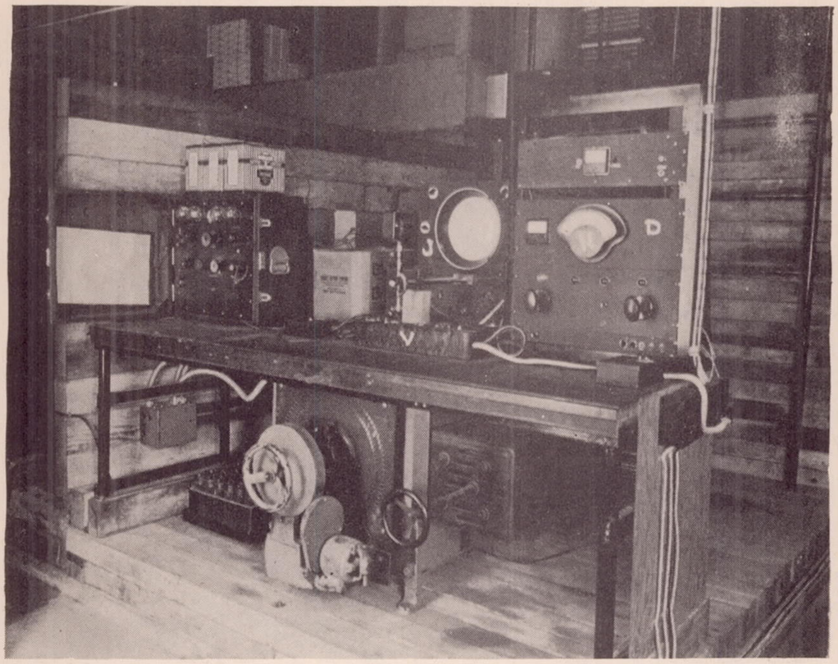

Figure 3.- Control panel and oscillograph.

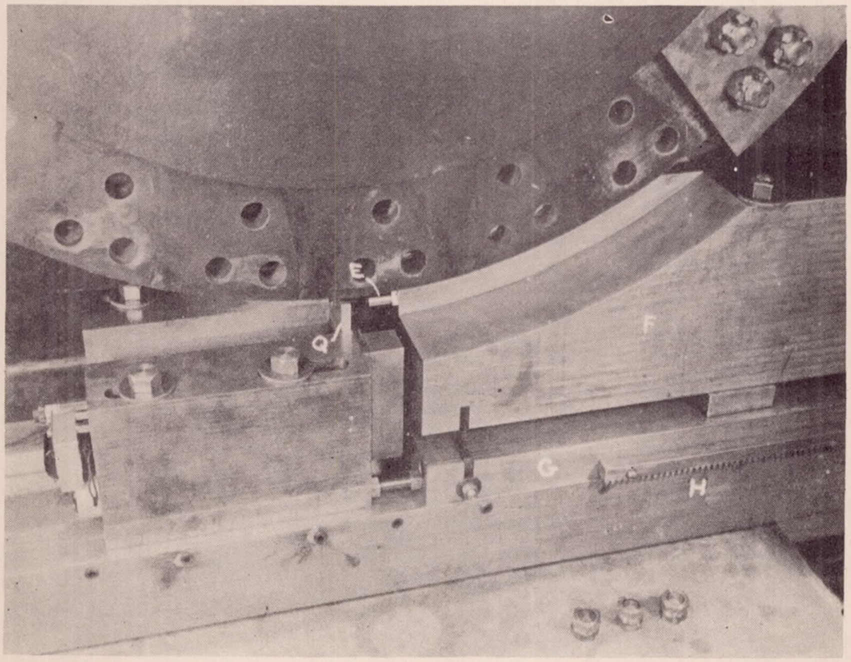

Figure 4.- Dynamometer, anvil, and striking jaws.

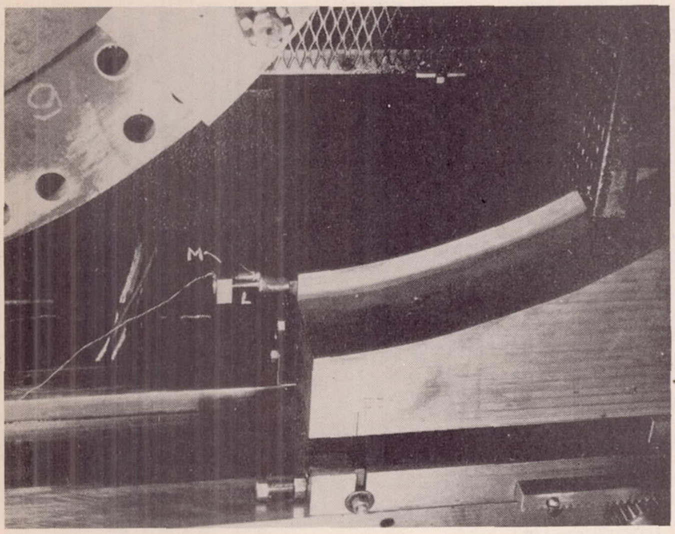

Figure 5.- Specimen, dynamometer, and extensometer.

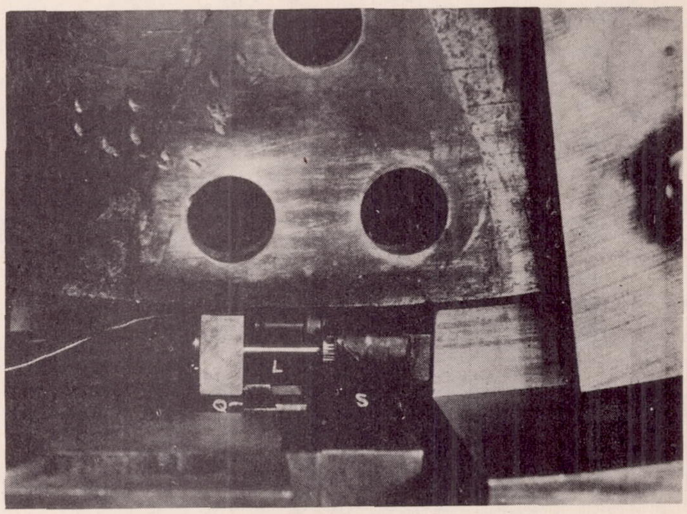

Figure 6.- Specimen, tup, and extensometer before impact.

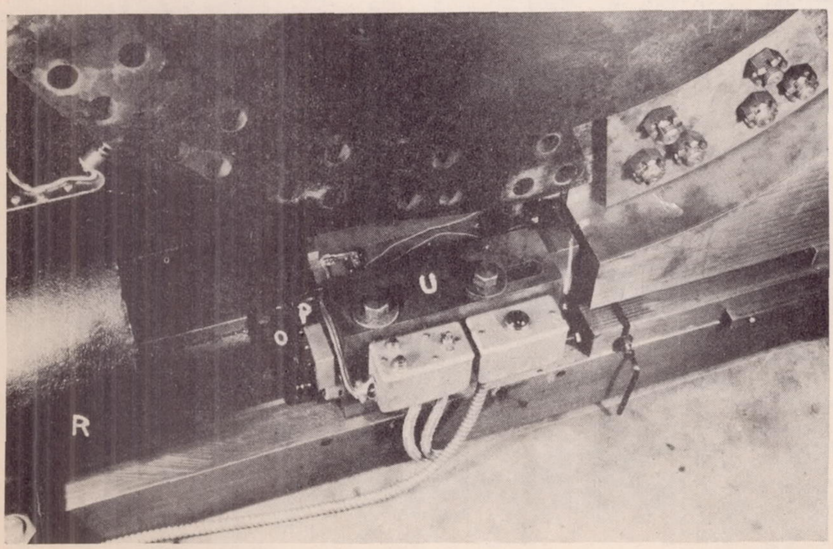

Figure 7.- Solenoid and trigger mechinism.

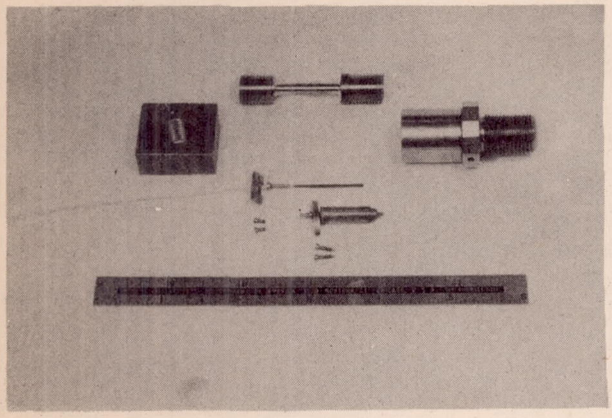

Figure 8.- Specimen, dynamometer, extensometer, tup (details).

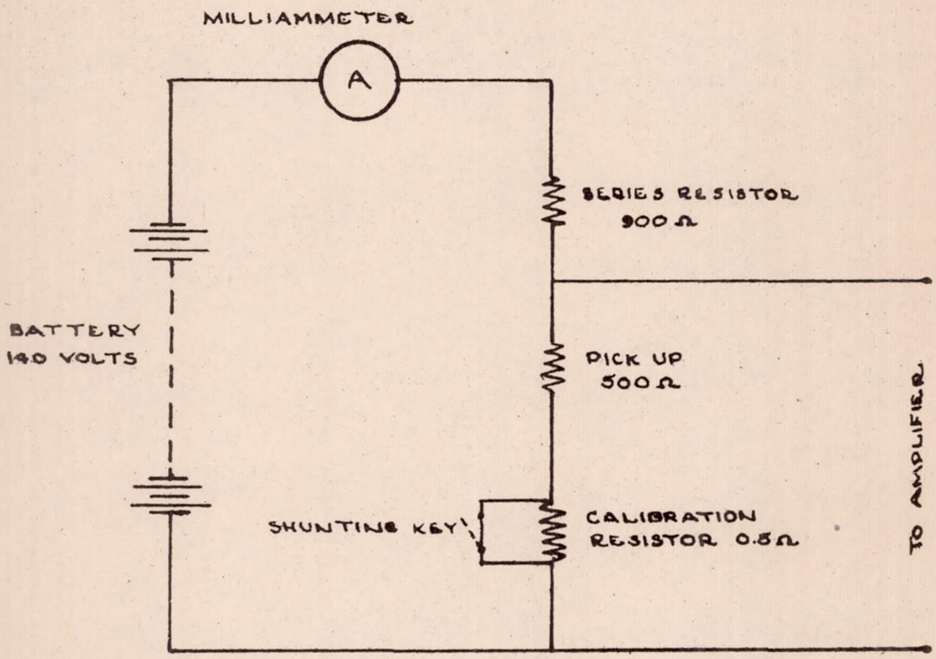

Figure 9.- Electrical circuit for dynamometer.

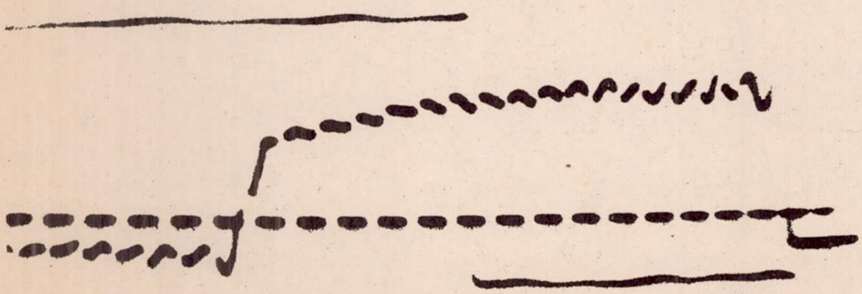

Figure 10.- Force-time elongation diagram (beginning of diagram at right).

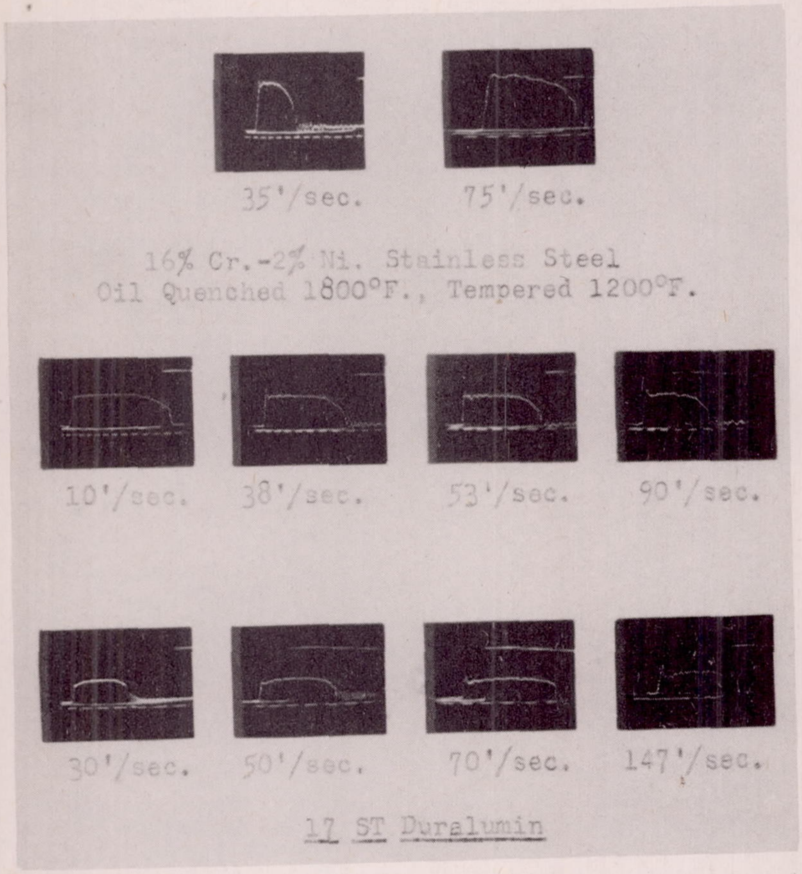

Figure 11.- Typical force-time diagrams.

