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DYNAMIC COMPRESSIVE STRAIN RATE TESTS ON SEVERAL GRADES OF BERYLLIUM

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Air Force Materials Laboratory
Wright-Patterson Air Force Base, Ohio

November 1974

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Results of static and dynamic compression tests on several grades of beryllium and lockalloy are presented. A split Hopkinson pressure bar system, used to generate data at strain rates up to 10^3 sec^{-1}, is described in detail. Stress-strain curves show several different grades of beryllium to have a moderate amount of strain rate sensitivity in compression in the plastic region.

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FOREWORD

This report was prepared by the Metals Behavior Branch, Metals and Ceramics Division, under Project Number 7351, "Metallic Materials", Task Number 735106, "Behavior of Metals". The research work was carried out at the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, by Dr. T. Nicholas and Mr. M. J. Sever of the Metals Behavior Branch (AFML/LLN).

The authors would like to express their appreciation to Mr. J. Paine, Systems Research Laboratories Inc., Dayton, Ohio for his assistance in conducting the experimental tests and to Brush Wellman Inc., Cleveland, Ohio and Kawecki Berylco Industries, Hazelton, Pa., who furnished the test samples.

This report covers work performed from November 1973 to June 1974.

This report was released by the authors August 1974.

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INTRODUCTION

Numerous structural systems encounter operational environments which subject them to severe dynamic loading conditions. The proper design and analysis of such systems depends heavily on a knowledge of the dynamic mechanical response characteristics of the component materials. In applications where ring or shell type structures are subjected to blast or impulsive type loads, compressive stress-strain curves at the appropriate high strain rates are required. Unfortunately, such information is not always available in design manuals or in the technical literature.

An experimental technique which has been developed for obtaining compression stress-strain data at high strain rates is the split Hopkinson pressure bar technique. This method, developed by Kolsky in 1948 (Reference 1) has been used by numerous investigators to determine the mechanical response of a number of materials at compressive strain rates over 1000 sec^{-1}. The apparatus and the associated analysis are well documented in the literatures (Reference 2). In addition, a number of studies have been carried out to evaluate the assumptions and limitations of this experimental technique (References 3, 4, 5 and 6). It has been shown, in general, that valid dynamic stress-strain curves can be obtained for most materials if proper techniques are employed (Reference 6).

One material, which is receiving attention because of its high stiffness and light weight for potential application in aerospace structures subjected to dynamic loading, is beryllium. There are few data available on the dynamic response of the various commercially available beryllium grades. This investigation was undertaken to obtain such data and to study the strain-rate sensitivity of several existing and some new grades of beryllium. The materials investigated consisted of berylliums consolidated by both hot pressing and cold isostatic pressing followed by hot isostatic pressing (CIP/HIP) and include higher purity materials, cross-rolled plate, and a beryllium-aluminum alloy, lockalloy.

This report presents the results of static and dynamic compression tests along with a complete description of the apparatus and instrumentation used in the experimental investigation. The data are presented in the form of compression stress-strain curves at strain rates of 10^{-3} and 10^{3} sec^{-1}.

SECTION II
DESCRIPTION OF APPARATUS

The apparatus and instrumentation used in this investigation are shown schematically in Figure 1. The split Hopkinson pressure bar system consists of a 4' long striker bar, incident and transmitter bars, each 10' long, and the electronic instrumentation used for recording the data. The ½" diameter steel bars are mounted in teflon bushings which assure accurate axial alignment while permitting stress waves to pass without dispersion. The specimen is sandwiched between the incident and transmitter bars.

The striker bar is accelerated using the energy stored in a 7' long torsion spring. The bar is drawn back against the torque in the spring by means of a hydraulic actuator. At a preset drawback a pin is sheared releasing the stored energy and accelerating the bar. Two circumferential grooves machined in the bar at a spacing of 0.5 in. pass through a magnetic pickup, generating two pulses which are in turn fed into a time interval counter to allow the calculation of the striker bar velocity.

When the striker bar impacts the incident bar, constant amplitude compressive pulses are generated in both bars. The length or duration of the compressive pulse generated in the incident bar is twice the wave transit time in the striker bar and the magnitude is directly proportional to the striker velocity.

When the compressive pulse in the incident bar reaches the specimen, part of it is transmitted through the specimen and part reflected due to the mis-match in cross-sectional area and acoustic impedance between the bar and the specimen. The area and mechanical behavior of the specimen determine the exact shape of the reflected and transmitted pulses. Knowledge of the strain-time history of a travelling pulse at some point along the bar obtained from strain gages allows one to deduce the strain-time history at the end of a bar. This is the basic principle of the Hopkinson bar and depends upon the knowledge of the longitudinal wave speed to shift the pulse in time and the assumption of non-dispersive elastic waves in the pressure bars.

SECTION III
ANALYSIS

Derivations of the equations governing this experiment have been presented many times in the literature (see Reference 2 for example). The equations are presented here for the sake of completeness.

Figure 2 shows the specimen sandwiched between the two bars. The incident, reflected and transmitted waves are defined as ε_i, ε_r, and ε_t respectively. The displacements, u, at any time t of the two ends of the specimen are given by

$$u_1 = \int_0^t c_o \varepsilon_1 dt$$
$$u_2 = \int_0^t c_o \varepsilon_2 dt \qquad (1)$$

where subscripts 1 and 2 refer to the two ends of the specimen as shown in Figure 2, c_o is the elastic wave velocity for longitudinal waves in the pressure bars, and ε is the longitudinal strain. In terms of the strain pulses travelling through the bars:

$$u_1 = c_o \int_0^t (\varepsilon_i - \varepsilon_r) dt$$
$$u_2 = c_o \int_0^t \varepsilon_t dt \qquad (2)$$

Average strain in the specimen is defined as the change in length of the specimen divided by its length, L:

$$\varepsilon_s = \frac{u_1 - u_2}{L} \qquad (3)$$

Using equations (2), specimen strain reduces to

$$\varepsilon_s = \frac{c_o}{L} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) dt \qquad (4)$$

If P_1 is the load on face #1, and P_2 is the load on face #2 then, in terms of the pulses in the bar:

$$P_1 = EA(\varepsilon_i+\varepsilon_r)$$
$$P_2 = EA\ \varepsilon_t \tag{5}$$

where it is noted that ε_r is a pulse travelling in the opposite direction of ε_i and ε_t. The average load on the specimen can be expressed as

$$P_{av} = \frac{EA}{2}(\varepsilon_i+\varepsilon_r+\varepsilon_t) \tag{6}$$

The wave transit time in the short specimen is assumed to be small compared to the total time of the entire test, thus many wave reflections take place in the specimen. It is assumed, therefore, that a state of constant stress occurs along the length of the specimen at any time. Since the input and transmitter bars are of the same material and cross-sectional area, the incident, reflected and transmitted waves can then be related by virtue of equation (5)

$$\varepsilon_i + \varepsilon_r = \varepsilon_t \tag{7}$$

Using equations (4) and (7), the strain in the specimen can now be expressed

$$\varepsilon_s = \frac{c_o}{L}\int_o^t(\varepsilon_t-\varepsilon_r-\varepsilon_r-\varepsilon_t)dt \tag{8}$$

which simplifies to

$$\varepsilon_s = \frac{-2c_o}{L}\int_o^t \varepsilon_r dt \tag{9}$$

The average stress in the specimens is then obtained from equations (6) and (7)

$$\sigma_s = E(\frac{A}{A_s})\varepsilon_t \tag{10}$$

where E and A are the modulus of elasticity and cross-sectional area of the pressure bars, and A_s is the area of the specimen. If both sides of equation (9) are differentiated with respect to time, the expression for strain-rate is obtained.

$$\dot{\varepsilon}_s = -\frac{2c_o}{L}\varepsilon_r \qquad (11)$$

SECTION IV
INSTRUMENTATION

Strain gages are placed on both the incident and transmitter bars equidistant from the specimen so that the reflected and tramsitted waves arrive at the respective gages at the same time. The bars are long enough to permit observation of the entire loading event without interuptions caused by wave reflections from the free ends. The strain gage bridges consist of two active gages to cancel bending and are powered by a small 7 volt, D.C. power supply. All signal leads coming from the bridge are differential in order to reduce electronic noise levels in the system to a minimum.

