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A METHOD OF OBTAINING STRESS-STRAIN DATA IN THE PLASTIC RANGE

A THESIS

Presented to

the Faculty of the Graduate Division

by

Theodore Glenn Stastny

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in the School

of Mechanical Engineering

Georgia Institute of Technology

September, 1958

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A METHOD OF OBTAINING STRESS-STRAIN DATA

IN THE PLASTIC RANGE

Approved:

Date Approved by Chairman:

Sept. 24, 1958

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Dr. Joseph P. Vidosic, the adviser for this thesis, gave invaluable assistance and guidance in the preparation and completion of the project and the thesis.

Most devoted thanks go to the author's wife Charlotte, who with her continuous encouragement and assistance has made this thesis possible.

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SUMMARY

A need exists in the metal forming industry for a reliable method of determining the properties of metals in the plastic range. Although theories exist about these properties, certain information is missing to evaluate springback in metal forming. This information can be gotten from a reliable stress-strain curve in the plastic range, if the curve can be obtained.

A photographic method for determining the stress-strain diagram in the plastic range has been developed. It consists of photographing a gridwork of vertical and horizontal lines 0.01 inches apart on a standard, round tension specimen. This is done with a negative of the gridwork and a cold-top enamel emulsion and developer. Using a high resolution camera and film, the specimen is photographed in order to obtain a record of the original gridwork. As the specimen is pulled apart, photographs are taken at desired loads. The result is a record of the specimen as it changes configuration during elongation and necking. The elongation of the gridwork is apparent on the photograph, especially in the area of the necking. By measuring the elongation of a certain number of lines across the necked-down portion of the specimen, the true plastic strain is obtained. Correspondingly, for determining the true stress, the necked-down diameter of the specimen is measured from the film. These measurements are made with a micrometering microscope of high accuracy.

The resulting true stress-strain diagrams agree with the work of other investigators who determined the strain mathematically from the diameter, using certain assumptions.

It is recommended that this photo-grid method be used to show the convergence of stress-strain diagrams by using smaller and smaller gage lengths. By using a small gage length of 0.01 inches, studies could be made of strains at a point.

CHAPTER I

INTRODUCTION

Introduction to problem.--Difficulties arise in the design of metal forming dies due to the springback of metals. After pressing the blank, the piece must be hand-formed to obtain the proper dimensions, or else the die must be redesigned.

Up to this time the designing of dies has been a trial and error process, often expensive and time consuming. If the proper design is to be obtained, the elastic and plastic properties of the materials must be known. While the elastic properties of most metals are readily obtainable from stress-strain diagrams, the plastic properties are not well defined.

The stresses in a tension specimen are usually calculated by dividing the load by the original cross-sectional area, even after the specimen begins to neck down. Likewise, strains are measured over gage lengths of either two or eight inches, but most of the strain occurs in the necked-down section. Therefore, if the diameter could be measured with each successive load, the true stress could be determined. Also, if there were some method of measuring the axial change in length of the necked-down portion, a more realistic true strain could be obtained.

A photo-grid technique has been developed here which yields a permanent record of the diameter and of the axial strain of the specimen

at any desired load. Using these data the true stress-strain curve may be obtained.

Review of the literature.--A brief resume by MacGregor (1)* reveals that the most common methods of recording graphically the behavior of a metal subjected to tensile stresses is to plot the tensile stress S_o as a function of the strain ϵ_o. The stress S_o is obtained by dividing the load P by the original area A_o. The strain ϵ_o is defined as the change in the gage length ΔL_o divided by the original length L_o. While this procedure has proved of considerable value in the routine testing of materials, Ludwik (2) has pointed out that it does not have a sound physical basis. The disadvantage is that the true physical behavior of the material, when subjected to tensile stress, is not evident. Some of the objections are that: (1) a fictitious stress value is obtained; (2) the strain ϵ_o becomes less and less exact for large values of ΔL_o; (3) when necking starts the strain varies considerably over the gage length and ϵ_o is not the true strain at every point of the bar; and (4) the axial strain varies over the cross-section of the necked portion, and ϵ_o does not represent the average of these strains.

To overcome some of these objections various methods have been suggested. In some of these, only the stress is corrected by dividing the load by the actual area of the bar when the load is acting (3), thus using the same definition of strain as mentioned above.

---

*Numbers in parenthesis refer to the reports and papers appearing in bibliography.

Ludwik (2) and later Heneky (4) suggested that true strain be defined as

$$\epsilon = \int_{L_o}^{L} \frac{dL}{L} = \log \frac{L}{L_o} .$$

This definition holds for strains both large and small and approaches ϵ_o for small values of ΔL_o. The definition of strain given by Ludwik refers the change in gage length to the length across which the change occurs rather than the original length. According to this suggestion then $S = P/A$ would be plotted as a function of $\epsilon = \log L/L_o$. Because it assumes a fixed cross section, ϵ, computed as explained above loses its significance after necking starts. To apply this method in the necking region of the bar using a small gage length certain practical difficulties become at once evident.