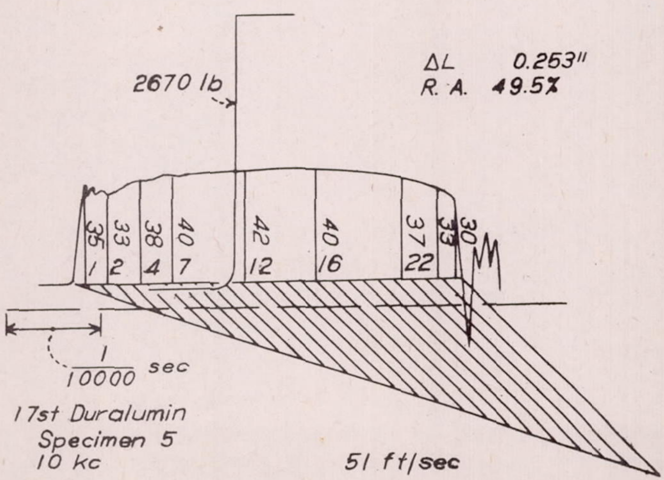

Figure 12.- Typical analysis of enlarged force-time diagram.

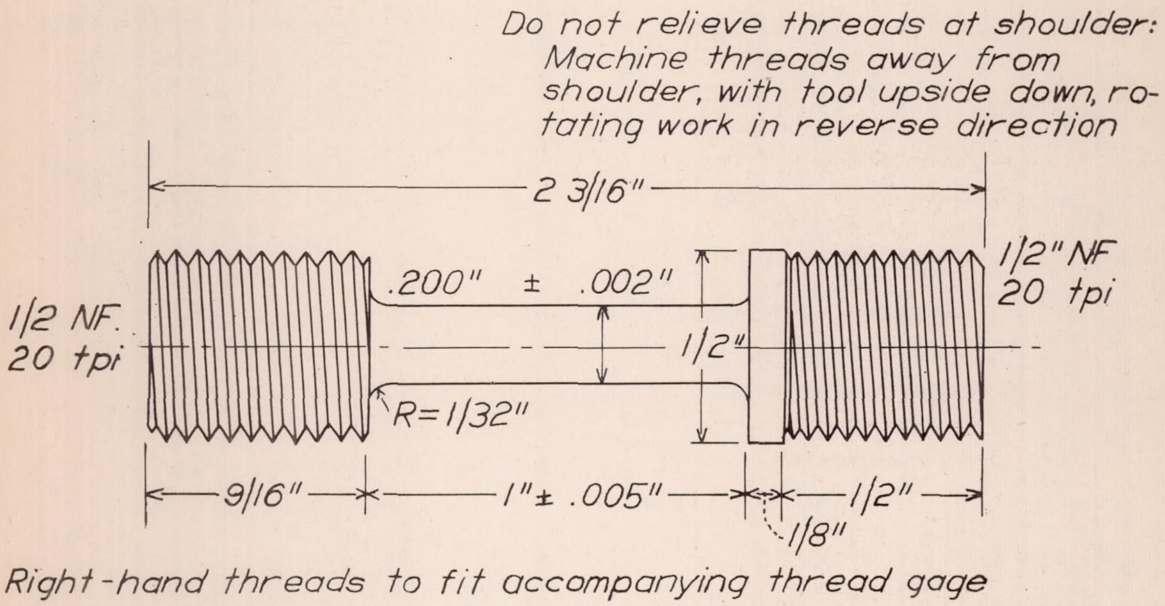

Figure 13.- Tension Specimens. Scale: twice full size.

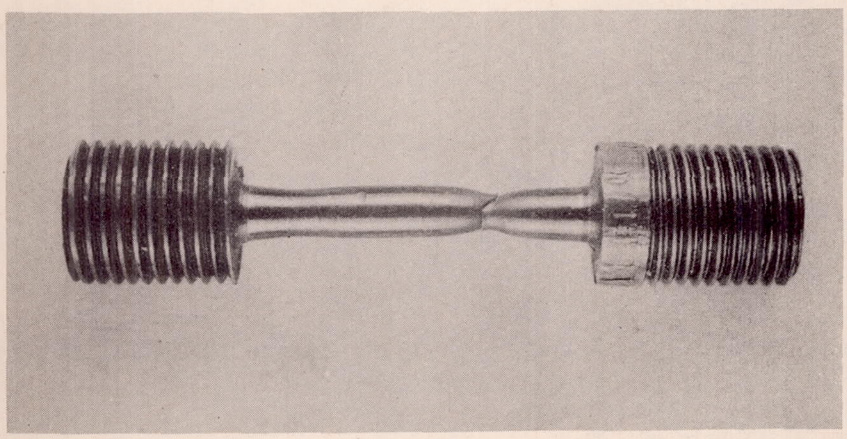

Figure 14.- Double necked specimen.

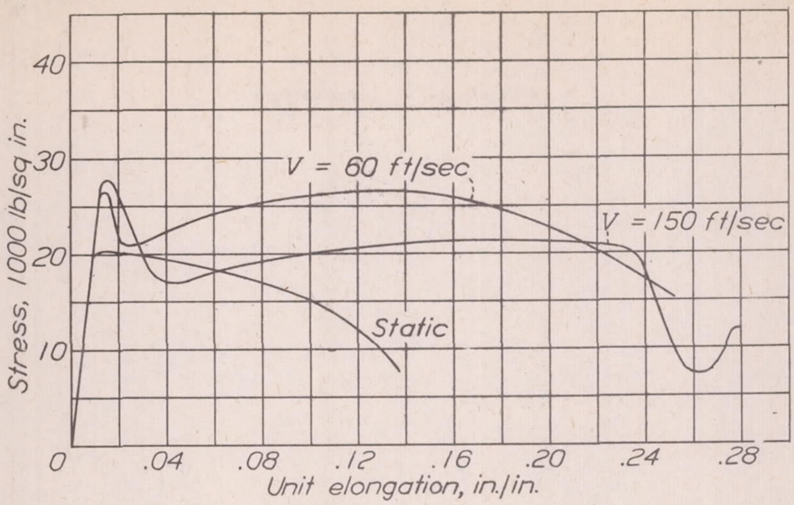

Figure 15.- Stress strain curves, aluminum.

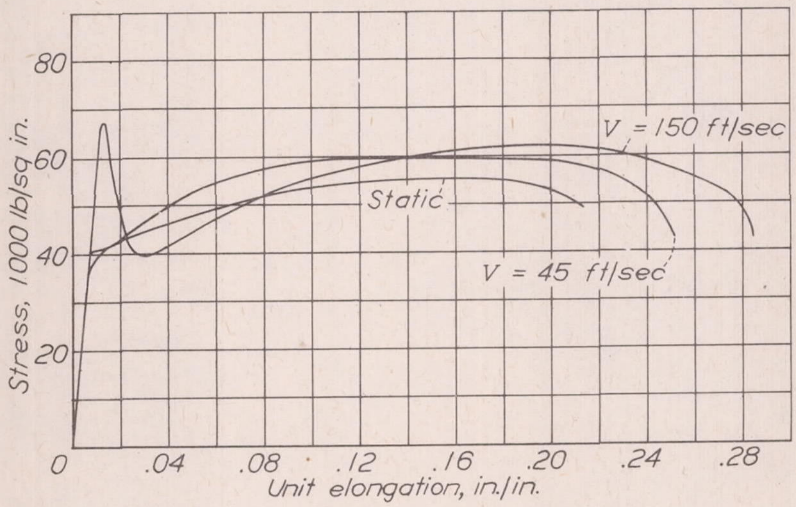

Figure 16.- Stress strain curves, 17ST duralumin.

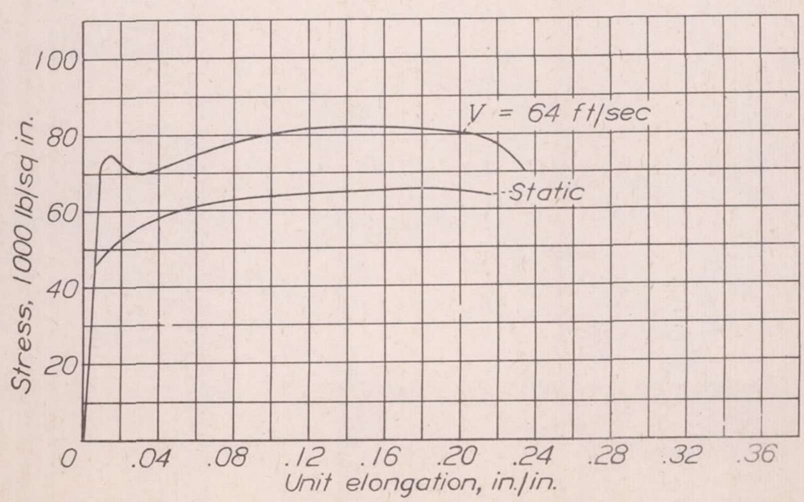

Figure 17.- Stress strain curves, 24ST aluminum alloy.

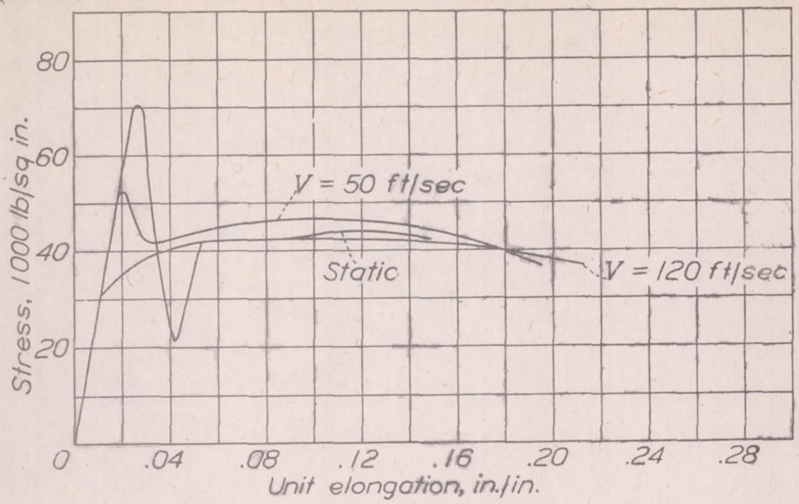

Figure 18.- Stress strain curves, Dow metal J.

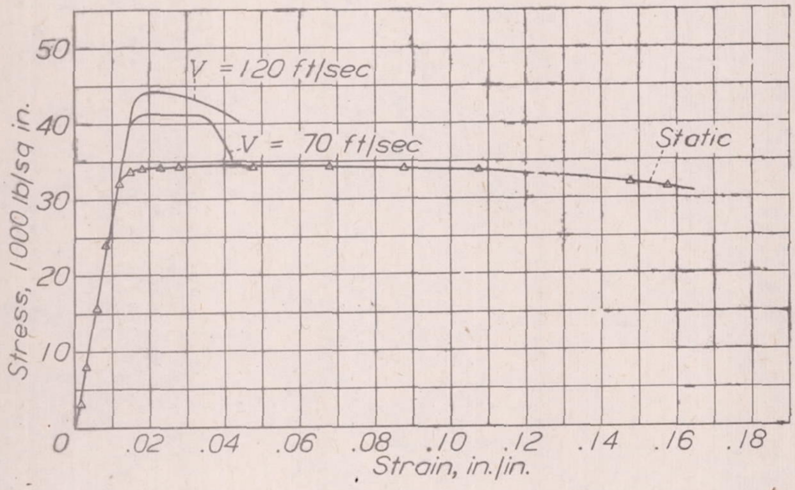

Figure 19.- Stress strain curves, Dow metal M.

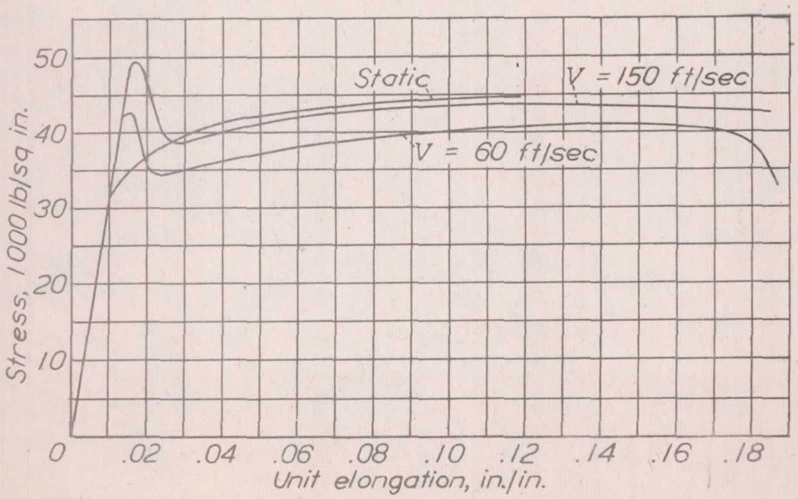

Figure 20.- Stress strain curves, Dow metal X.

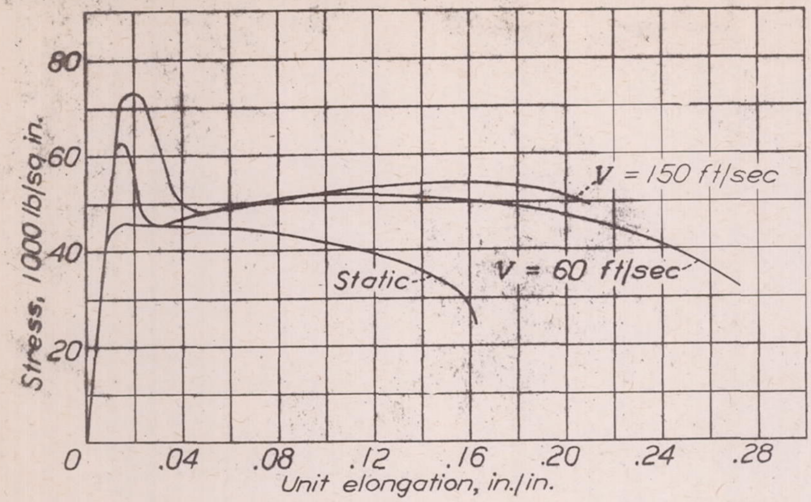

Figure 21.- Stress strain curves, copper.