Data are recorded on two oscilloscopes. The complete strain-time histories of the incident, reflected and transmitted pulses are recorded on a Tektronix type 565 dual beam oscilloscope with 2 type 3A3, high gain, dual trace, differential preamplifiers. The first beam of the scope is triggered so that the incident pulse, ε_i, can be recorded as it passes the first gage. The second beam is utilized in a chopped mode to display the output from the transmitter bar, ε_t (which is proportional to load), and the reflected signal on the incident bar, ε_r (which is proportional to strain-rate). The second trace is delayed relative to the first one and swept at a faster rate to obtain maximum time resolution. Typical traces are shown in the first photograph of Figure 3.

For direct recording of stress-strain curves, the reflected pulse is passed through an electronic integrator to obtain a signal that is directly proportional to strain in the specimen (see equation (11)). This signal is fed to the X axis of an Tektronix type 531 X-Y oscilloscope, while the output from the transmitter bar, proportional to stress (see equation (10)) is fed to the Y axis. A typical stress-strain curve for beryllium is shown in the second photograph of Figure 3.

Electronic triggering of the oscilloscopes is easily accomplished by applying a D.C. voltage to the incident bar while the striker bar is electronically grounded. When contact occurs, the incident bar is instantly grounded causing a trigger circuit to be activated. This circuit generates a rectangular pulse which is used to unblank the X-Y scope and to trigger the dual beam oscilloscope. The width and delay of the generated pulse are variable over the range from approximately 200-1500 μ secs and are used to obtain triggering at the proper times.

The system is calibrated dynamically by passing a known stress wave past the gages on both the incident and transmitter bars which are butted together without a specimen. The magnitude of the pulse set up in the bars is Vo/2Co where Vo is the measured velocity of the striker bar and Co the longitudinal wave speed.

The output from the strain gages on the incident bar is electronically integrated and produces a voltage which drives the horizontal axis of the X-Y oscilloscope to the left. During a test, the pulse reflected from the specimen will be of opposite sign to the loading pulse, thus driving the beam to the right.

The horizontal deflection of the beam is directly proportional to the area under the strain-time curve. The use of a Tektronix type W precision D.C. offset preamplifier on the X-axis allows setting the gain on the strain axis as high as desirable for maximum resolution.

Since the amplitude of the pulse is known, the load calibration is determined by observing the deflection on the vertical axis of the X-Y oscilloscope.

An alternative method of calibration is sometimes used to check the dynamic calibration. This merely involves shunting a known calibration resistor across one arm of the strain gage bridges. This produces a simulated strain of

$$\varepsilon_{sim} = \frac{1}{2G.F.} \frac{R_g}{(R_c+R_g)} \qquad (12)$$

where G.F. is the gage factor and R_g and R_c are the gage and calibration resistances. This method verifies the dynamic calibration to within several percent.

Although the dual beam oscilloscope traces contain all of the data from the test, they are used only to obtain the strain rate information. Since the strain rate is directly proportional to the reflected pulse, ε_r, the compression Hopkinson bar test is not a constant strain rate test as can be seen in Figure 3. Although the input pulse, ε_i, to the specimens is of constant magnitude, as the material strains the cross sectional area of the specimen increases making the specimen appear stiffer. The specimen material also work hardens as deformation proceeds making it stiffer as strain increases. Since the reflected strain, and hence strain rate, depends on the stiffness of the material, the strain rate generally decreases during the test. The strain rate figures quoted in this report are, therefore, average values.

The stress-strain relationship is obtained from the X-Y scope trace. The vertical axis is proportional to the transmitted stress and the horizontal to the integral of the reflected wave (strain). In order to obtain true stress, equation (10) is modified to

$$\sigma_t = E\left(\frac{A}{A_s}\right)\varepsilon_t\frac{1}{(1+\varepsilon_s)} \tag{13}$$

under the assumption of incompressible plastic flow.

All data presented here were reduced using a Hewlett Packard 9800 series calculator and digitizer. The digitizer is a means of entering X and Y coordinates into the calculator for subsequent operations. The digitizer reads to an accuracy of ten mils (.01") so that practically no error was introduced into the results by the reduction of oscilloscope traces recorded on Polaroid film to stress-strain curves.

SECTION V
MATERIALS AND SPECIMENS

Several different grades of beryllium and a beryllium alloy, lockalloy were obtained for testing in compression. The beryllium tested included materials fabricated by conventional hot pressing techniques as well as some consolidated by cold isopressing followed by hot isostatic pressing (CIP/HIP). A summary of the materials is presented in Table I which gives the chemistry and the uniaxial tensile properties as furnished by the producers.

P-1 beryllium was consolidated by the CIP/HIP process at Battelle Columbus Laboratories (BCL) from high purity electrolytic refined powder supplied by Kawecki Berylco Industries (KBI). Minus 325 mesh powder was hot isostatically pressed at 15000 psi and 1675°F for a period of 3 hours into the form of a thick walled hollow cylinder 8" diameter by 12" long. A second CIP/HIP material designated as GB-2 was fabricated at BCL from KBI powder. This is a commercial grade powder, -200 mesh, and was processed at 5000 psi and 1700°F for 3 hours. A detailed description of the processing is presented in Reference 7. S-65 is a newer structural grade of hot pressed block produced by Brush Wellman (BW) from impact pulverized powder. It is a low oxide material exhibiting more isotropic behavior and is of higher purity than ordinary commercial grades of hot pressed block. S-200E is such a commercial grade of hot pressed block from BW while S-200YP designates a selected pressing of the same material which exhibited very well defined yield points in uniaxial tension. Another variation of this material is a high temperature brake grade designated as BG-170. Two other materials produced by BW were evaluated in this program. A highly textured material in the form of a cross rolled plate, .312" thick was tested in two directions. For the cross rolled plate, designated PR-200D, the L direction is the pressing or rolling direction, i.e. through the thickness of the plate, while T denotes a direction in the plane of the plate. BIP is used to designate a special high purity powder which was hot pressed for evaluation in a program looking at improving the high temperature creep behavior of beryllium described in Reference 8. Lockalloy is an alloy of 62 percent beryllium and 38 percent aluminum produced by KBI.

Specimens were cut from the billets and machined and etched to a cylindrical shape having final dimensions of approximately 0.2" diameter by 0.2" long. L and T are used to designate the longitudinal (or pressing) and transverse directions, respectively, in hot pressed block. For the CIP/HIP hollow cylinders L, C, and R denote the longitudinal (or axial), circumferential, the radial directions, respectively.

SECTION VI
RESULTS AND DISCUSSION

Quasi-static data were generated on a standard floor model, 10,000 lb. capacity Instron testing machine. The same specimen geometry as in the dynamic tests was used. Special fixtures made of hardened steel were used to load the specimen. In addition, a very thin layer of molykote was used to lubricate the ends of the specimen in an effort to reduce end friction and specimen barreling. Data in the form of load versus deflection were recorded on a Honeywell X-Y recorder. Load was obtained directly from the Instron load cell while displacement was measured by means of a capacitive transducer mounted on the loading heads. In this manner machine deflection was eliminated. Data were reduced to true stress-strain curves by the conventional formulas.

A minimum of two samples of each of the materials were tested at a cross head velocity of .01 in/min which corresponds to a compression strain rate in the specimen of approximately 10^{-3} sec^{-1}. The data are presented in the form of true stress-strain curves up to 14 percent engineering strain in Figures 4 through 12. These static test data are denoted by S in the figures.