Stead (5) proposed that the average true stress P/A be plotted as a function of the decreasing diameter. This procedure is free from certain of the disadvantages of other methods. A convenient linear relationship is obtained between P/A and d for the portion of the curve from maximum load to fracture.

Norris (6) has obtained some interesting relationships by plotting the log of the true stress as a function of the log of the true strain ϵ_o. It was found that a straight line was obtained for most materials throughout the major portion of the diagrams.

A method was suggested (7) where the average true stress $S = P/A$ is plotted as a function of the true reduction in area $q' = \log A_o/A$.

This method is described in the following chapter. Its results are applied in the evaluation of the photo-grid technique developed in this investigation. This important fact is the straight line relationships of the S-q' curve past the maximum load.

CHAPTER II

MACGREGOR'S METHOD (1)

Tensile tests with round bars were made on various materials in which the diameters of standard, 0.505 inch, test pieces were measured by means of a specially designed clamp and dial gauge. Knife edges were provided so that the diameter could be determined accurately during the necking stage.

Curves of the average true stress, the load divided by the immediate area, plotted against the true reduction of area as the log of the original area divided by the immediate area, gave straight lines from maximum load to fracture load.

Mathematically the true strain ϵ_o and the true reduction in area q' are given as

$$\epsilon = \int_{L_o}^{L} \frac{dL}{L} = \log \frac{L}{L_o}$$

$$q' = -\int_{A_o}^{A} \frac{dA}{A} = \log \frac{A_o}{A} .$$

Using the assumption that there is no change in volume after necking, $AL = A_o L_o$; $L/L_o = A_o/A$.

This shows mathematically that the true strain ϵ_o is equal to the true reduction of area q'; and that the experimental evidence given by MacGregor yields a straight line for the true stress-strain relationship in the plastic range.

MacGregor gives graphical results of the straight line relationship for materials such as SAE 1045 steel, SAE 1040 steel, cold-drawn brass, VD-95C annealed steel, and annealed mild steel.

CHAPTER III

TEST EQUIPMENT AND OPERATION

Test specimens.--Four typical engineering materials were used in developing this technique of obtaining stress-strain data in the plastic range. These materials were 1018 steel, 1100 aluminum, 2017-T4 aluminum, and free cutting brass. The test specimens were standard test bars. Each specimen was 3/4 inch nominal diameter with a smoothly turned nominal 0.505" diameter test section, 2 1/4 inches long.

Grid negative and chemicals.--In order to examine various small gage lengths the Bureau of Standards developed a fine gridwork of lines and photographed them (8). The vertical and horizontal lines are 0.006 inch thick and 0.01 inch apart, covering an area of 2.07 inches by 2.16 inches.

A copy of this negative was obtained from the Lockheed Aircraft Corporation and several more copies reproduced for use in this investigation. With this gridwork of lines, photographed on the test section of a specimen, any gage length from 0.01 inch to 2.00 inches could be recognizable throughout the entire test.

Freuendorfer Cold Top Enamel and Developer by Phillip Lochman Company provided a satisfactory emulsion for developing the gridwork onto the specimens. A 95 per cent grade A alcohol is required to clean the specimens and remove excess developer.

Since the Cold Top Enamel is insensitive to ordinary light a 100 watt AH-4 mercury arc lamp is sufficient to expose the enamel on the specimens.

Tension machine.--Three scales are available on the Tinius-Olsen plastiversal testing machine for tension testing. These include a 0-500 lb. scale, 0-10,000 lb. scale and a 0-20,000 lb. scale. The calibration was checked using an electric strain gage indicator and SR4 strain gages attached to a tensile specimen. The tensile specimen was large enough to withstand the maximum load and still remain in the elastic range. This permitted a check of corresponding loads as first calibrated by another machine. With this load-strain curve the Tinius-Olsen machine was found satisfactorily calibrated to within $\pm$ 0.1 per cent.

Photographic equipment.--Since the gridwork on the specimens was so fine, a short focal length camera was necessary to obtain clear definition. For this purpose a Graflex Photo-Record was used. In order to obtain high resolution a 35 mm. microfile film had to be used. In addition to the high resolution property, the toughness of the film permitted ease of handling in developing and reading the strains without distortion.

Two 150 watt reflector spots provided adequate illumination for photographing. A small curved reflector behind the specimen was used to outline the specimen effectively.