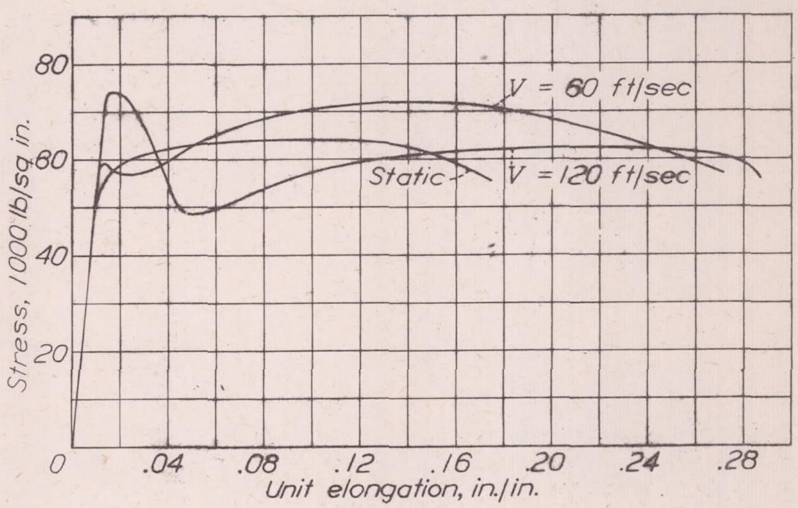

Figure 22.- Stress strain curves, brass.

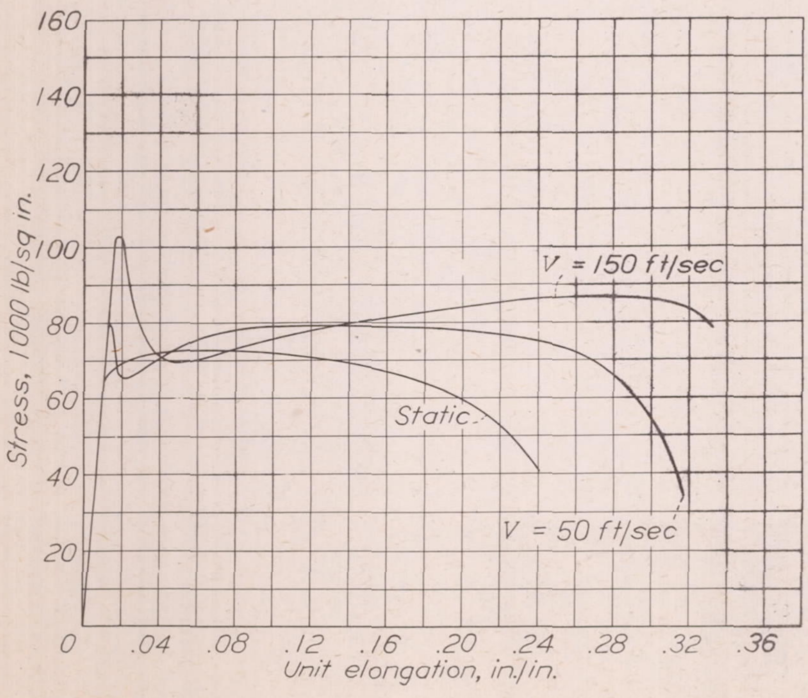

Figure 23.- Stress strain curves, silicon bronze.

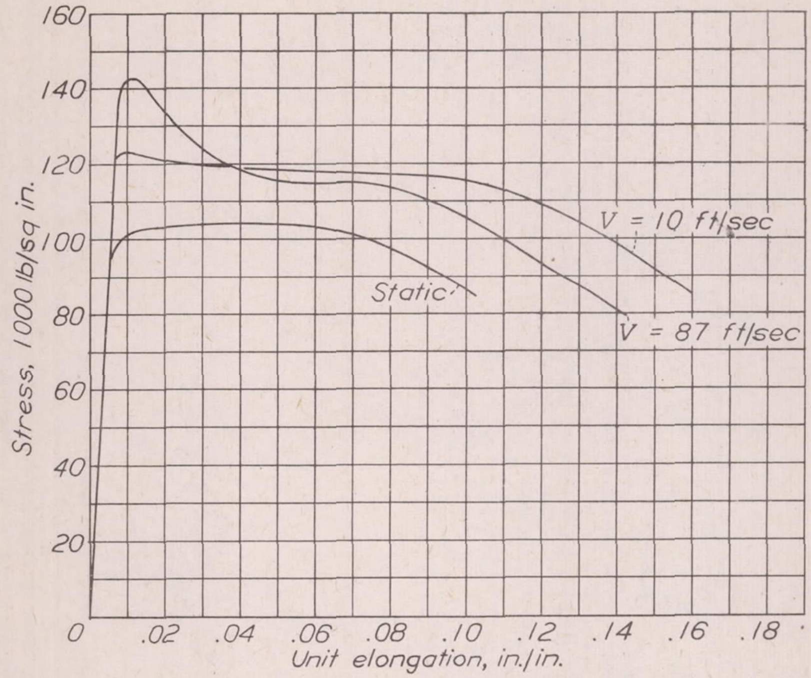

Figure 24.- Stress strain curves, SAE 1112 steel, cold drawn.

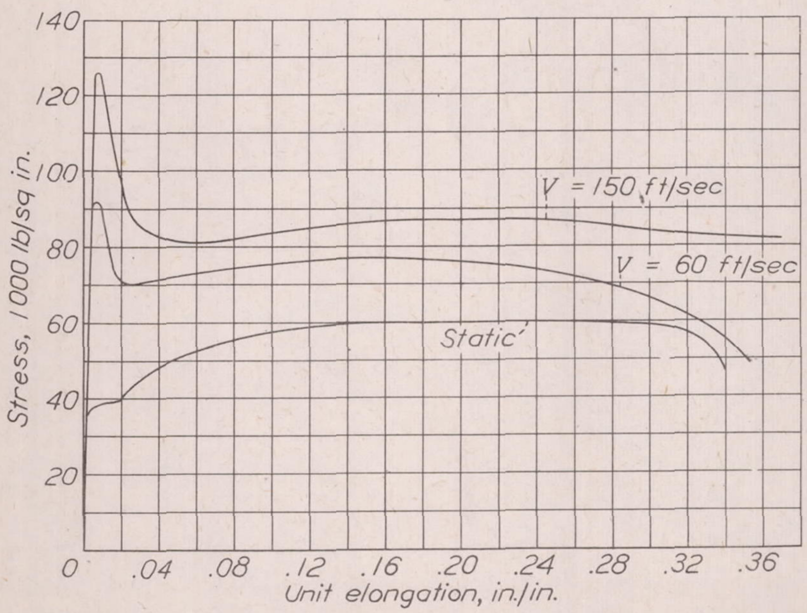

Figure 25.- Stress strain curves, hot rolled steel.

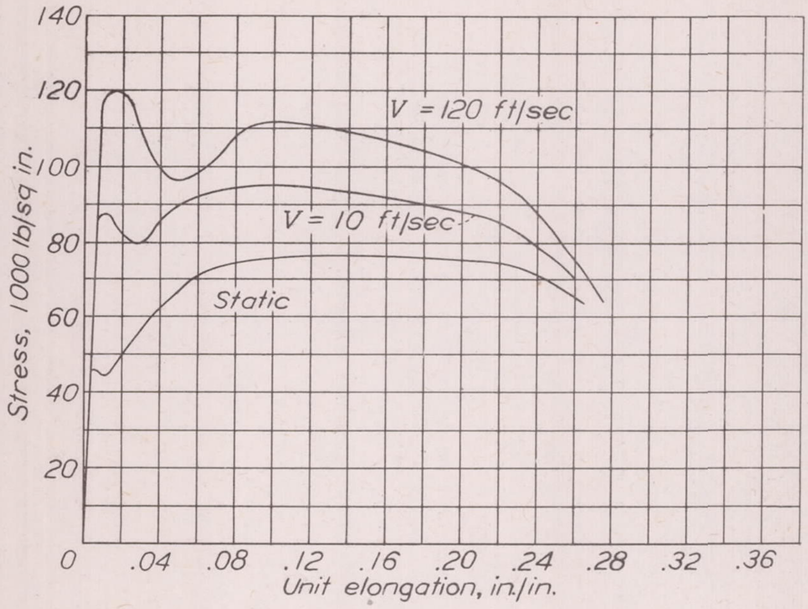

Figure 26.- Stress strain curves, SAE 1035 steel, fully annealed.

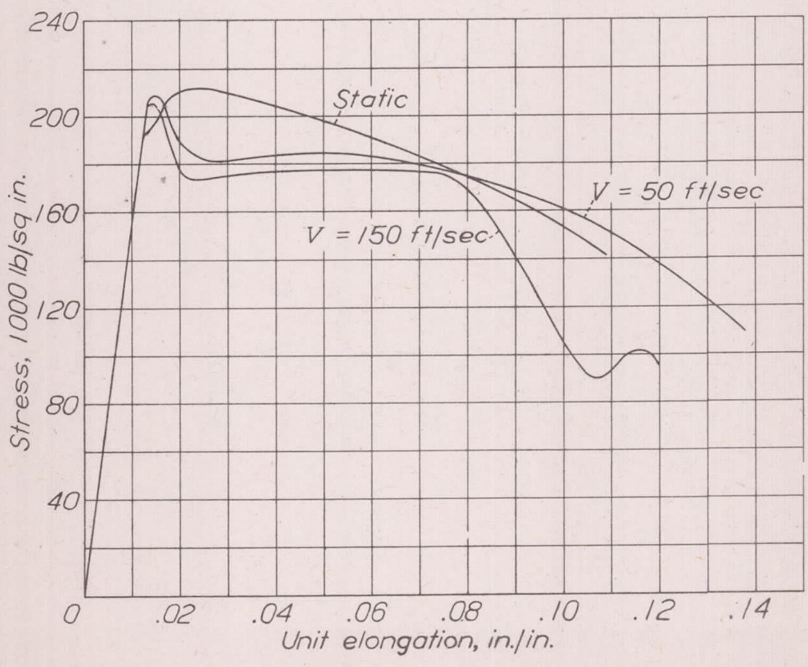

Figure 27.- Stress strain curves, SAE X4130, drawn 600°F.

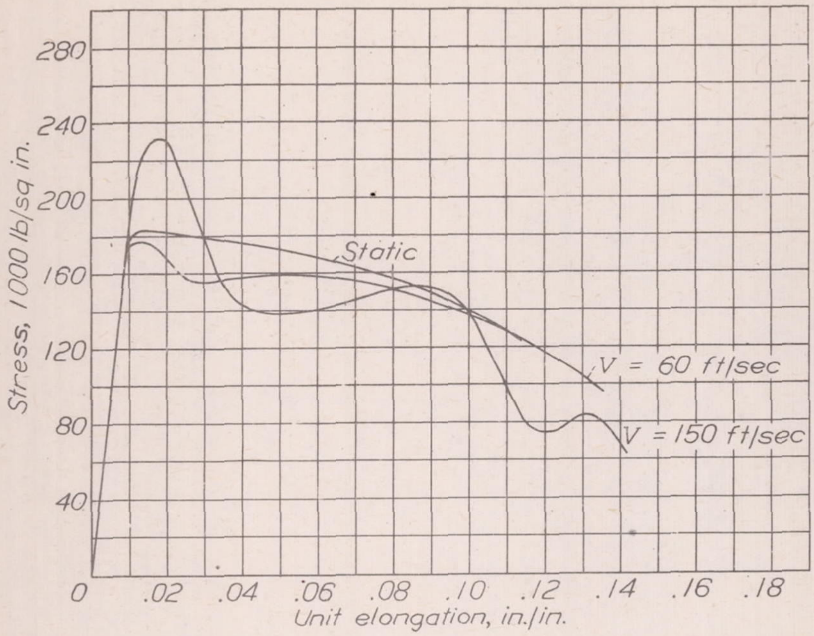

Figure 28.- Stress strain curves, SAE X4130, drawn 800°F.

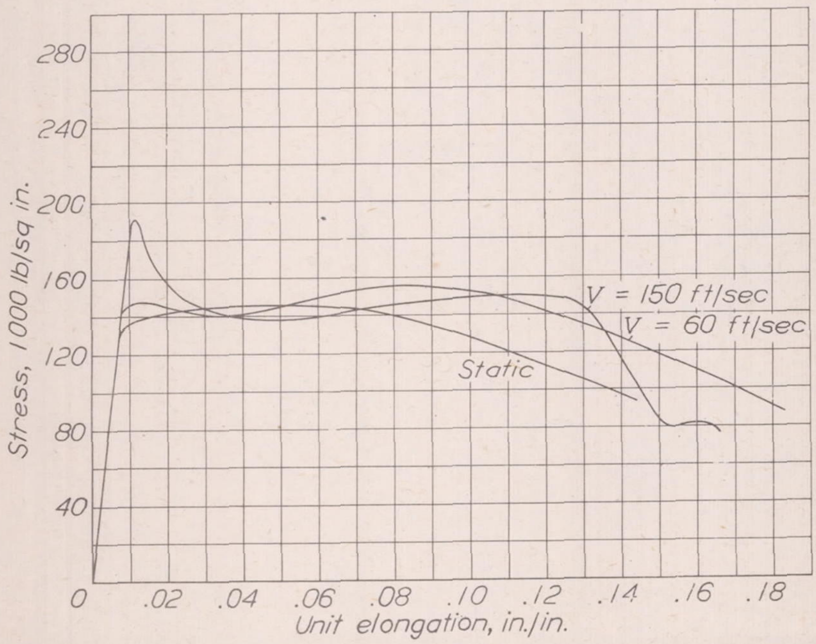

Figure 29.- Stress strain curves, SAE X4130, drawn 1000°F.