Dynamic data at an average strain rate of approximately 10^{3} sec^{-1} were obtained using the split Hopkinson bar apparatus described previously. In order to obtain an average strain rate which was the same for each material, the striker bar velocity had to be varied for each material using a trial and error method. The stronger materials had to be impacted at higher velocities than the softer materials to obtain the same magnitude of reflected pulse which determines strain rate. For the hardest materials it was difficult to obtain anything close to a constant strain rate using the apparatus described herein. The dynamic data at this nominal strain rate of 10^{3} sec^{-1} are designated by D in Figures 4 through 12.

It should be noted that both the static and dynamic data were obtained on the same size sample, nominally 0.2" long by 0.2" diameter. This small size was chosen to be able to obtain a high strain rate in the Hopkinson bar test. The penalty that one pays in performing static tests on that small a sample is an inability to resolve strains in the elastic region because of the machining tolerances with regard to loaded surfaces of the specimen. Note that a deflection due to surface roughness or tilt of .001" is equivalent to 0.5 percent calculated strain in the specimen. A small amount of lubricant squeezed out under load would also affect the apparent strain calculated from cross-head displacement. Thus, the elastic regions are not shown in the figures and it is difficult to estimate the yield stresses defined by a 0.2 percent offset from the elastic modulus.

In the case of the dynamic tests using the Hopkinson bar apparatus, it is difficult to resolve data in the elastic region for additional reasons. The theory behind the equations assumes that many stress wave reflections have occurred in the specimen and a state of dynamic equilibrium has been achieved. This does not occur until some plastic deformation has taken place in the specimen (Reference 6).

At larger strains, in both the static and dynamic tests, the specimen will start to barrel. When this occurs, the equations for both stress and strain are no longer valid as they are based on an assumed state of uniform stress in the specimen. The use of a lubricant on the ends of the specimen minimizes the barreling effect but does not prevent it at larger strains.

Based on the above observations, it is determined that the static and dynamic stress-strain data are accurate over a range in strains from approximately 2 to 10 percent. For engineering analyses of dynamically loaded structures which are plastically deformed, the data presented here give some guidance as to the rate sensitivity and plastic flow stresses at strain rates up to 10^3 sec^{-1}. It can be seen from the stress-strain curves that the flow stress in beryllium in compression increases by approximately 30 percent at strains of 10 percent at a strain rate of 10^3 sec^{-1} over the quasi-static value. The increase in the flow stress of lockalloy is approximately half that of any of the beryllium grades tested. Since lockalloy consists of 38 percent aluminum which is known to be relatively strain-rate independent this rate dependence is consistent with what one would expect using a rule of mixtures type of reasoning. The strain hardening of beryllium appears to increase dynamically over the quasi-static values although the yield point does not appear to increase as much as the flow stress at larger strains. Part of this effect may be due to the non-uniform strain rate in the test. The incident pulse has a rise time of greater than 10 μ sec which means that the strain rate in the test is increasing during the rise time of the pulse. If the strain rate is assumed to increase linearly up to 10^3 sec^{-1} over a period of 10 μ sec, then a total strain of 0.5 percent would be reached in the specimen before the high strain rate is achieved. Since the offset yield stress occurs at strains below this for beryllium, the specimens are into the plastic region before the strain rate reaches its maximum. Thus no information is available on the yield stress at a (constant) strain rate of 10^3 sec^{-1}.

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TABLE I

MATERIAL CHEMISTRY AND TENSILE PROPERTIES

Material Lot Number		P-1 1578	S-65 0152	GB-2	S-200E 9439	S-200YP 8262	BG-170 7325	PR-200D 2028	BIP 1363	Lockalloy* H-161
Chemistry										
BeO (%)		.64	.50	1.81	1.67	1.67	.80	1.35	3.37	.57
C		.024	.02	.145	.11	.13	.08	.09	.067	.040
Fe		.015	.07	.143	.14	.13	.08	.10	.072	.058
Al		.006	.01	.070	.08	.05	.04	.04	.008	≈37%
Mg		.004		.030	.02	.03	.03	.03	.005	.004
Si		.006	.02	.050	.03	.04	.02	.04	.055	.030

* 62.6% Be

Tensile Properties										
L	UTS(ksi)	66	54	60	49	49				52.9
L	YS(0.2%)	45	34	49	34.5	41(43)**				40.4
L	%Elong	3.2	4.7	1.4	1.8	1.8				12.6
T	UTS	70	55			55	50	65.6	78.6	
T	YS	44	34			43(48)**	31	59.2	66.3	
T	%Elong	5.3	5.7			3.5	4	25.0	2.7	

** Numbers in parenthesis refer to yield point

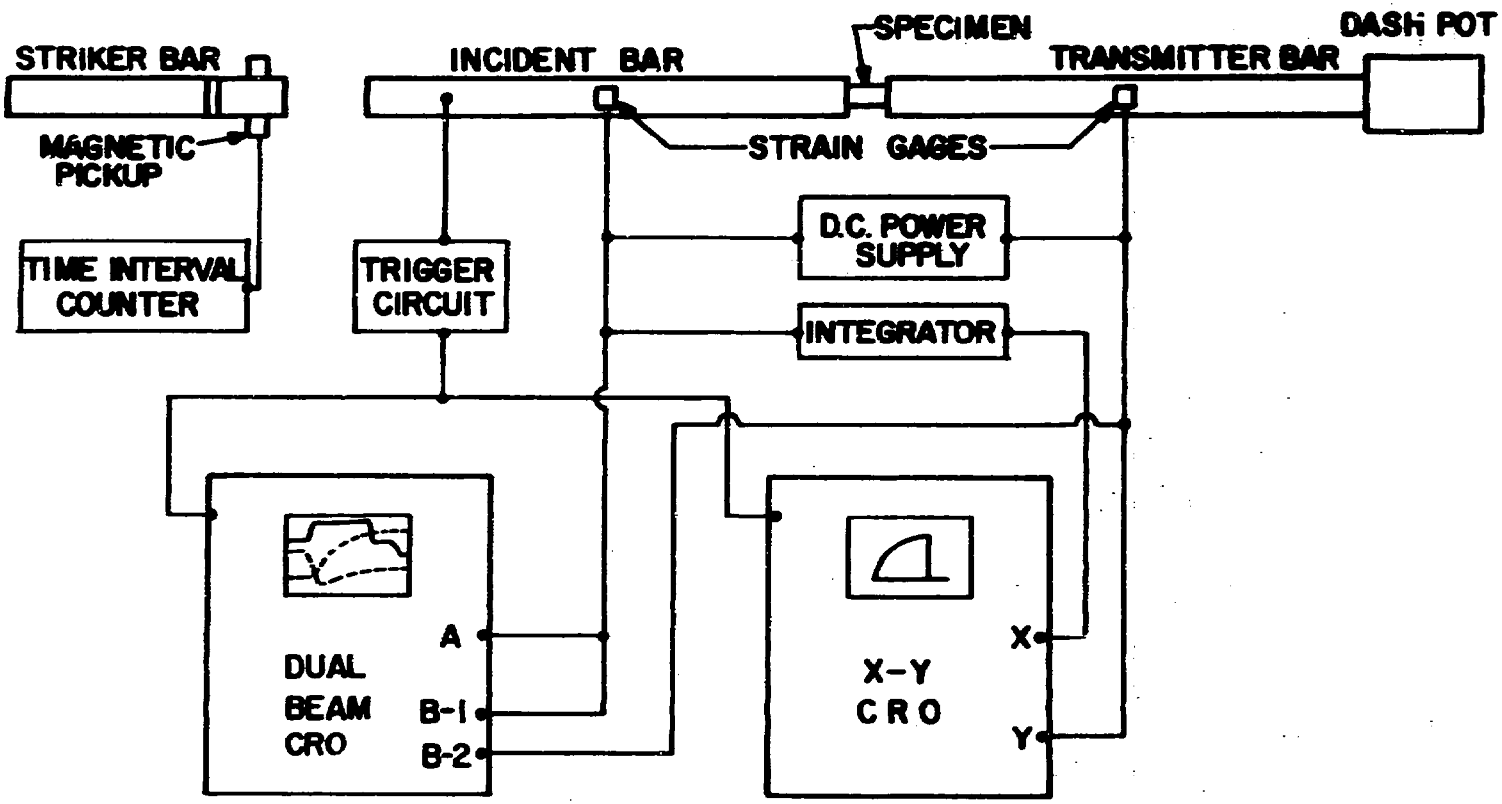

Figure 1. Schematic of Apparatus and Instrumentation.

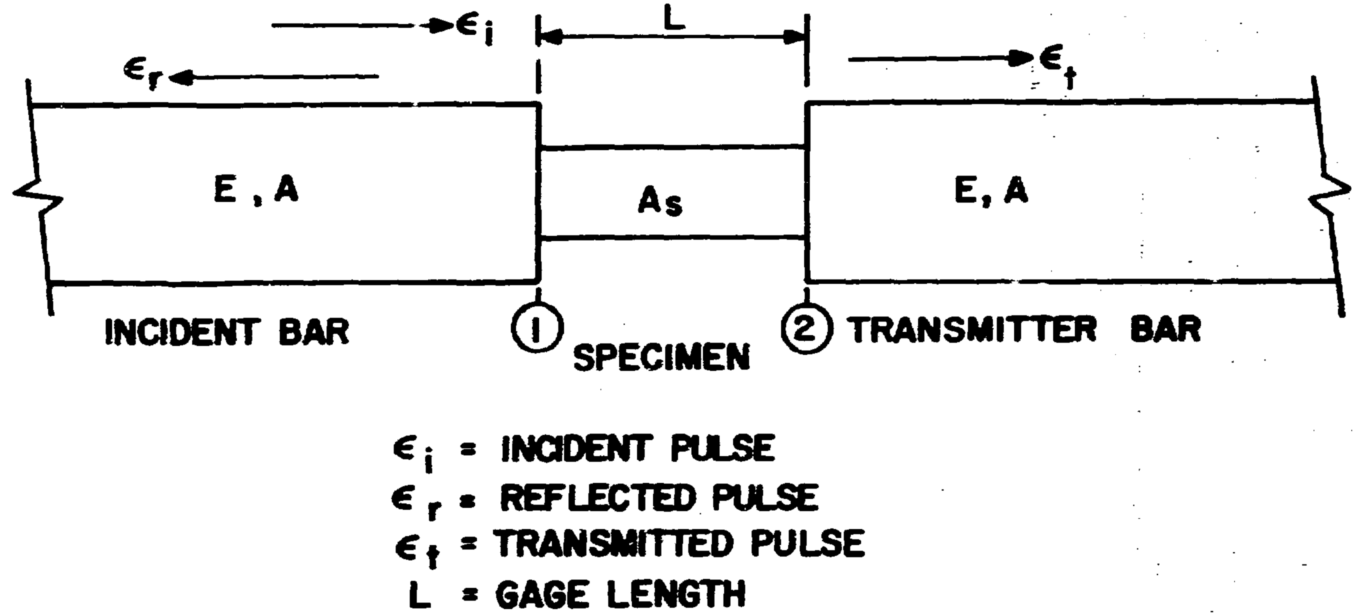

Figure 2. Schematic of Specimen and Strain Pulses.

Dual beam CRO traces. (A) ε_i = 600 x 10^{-6}/div; (B) ε_r = 300 sec^{-1}/div; (C) ε_t = 28.1 ksi/div. Sweep time: (A) 100μ sec/div; (B) and (C) 50μ sec/div.

X-Y CRO trace for S-65 Beryllium. Vertical = 24 2 ksi/div; Horizontal = 2.97%/div.

Figure 3. Typical Experimental Data.

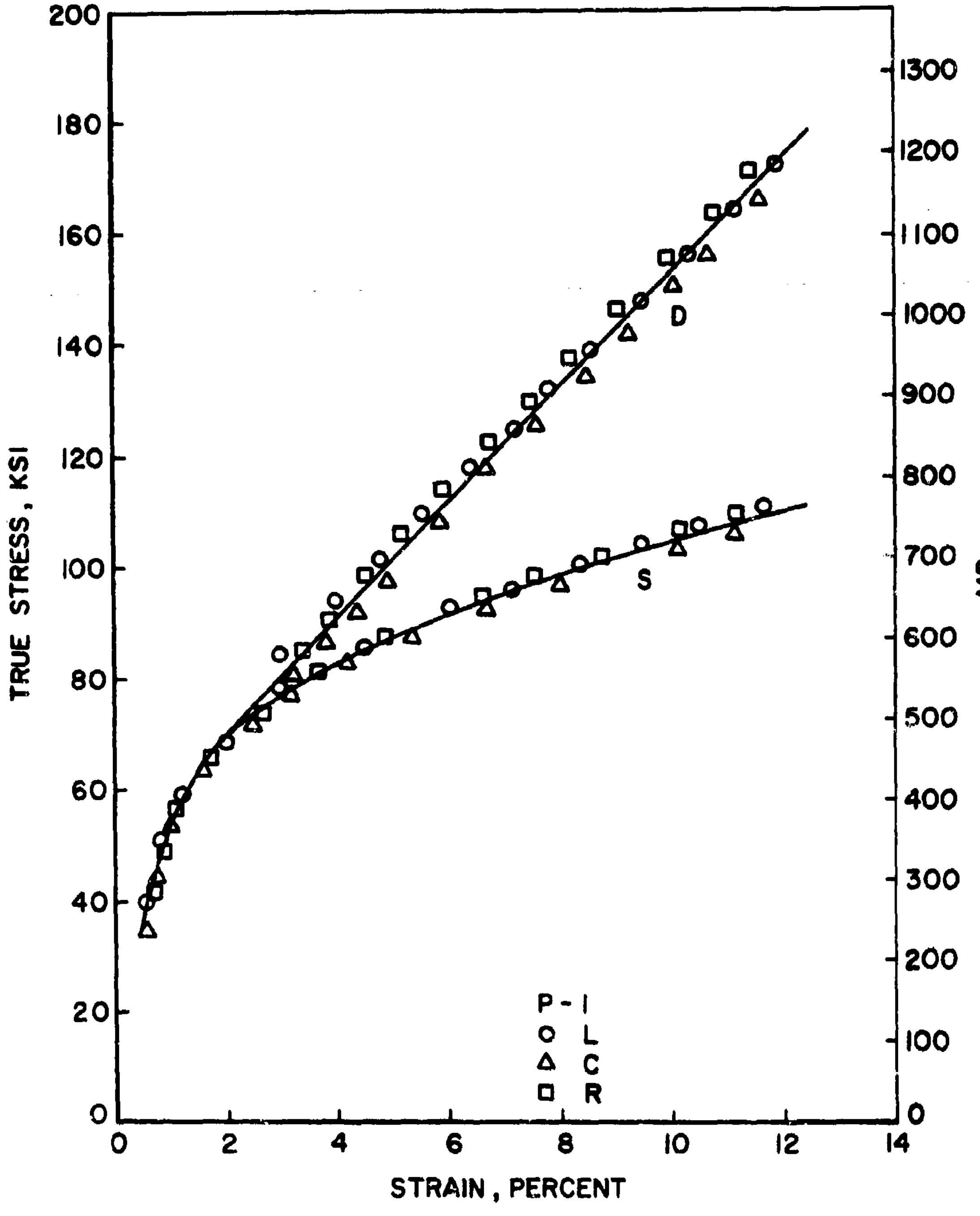

Figure 4. Compression Stress-Strain Curves for P-1 Beryllium.