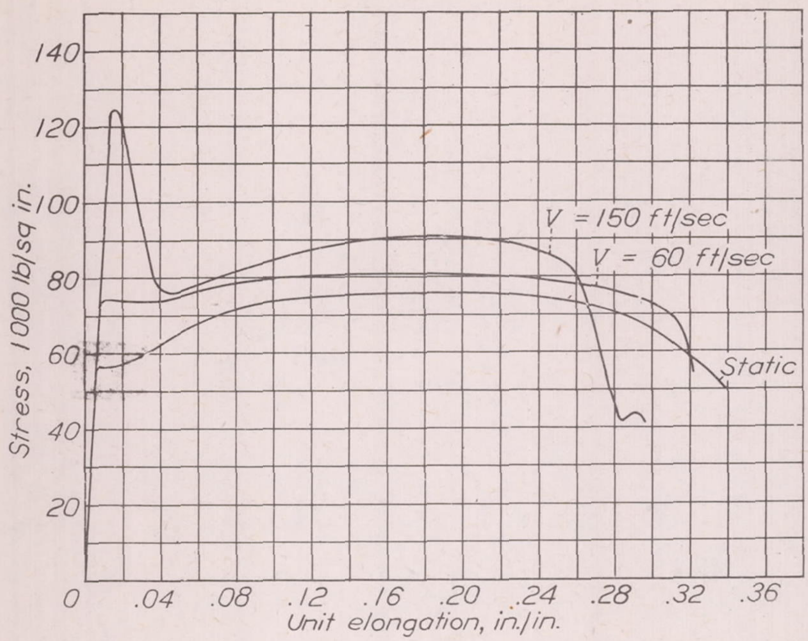

Figure 30.- Stress strain curves, SAE X4130 annealed.

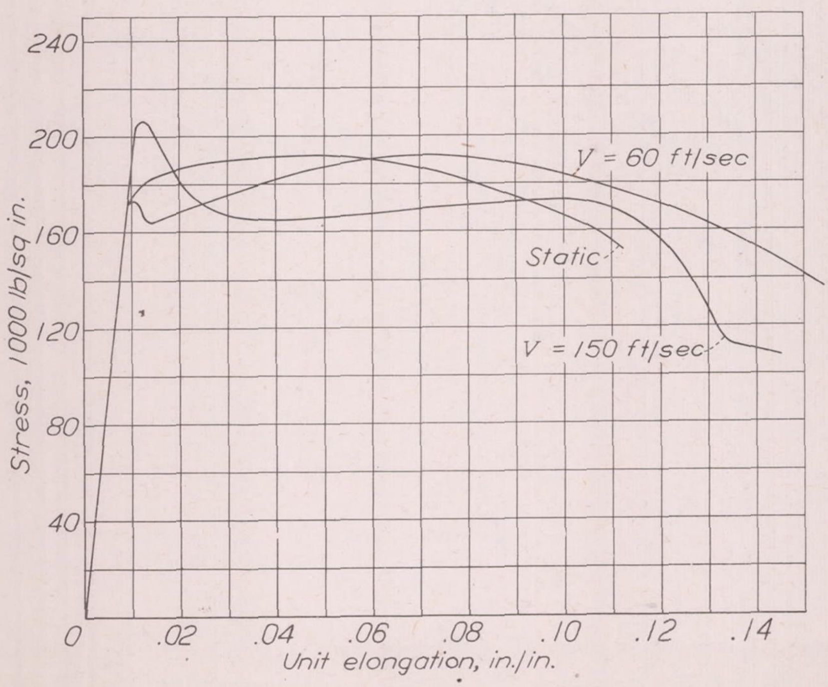

Figure 31.- Stress strain curves, SAE 6140, drawn 1020°F.

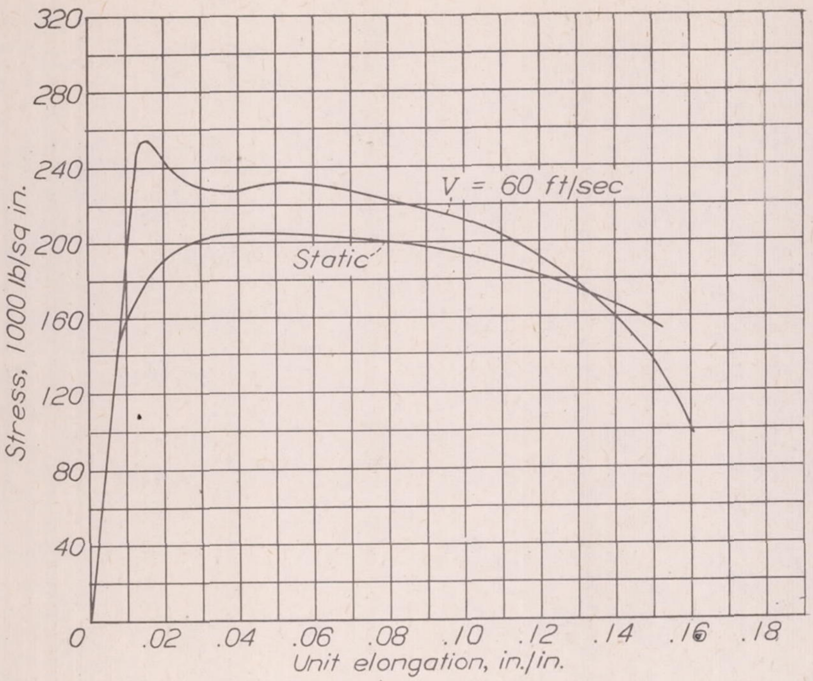

Figure 32.- Stress strain curves, 16-2 stainless steel, drawn 700°.

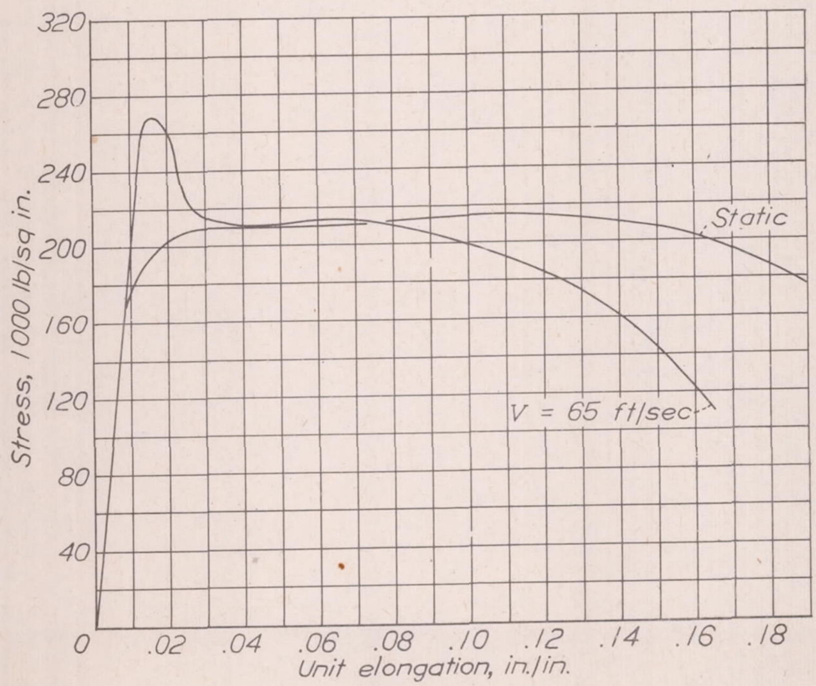

Figure 33.- Stress strain curves, 16-2 stainless steel, drawn 900°.

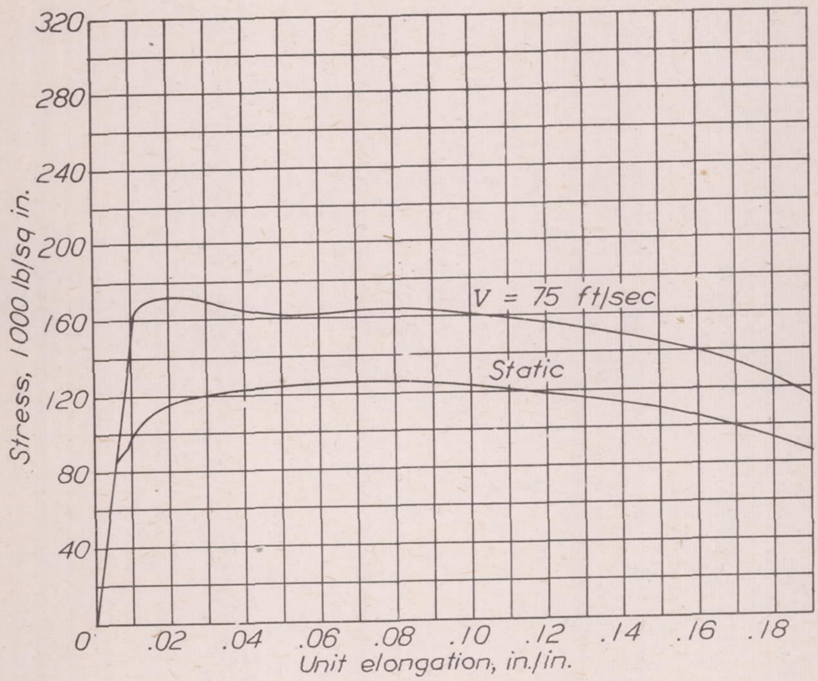

Figure 34.- Stress strain curves, 16-2 stainless steel, drawn 1200°.

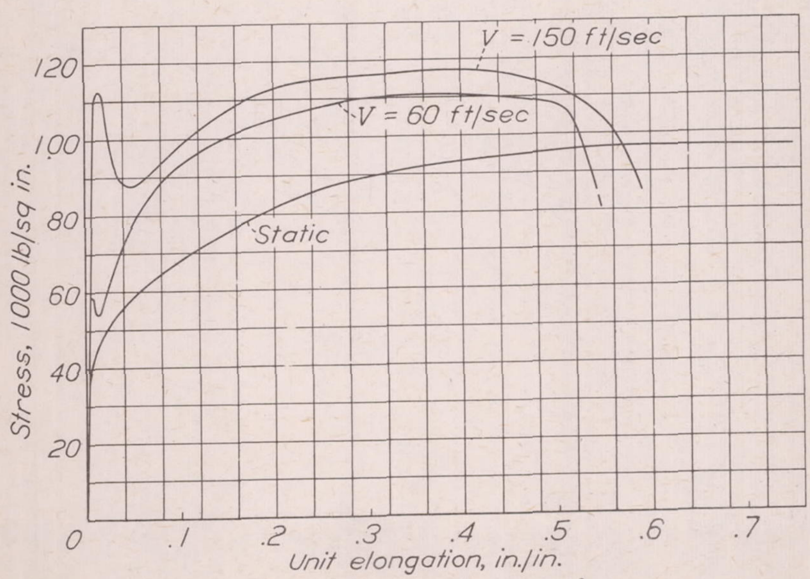

Figure 35.- Stress strain curves, 18-8 stainless steel.

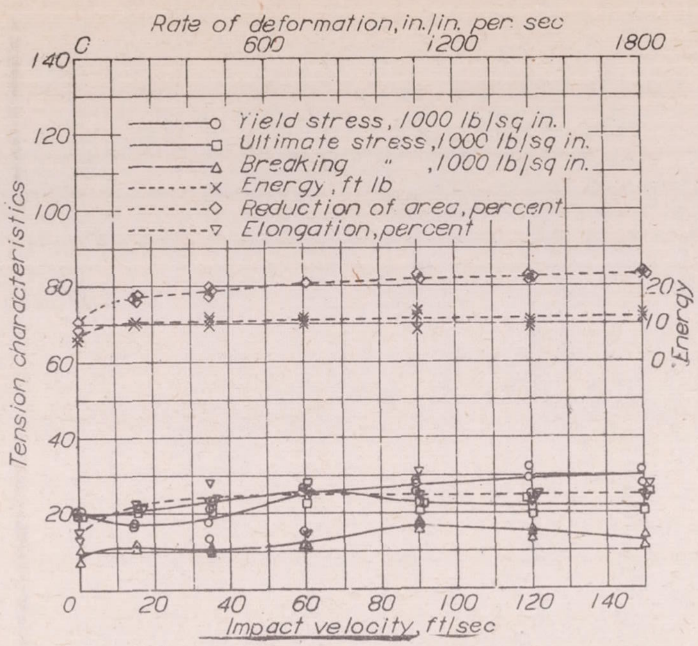

Figure 36.- Tension characteristics against impact velocity. Aluminum.

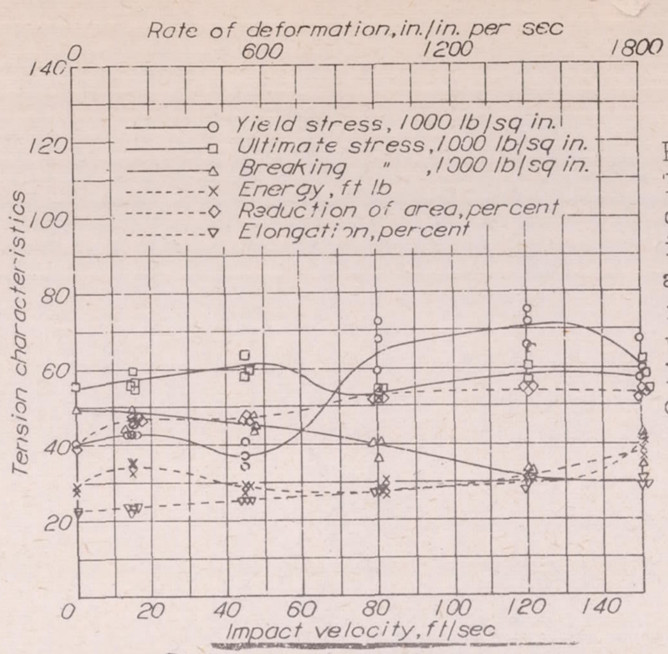

Figure 37.- Tension characteristics against impact velocity. 17ST duralumin.

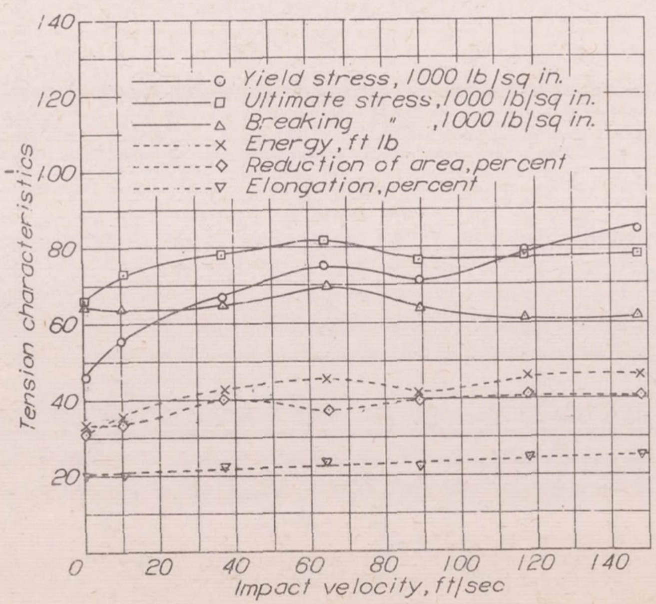

Figure 38.- Tension characteristics against impact velocity. 24ST aluminum alloy.

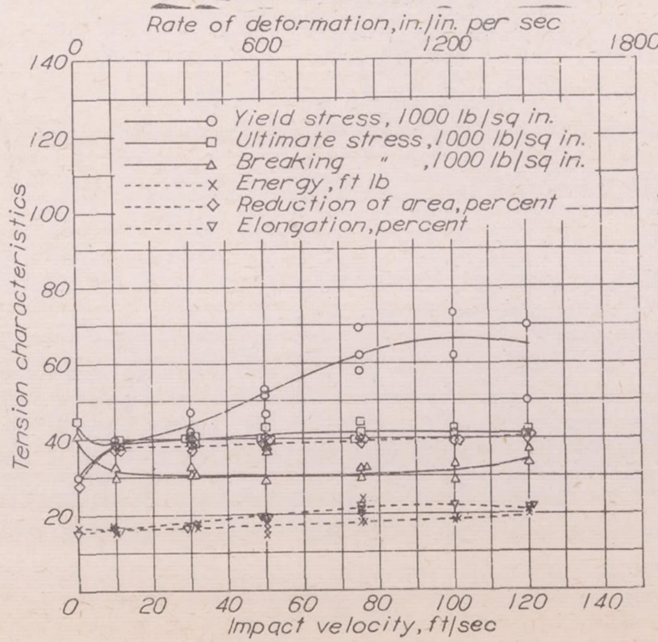

Figure 39.- Tension characteristics against impact velocity. Dow metal J.

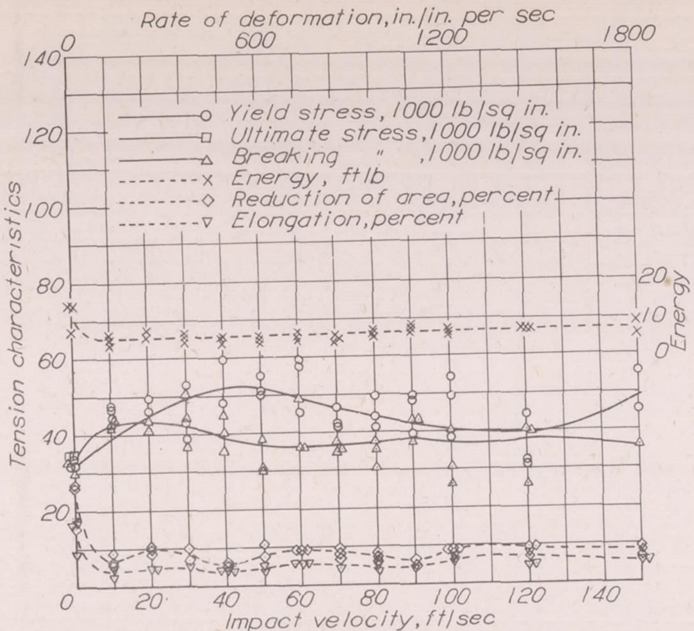

Figure 40.- Tension characteristics against impact velocity. Dow metal M.

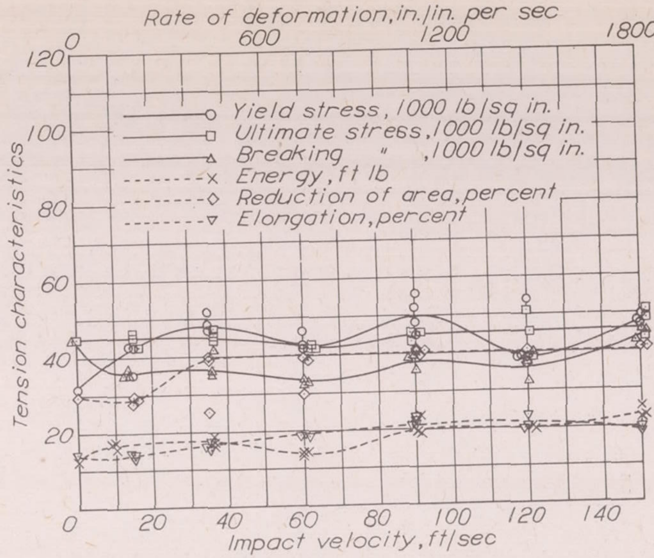

Figure 41.- Tension characteristics against impact velocity. Dow metal X.

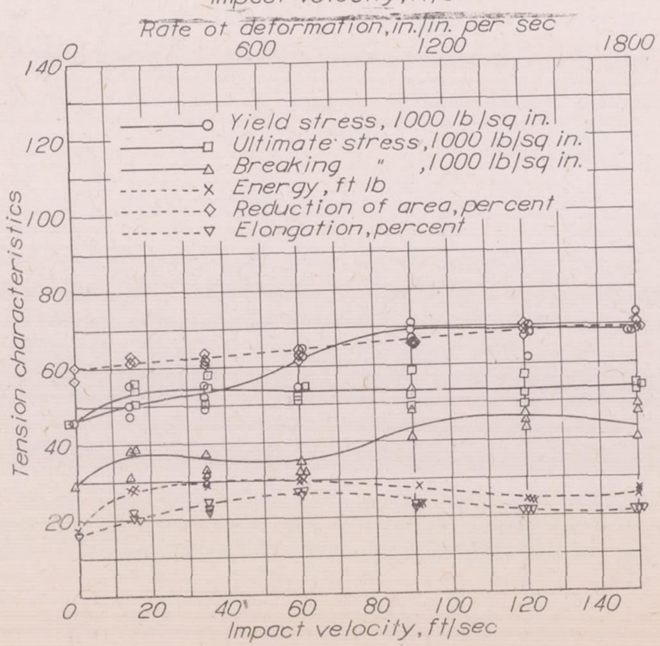

Figure 42.- Tension characteristics against impact velocity. Copper.

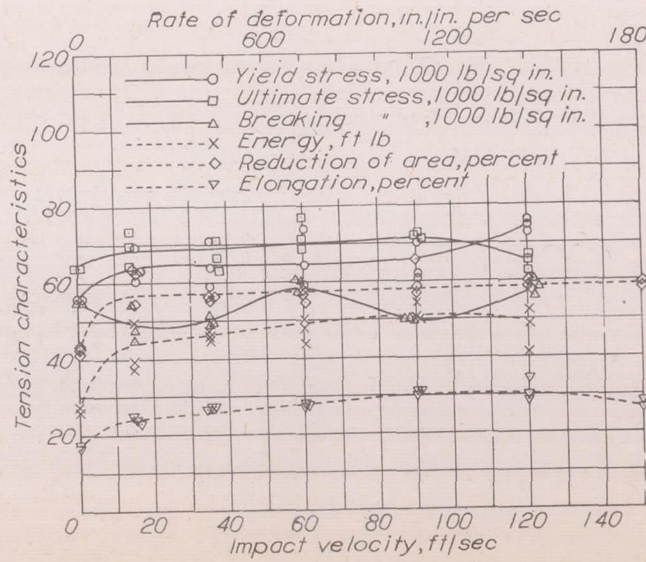

Figure 43.- Tension characteristics against impact velocity. Brass.

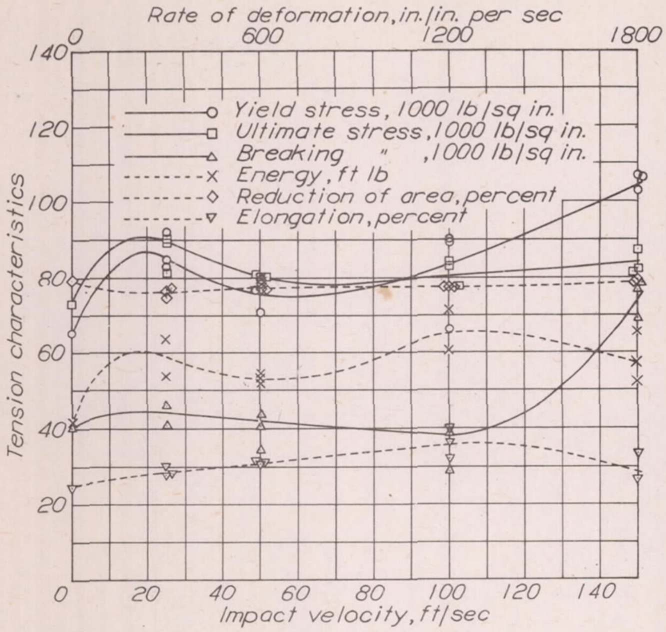

Figure 44.- Tension characteristics against impact velocity. Silicon bronze .

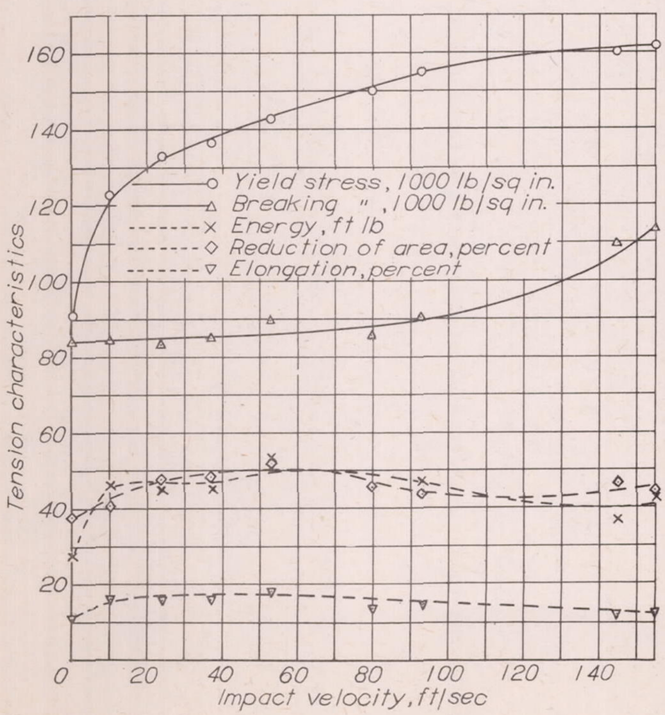

Figure 45.- Tension characteristics against impact velocity. SAE 1112 steel, cold drawn.

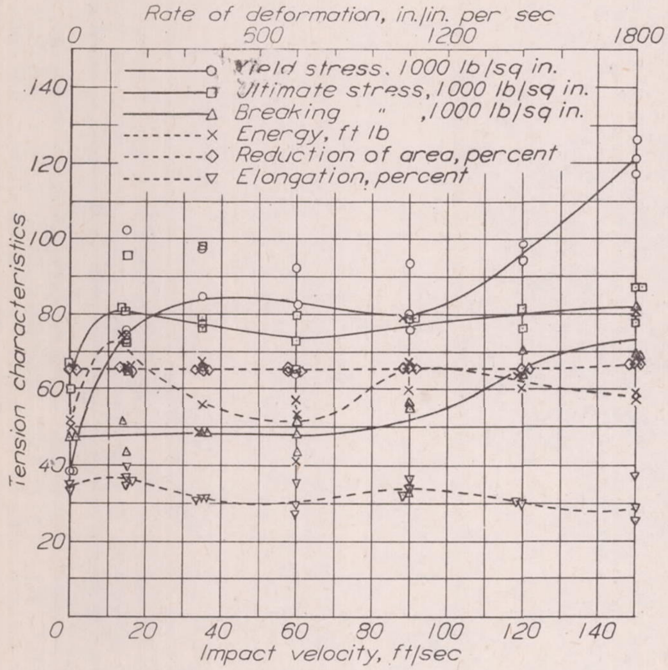

Figure 46.- Tension characteristics against impact velocity. Hot rolled steel.