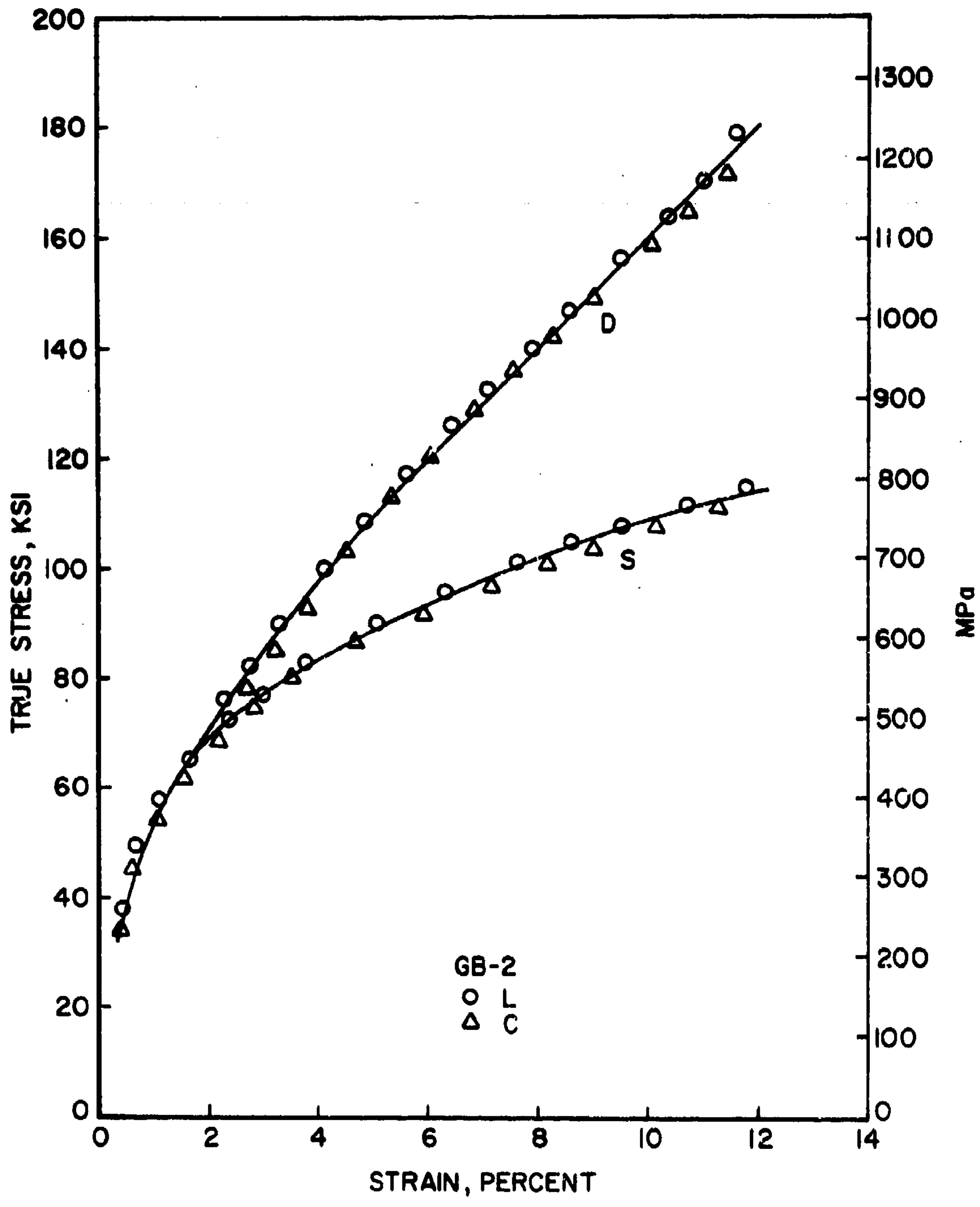

Figure 5. Compression Stress-Strain Curves for GB-2 Beryllium.

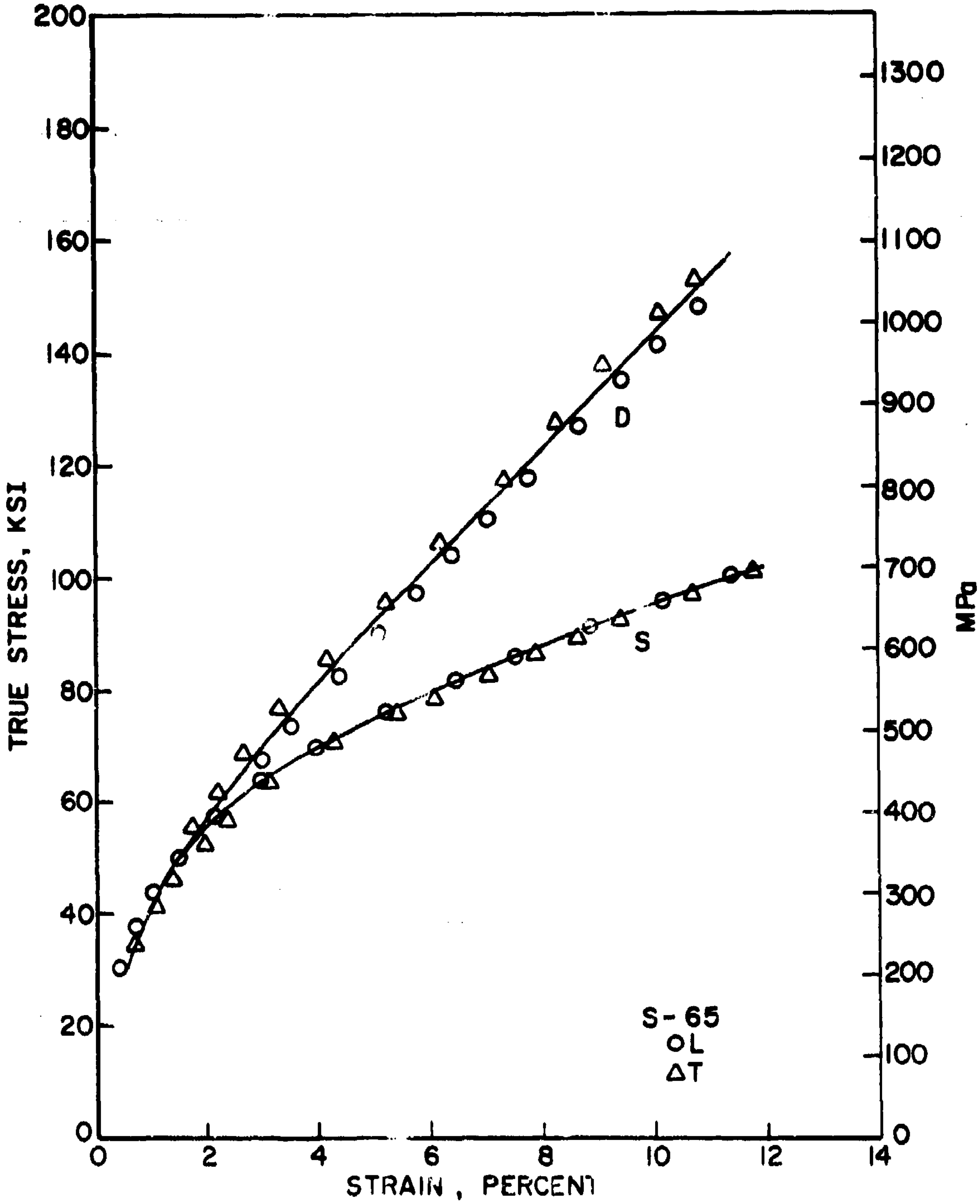

Figure 6. Compression Stress-Strain Curves for S-65 Beryllium.