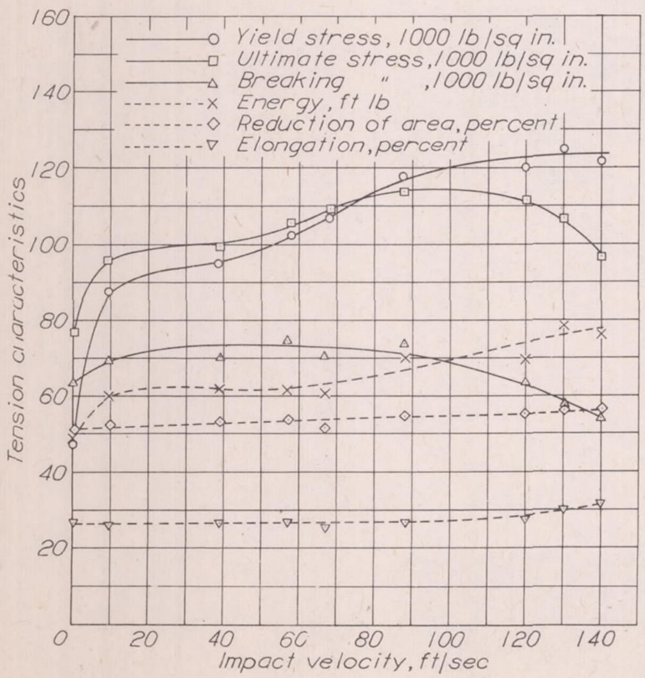

Figure 47.- Tension characteristics against impact velocity. SAE 1035 steel, fully annealed.

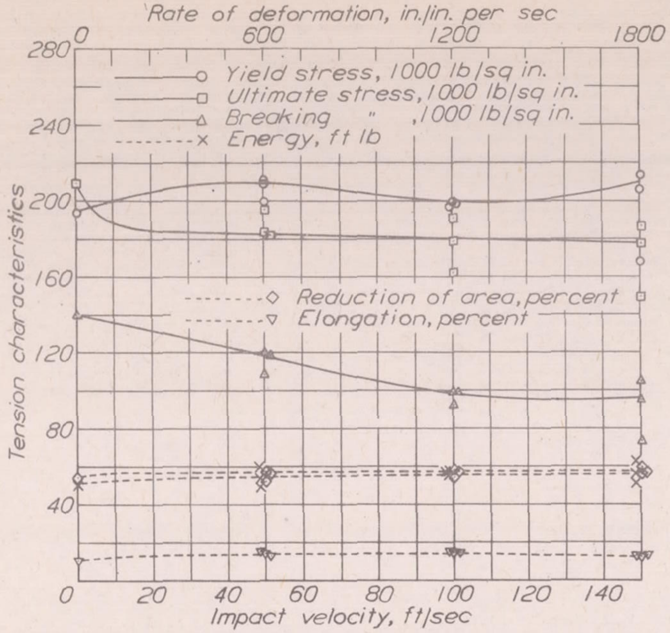

Figure 48.- Tension characteristics against impact velocity. SAE X4130 drawn 600°F

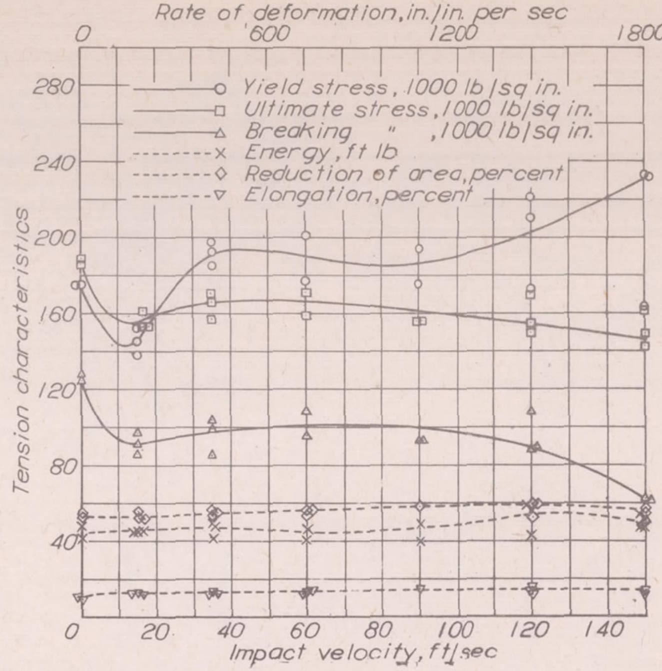

Figure 49.- Tension characteristics against impact velocity. SAE X4130 drawn 800°F.

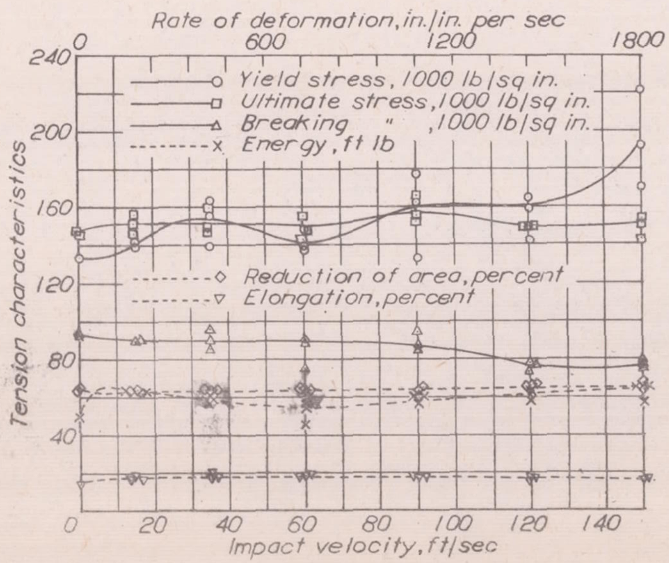

Figure 50.- Tension characteristics against impact velocity. SAE X4130 drawn 1000°F.

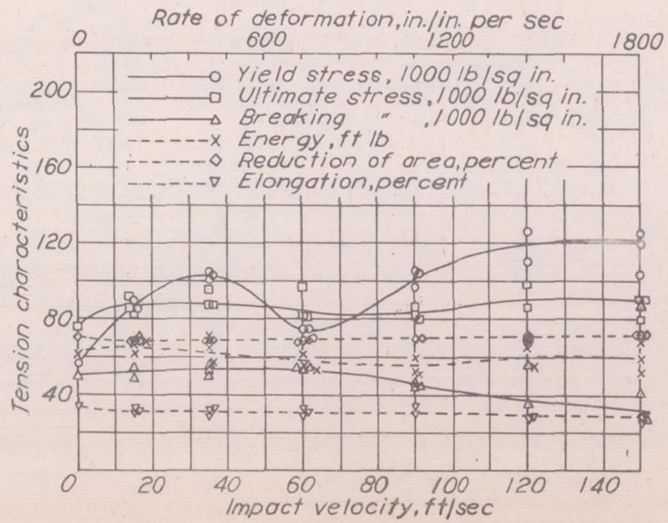

Figure 51.- Tension characteristics against impact velocity. SAE X4130 annealed.

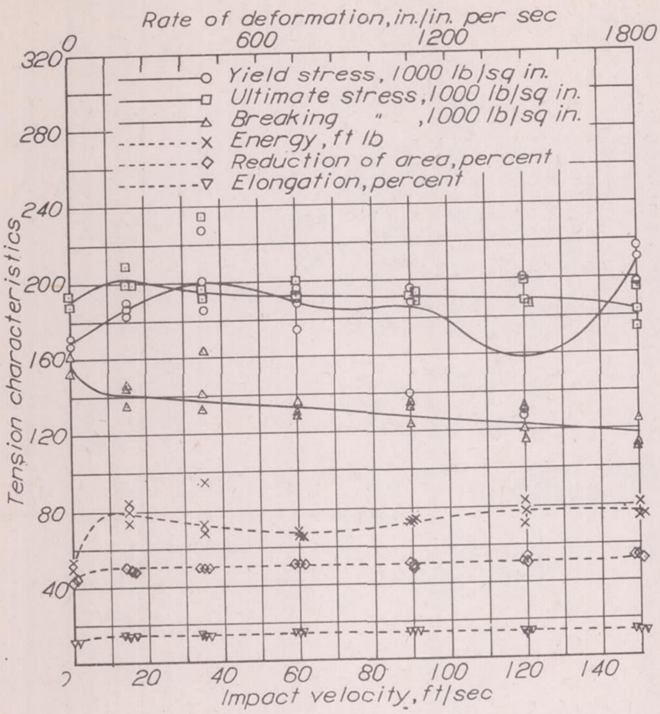

Figure 52.- Tension characteristics against impact velocity. SAE 6140 drawn 1020°F.

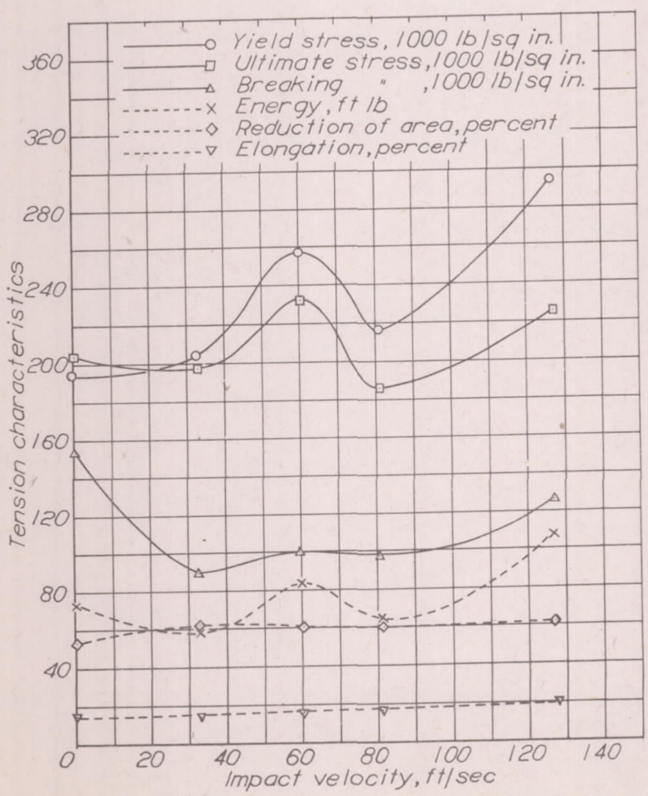

Figure 53.- Tension characteristics against impact velocity. 16-2 stainless steel, oil quenched, drawn 700°.

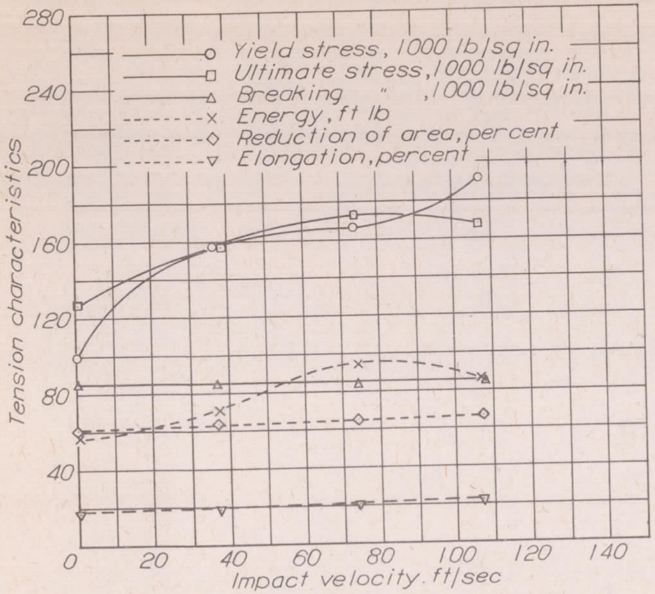

Figure 54.- Tension characteristics against impact velocity. 16-2 stainless steel, oil quenched, drawn 1200°

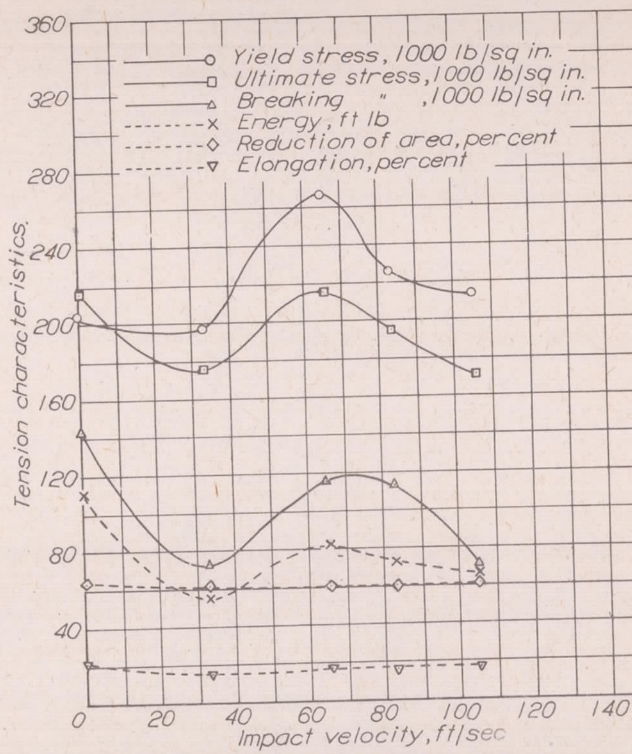

Figure 55.- Tension characteristics against impact velocity. 16-2 stainless steel, oil quenched, drawn 900°.