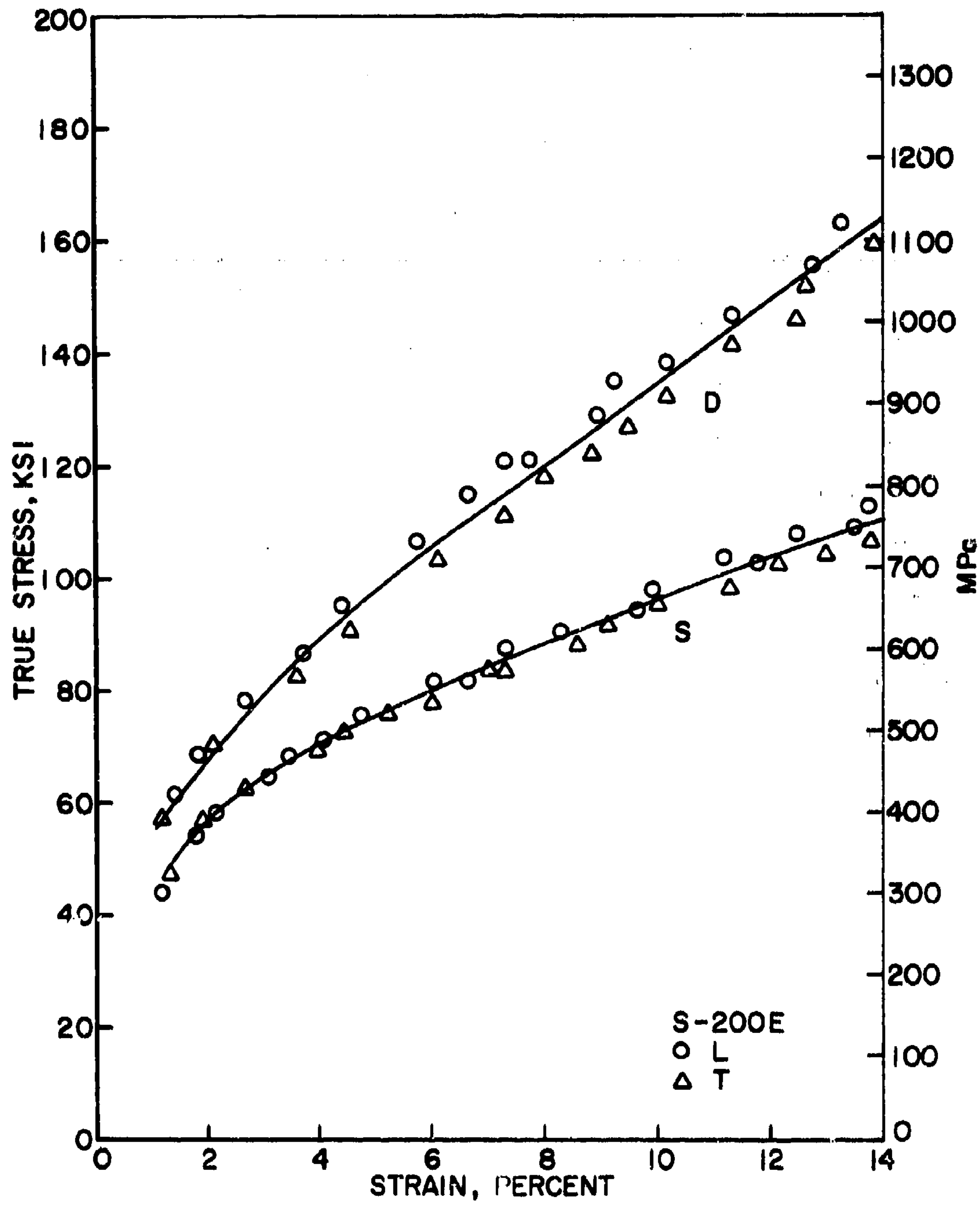

Figure 7. Compression Stress-Strain Curves for S-200E Beryllium.

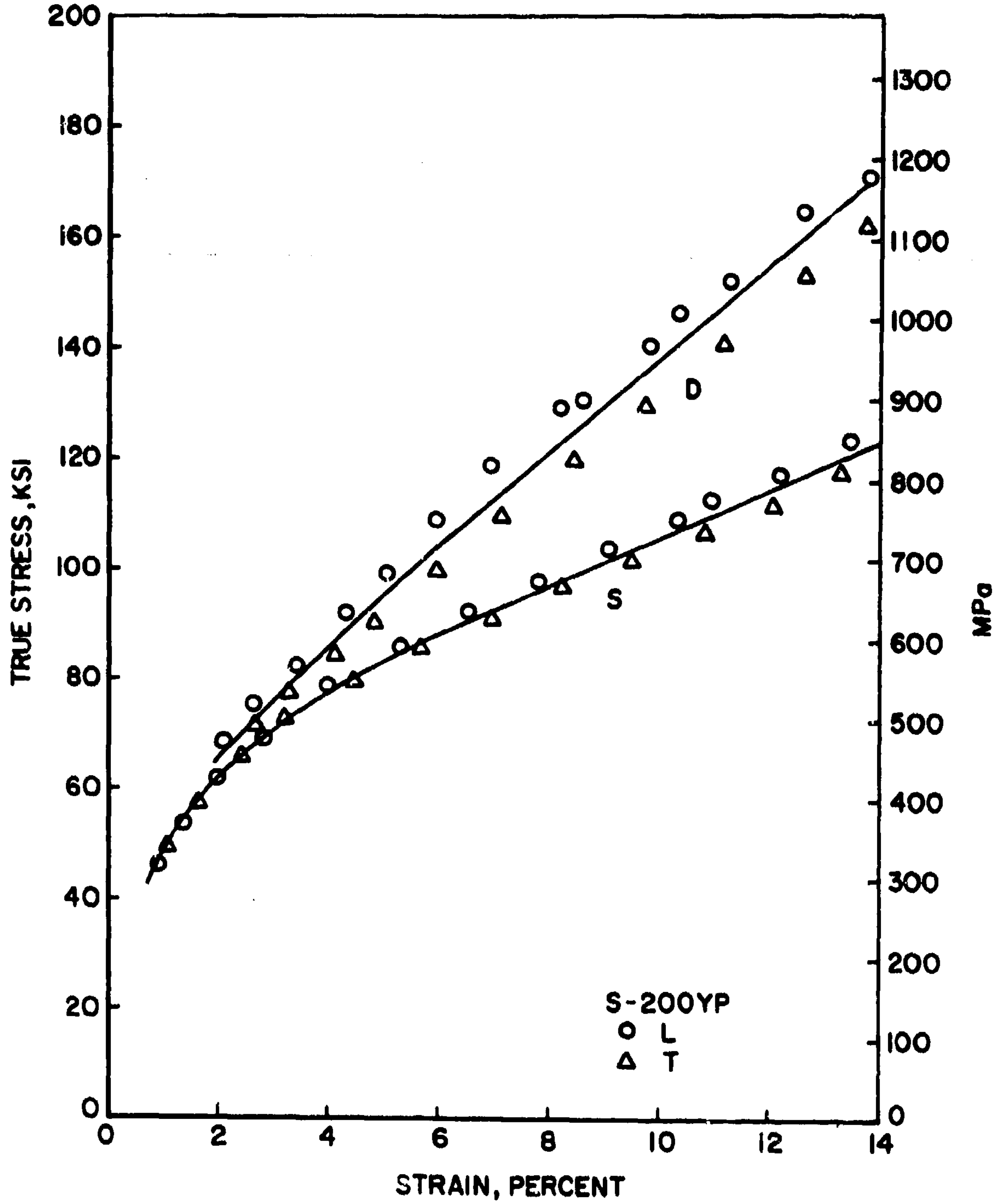

Figure 8. Compre.'sion Stress-Strain Curves for S-200YP Beryllium.

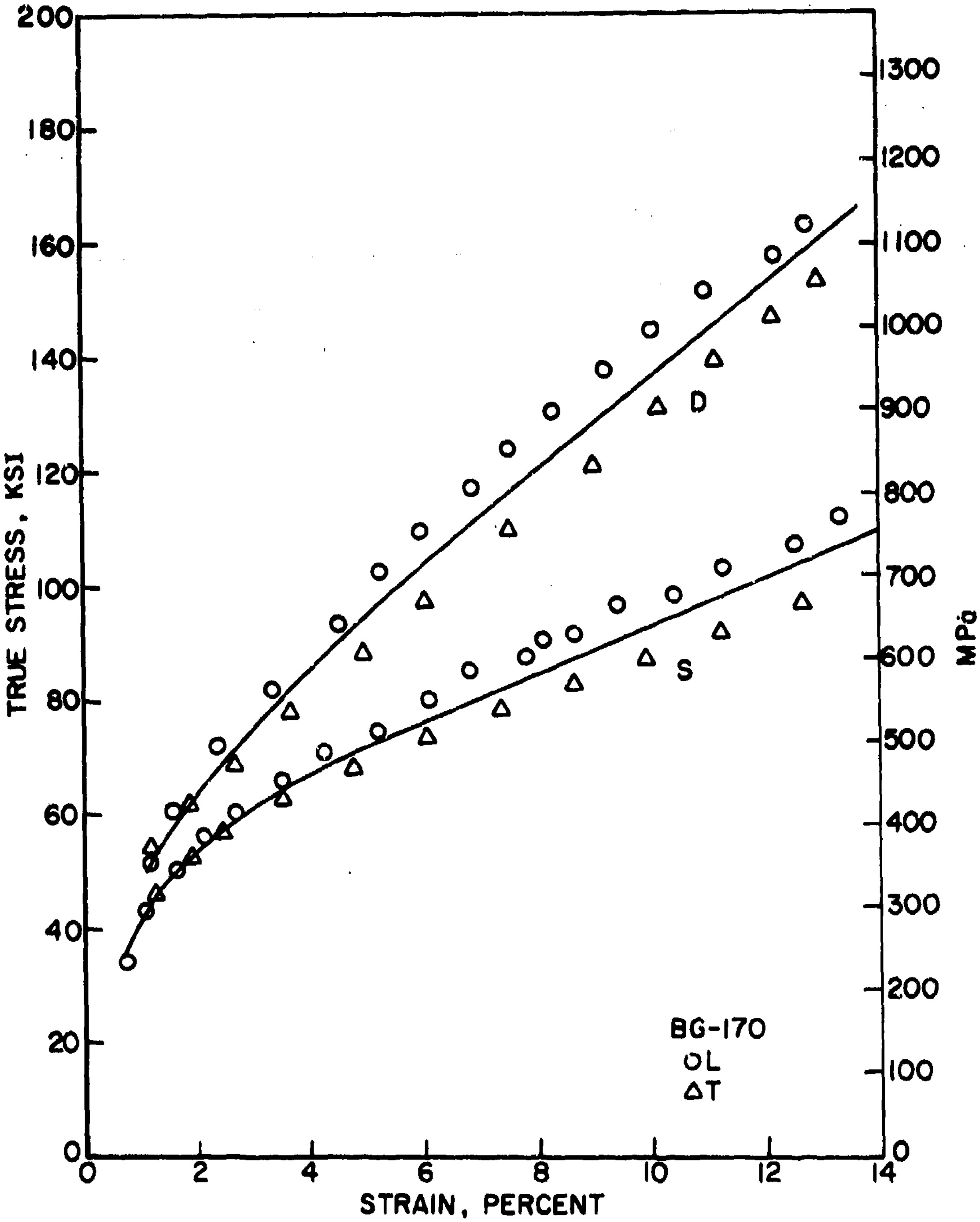

Figure 9. Compression Stress-Strain Curves for BG-170 Beryllium.

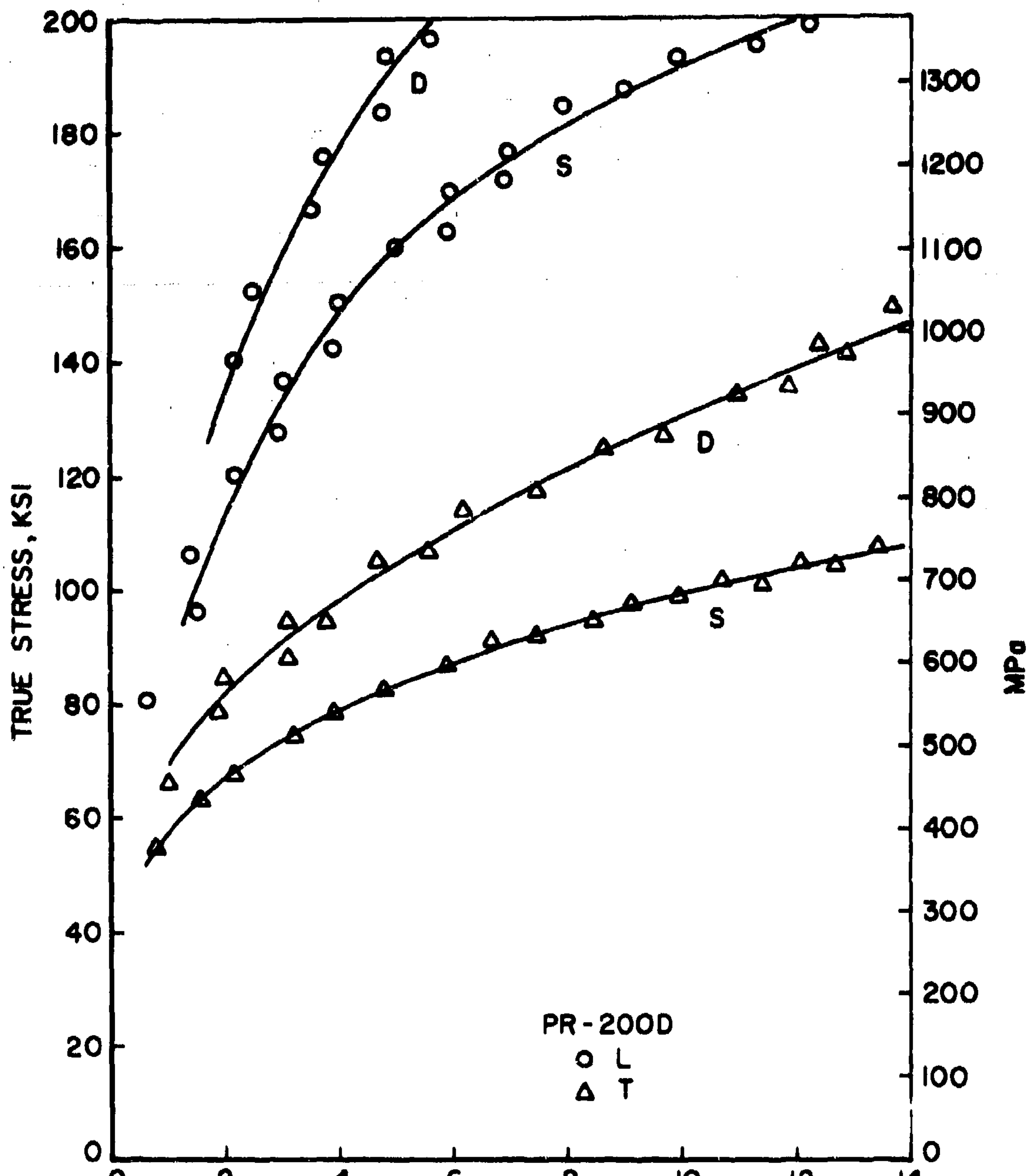

Figure 10. Compression Stress-Strain Curves for PR-200D Beryllium.