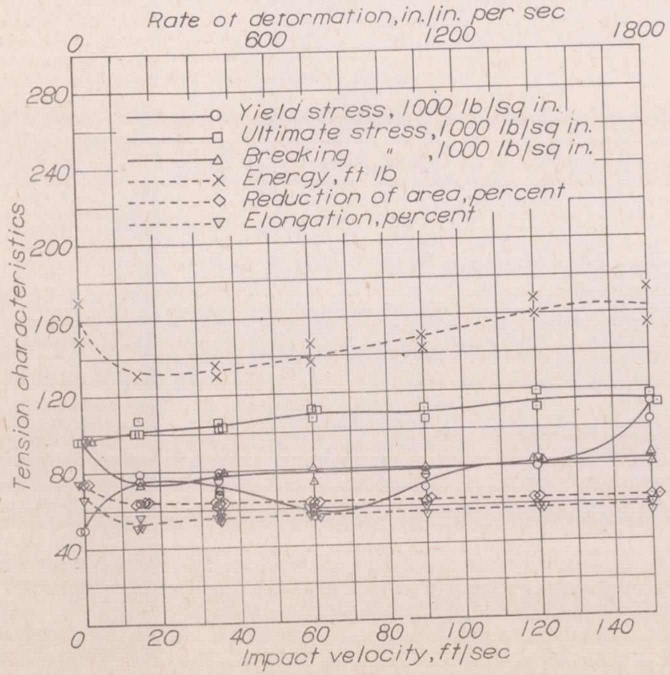

Figure 56.- Tension characteristics against impact velocity. 18-8 stainless steel.

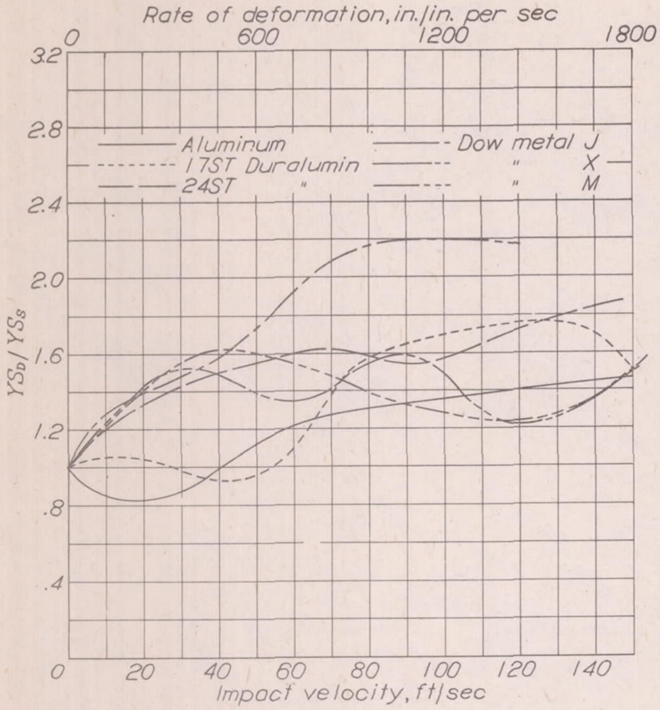

Figure 57a.- Ratio of dynamic to static yield stress against impact velocity. Aircraft materials.

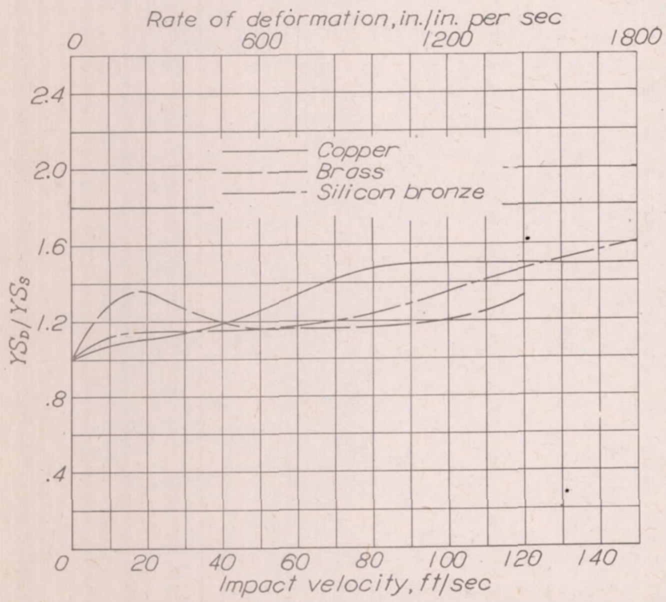

Figure 57b.- Ratio of dynamic to static yield stress against impact velocity. Copper and its alloys.

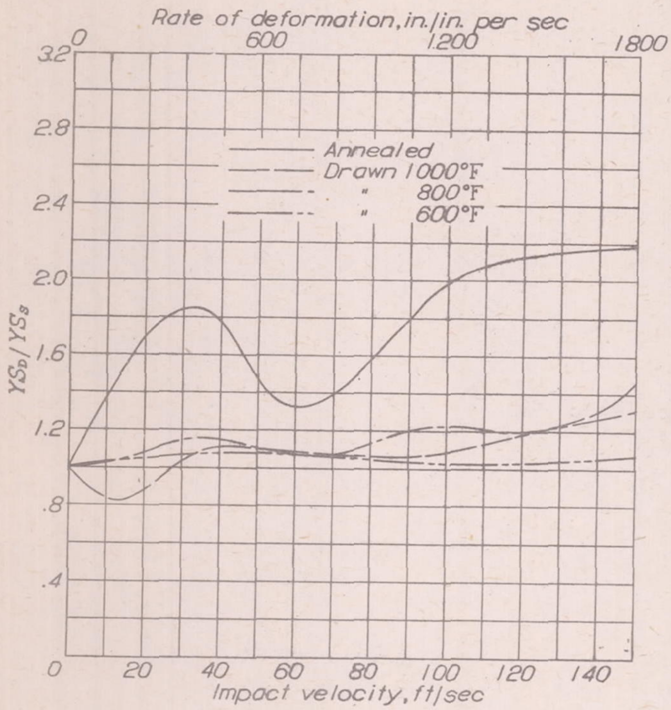

Figure 57c.- Ratio of dynamic to static yield stress against impact velocity. SAE X4130.

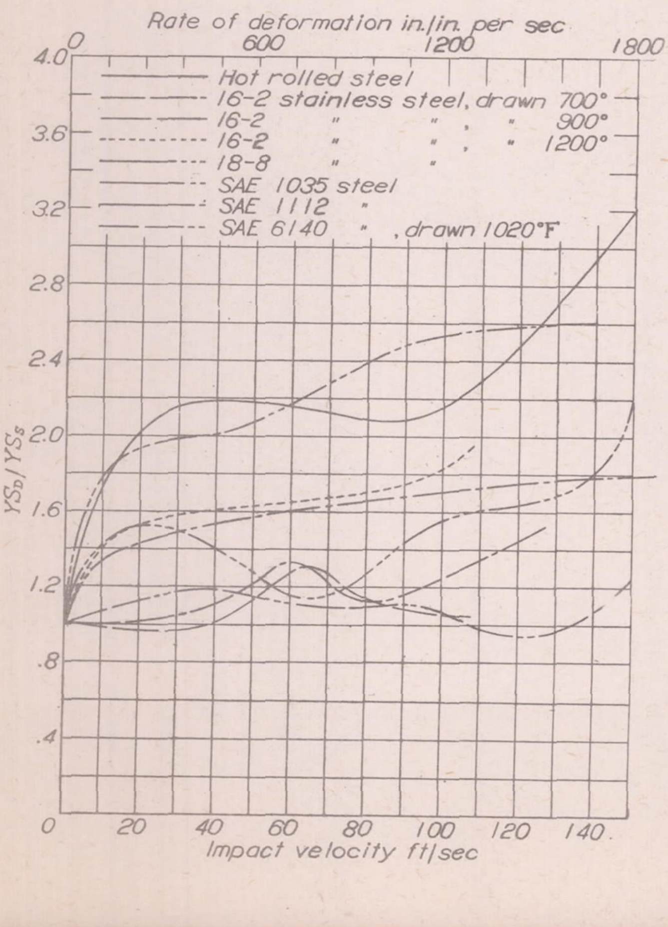

Figure 57d.- Ratio of dynamic to static yield stress against impact velocity. Miscellaneous steels.

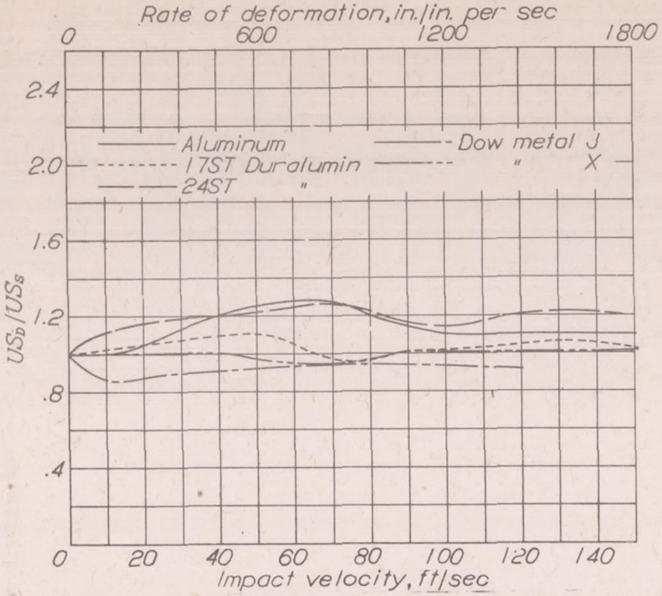

Figure 58a.- Ratio of dynamic to static ultimate stress against impact velocity. Aircraft materials.

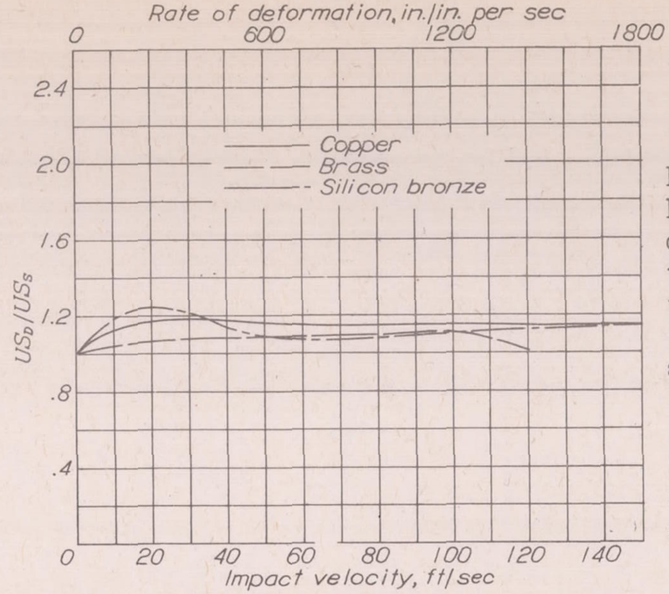

Figure 58b.- Ratio of dynamic to static ultimate stress against impact velocity. Copper and its alloys.

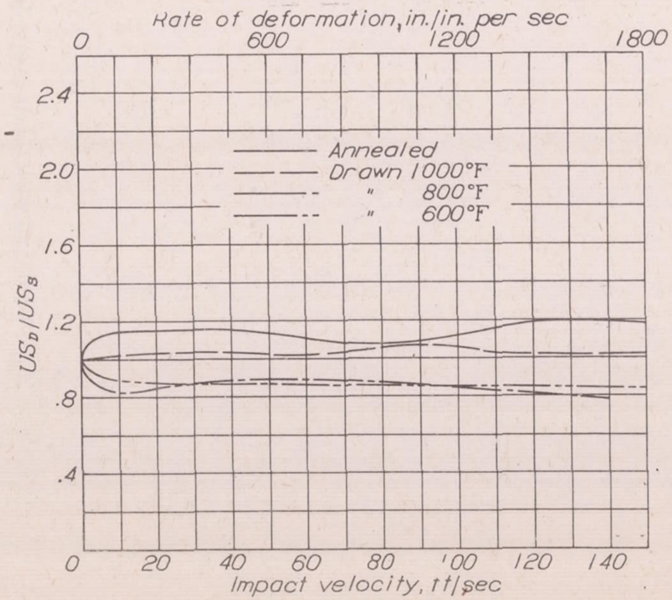

Figure 58c.- Ratio of dynamic to static ultimate stress against impact velocity. SAE X4130.

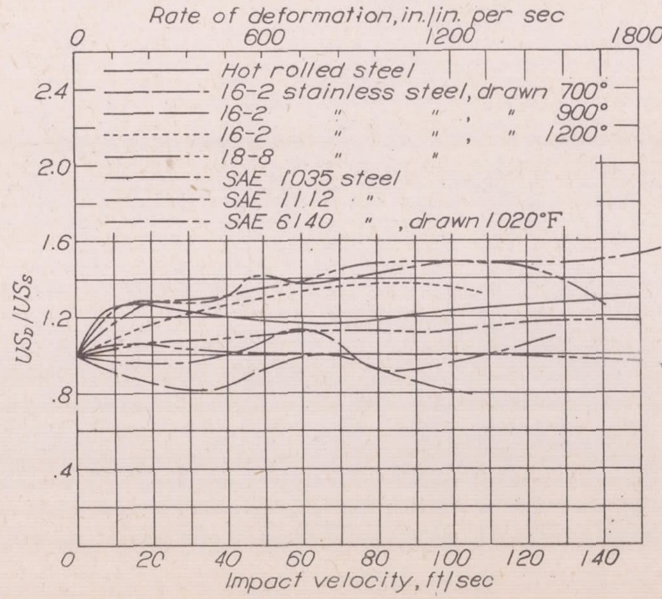

Figure 58d.- Ratio of dynamic to static ultimate stress against impact velocity. Miscellaneous steels.