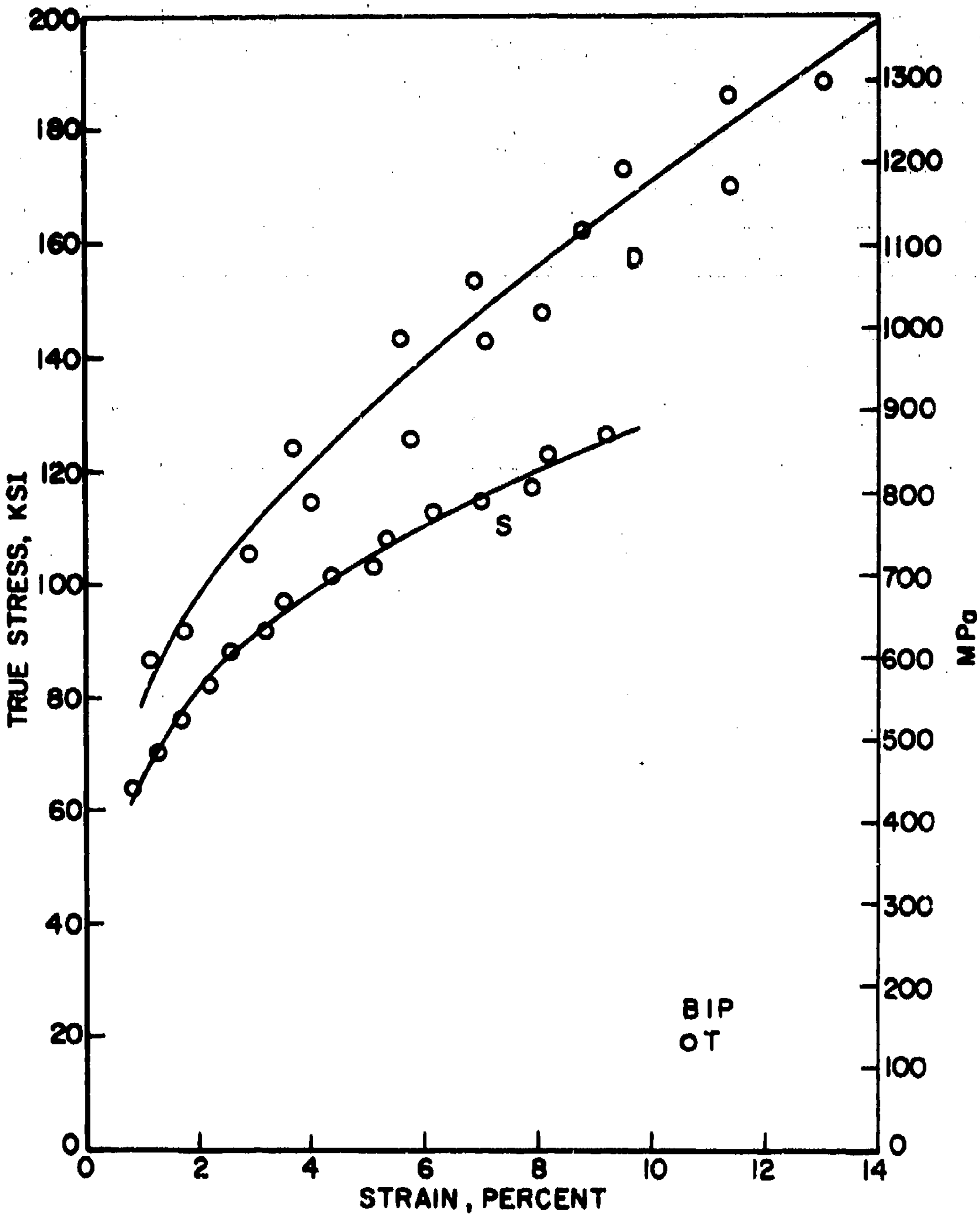

Figure 11. Compression Stress-Strain Curves for BIP Beryllium.

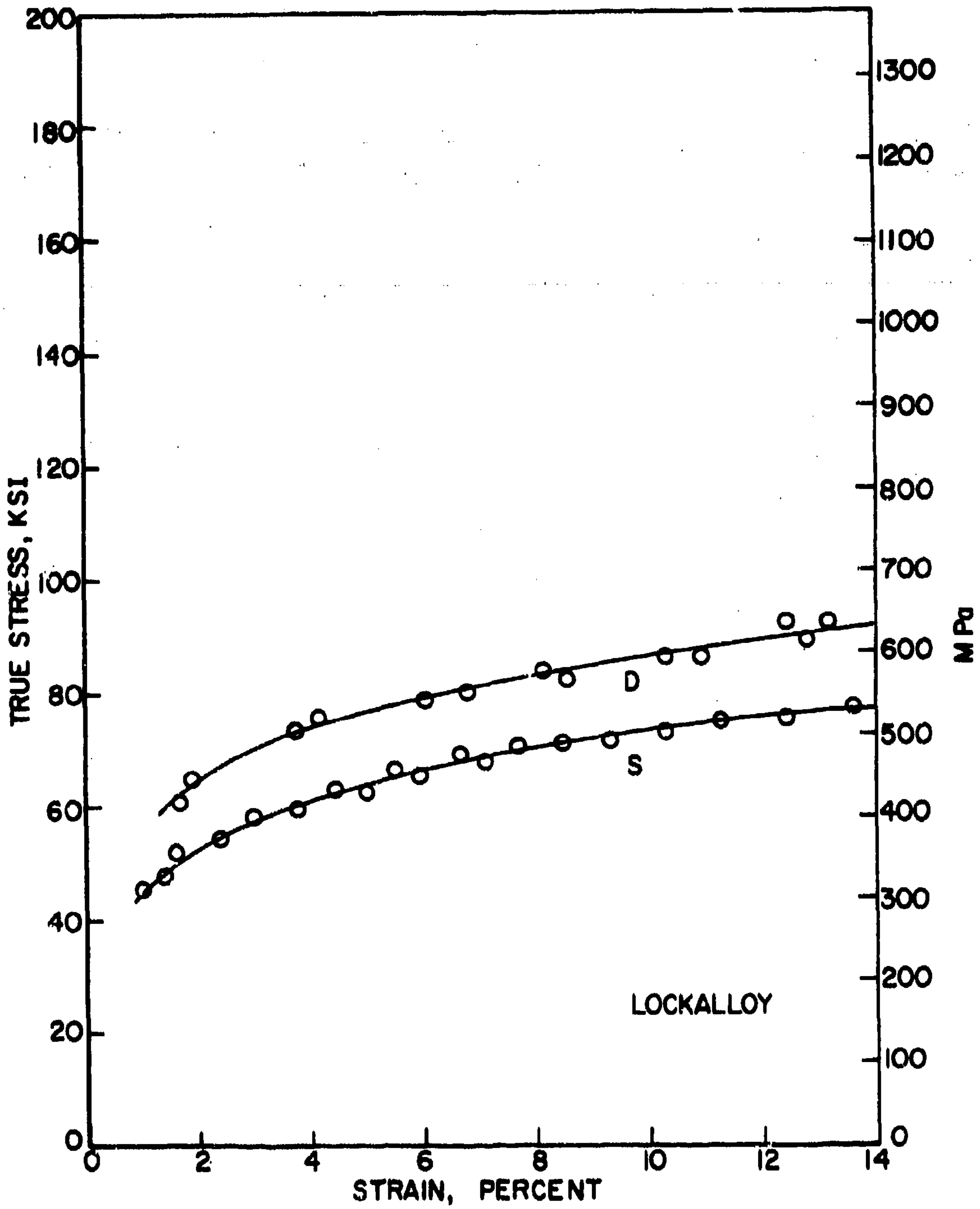

Figure 12. Compression Stress-Strain Curves for Lockalloy.

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