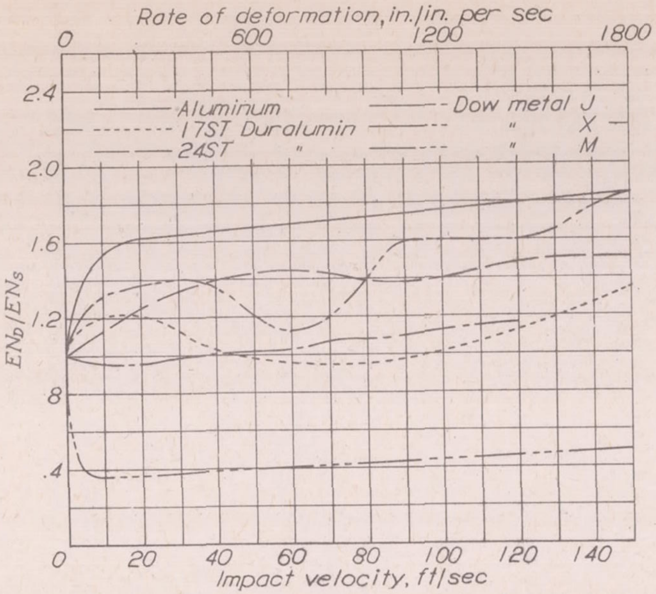

Figure 59a.- Ratio of dynamic to static energy against impact velocity. Aircraft materials.

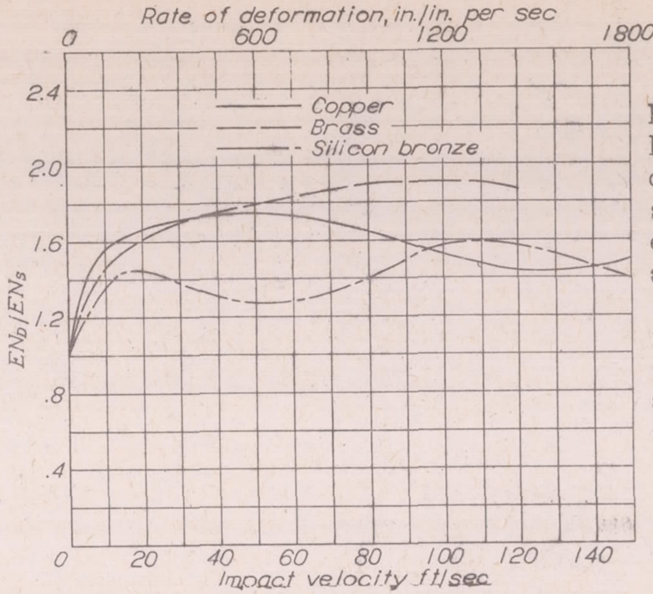

Figure 59b.- Ratio of dynamic to static energy against impact velocity. Copper and its alloys.

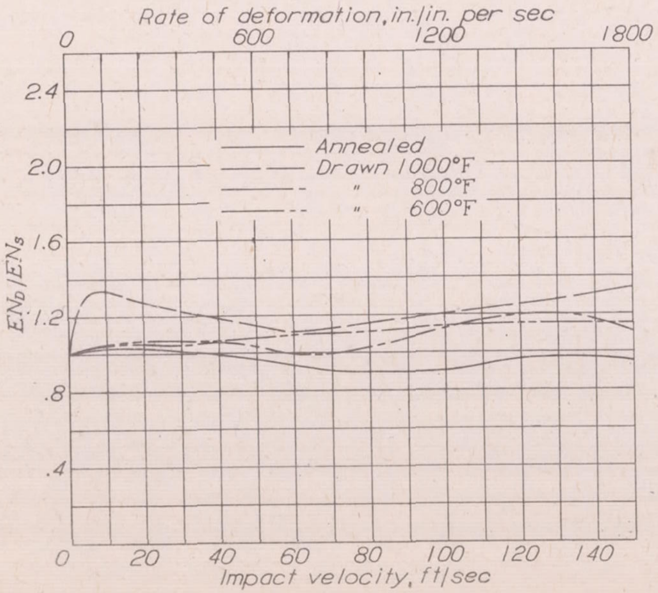

Figure 59c.- Ratio of dynamic to static energy against impact velocity. SAE X4130.

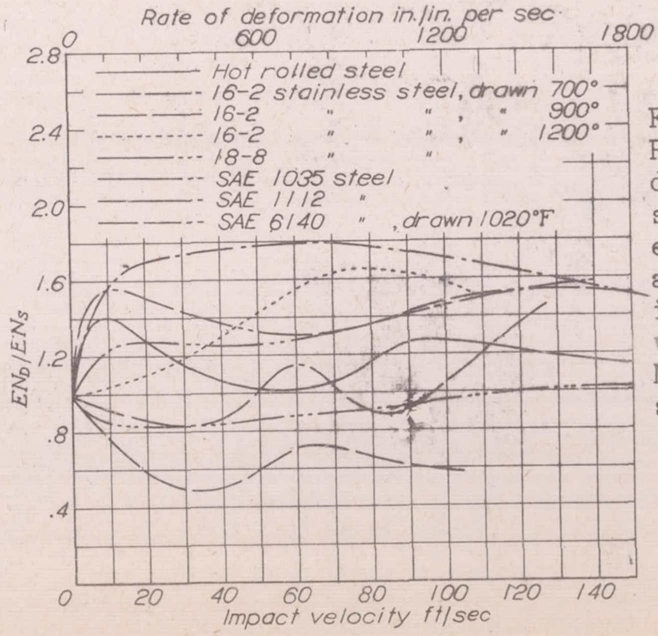

Figure 59d.- Ratio of dynamic to static energy against impact velocity. Miscellaneous steels.

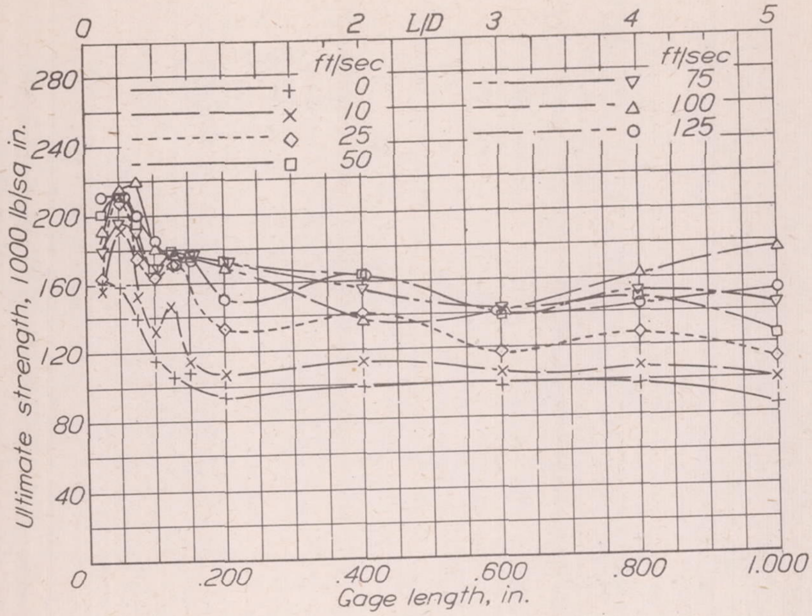

Figure 60.- Ultimate strength against gage length.

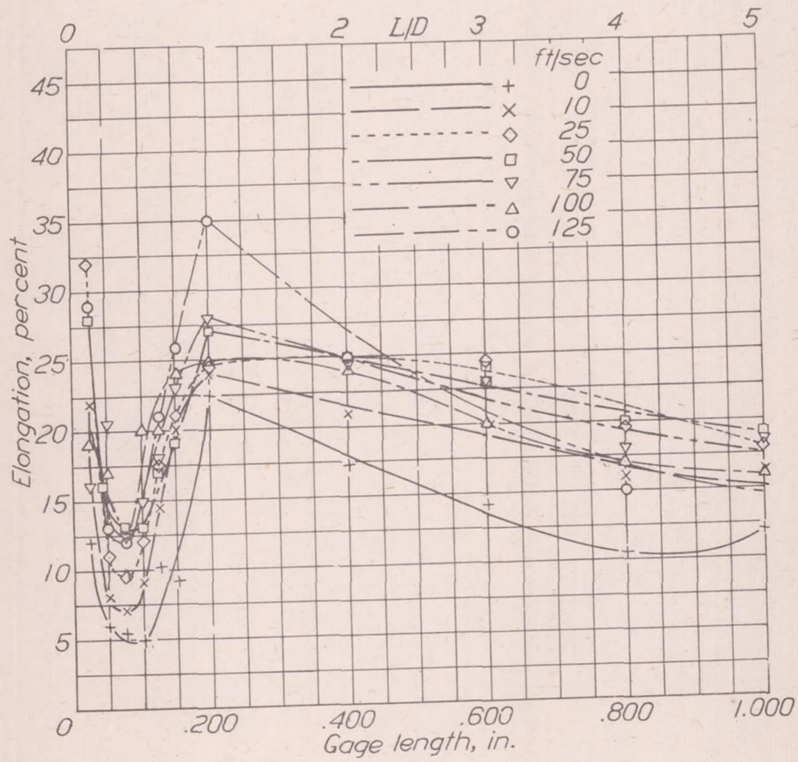

Figure 61.- Elongation against gage length.

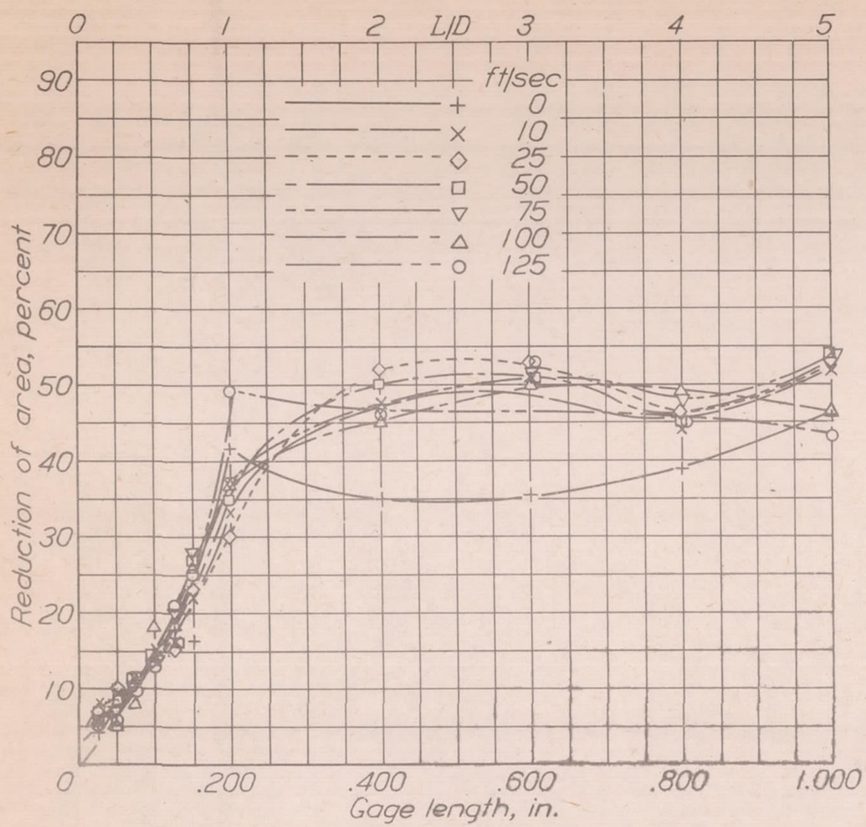

Figure 62.- Reduction of area against gage length.

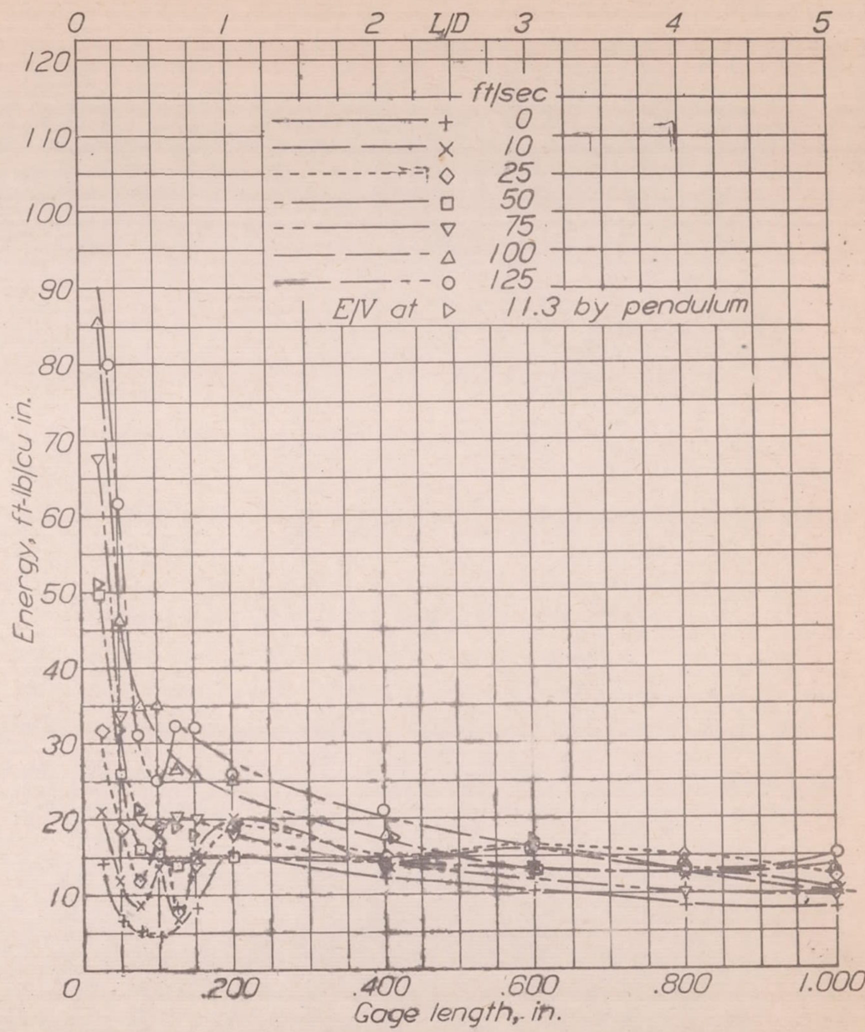

Figure 63.- Energy per unit volume against gage length.