CHAPTER IV

PROCEDURE

Applying the grid.--The application of the grid is a delicate operation, one which must be strictly adhered to for usable results. (9)

Cleaning of the test surface is most important. It must be free from dirt, grease and minute particles. Grade A 95 per cent alcohol was used to degrease the surface.

A small tray was used to hold several ounces of the Freundorfer Cold Top Enamel while two 8 1/2 x 11 inch stainless steel trays were used to hold 16 ounces of the developer and alcohol.

The enamel was painted over the test section with a small Delta No. 6 sable brush. Extra care was applied to obtain an extremely thin and even coat. Additional strokes were used only to remove small bubbles that would develop from having the brush too dry. After applying the enamel emulsion, an electric hair dryer was used to dry the specimen.

The grid negative was then placed around the specimen and clamped with the emulsion side down, assuring emulsion to emulsion contact.

Standing the specimen on end and five inches from the AH-4 100 watt mercury arc lamp gave adequate exposure in five minutes. Exposing at this distance for less time was inadequate in that the emulsion washed out in the developer.

After the specimen was exposed the grid was removed and the specimen rolled in the developer for fifteen to twenty seconds. Then

it was carefully agitated in the alcohol until all excess developer was removed leaving the gridwork of purple lines on the specimen. The specimen was then again dried with the hair dryer leaving it ready for testing purposes. Figure 2 on page 18 of the appendix shows the specimen with the applied gridwork.

Photographing the specimen.--Precautions were taken while inserting the specimen in the jaws of the machine to prevent a broken specimen from falling out and damaging the camera.

After the specimen was placed in the jaws, the camera, mounted on a heavy cast iron stand, was brought twelve inches from the specimen. A support clamped to the machine and camera base provided extra rigidity to reduce vibrations.

Focusing is a delicate operation and exactness must be maintained if suitable data is to be obtained. A ground glass attachment at the back of the camera was used for this purpose. However, a microscope had to be used for the final focusing. The microscope was first focused on the ground glass until the glass etchings were brought out as clearly as possible. Then the camera was focused with a slow motion screw adjustment until the grid lines themselves were seen on the image on the ground glass. Only when this was accomplished could the film reproduce suitable lines of grid data.

The two 150 watt reflector spot lamps were directed toward the specimen at a 45 degree angle, measured from the line of photography. These lamps gave adequate illumination at a distance of 30 inches from the specimen. One lamp was on each side of the camera and they were

connected to a common off-on switch. A semi-circular aluminum reflector with a dull finish was placed behind the specimen. Besides giving more light over the object, its bright background provided illumination which outlined the specimen well.

With this arrangement the film negatives showed a light gray specimen on a black background, two black lines on either side of the axial center and a clearly defined gridwork of white lines.

As a preliminary measure, a necked-down specimen with the gridwork was held in the machine and photographed over the range of lense openings to determine the most suitable contrast arrangement. Best results were obtained at a shutter speed of 1/25 and a lense opening at f8. A necked-down specimen was used to assure good definition in the plastic range where the configuration of the specimen changes.

Each specimen was individually focused before pulling. After focusing, the ground glass attachment was removed and the magazine containing the film was put in place. The first photograph was always used for identification. A small white card with black letters was placed in front of the specimen and photographed for this purpose. With the tension machine pulling at a constant strain rate of 0.025 inches per minute, several photographs were taken in the elastic range for possible future use. More photographs were then taken past the ultimate load which signified the entering of the plastic range. The two 150 watt spotlights were turned off after each photograph to prevent excess heating of the specimen. Photographs were taken throughout the test to fracture at specific loads. Approximately twenty-two photographs of each specimen were taken.

Measuring the strain.--A micrometering microscope was used to measure the lines on the 35 mm. film. This device could measure straight line distances by advancing the microscope with a micrometer screw as the microscope was focused on the film negatives. The microscope, calibrated by the Bureau of Standards, had a vernier scale permitting readings of 0.001 millimeters. The initial diameter of the specimen had been determined by a micrometer. Several readings of the diameter were taken from the photograph with the micrometering microscope. The average of these was multiplied by a scaling factor and set equal to the true diameter. This scaling factor was used to convert the image dimensions in millimeters to the true dimensions in inches. This factor was applied to the diameter only, since pertinent data of unit strain was the ratio of the change of length of 25 lines divided by the initial measured length of the same 25 lines.

CHAPTER V

DISCUSSION OF RESULTS

After some familiarity and experience were gained, satisfactory gridwork could be applied to the specimen in about fifteen minutes. The procedure, however, had to be followed exactly.

Occasionally the photograph of a pulled specimen appeared blurred and so had to be discarded. This was caused either by vibration of the testing machine or improper focusing of the camera. The satisfactory photographs gave repeatable data, plotted and presented in the Appendix.

It is necessary to have two persons running the experiment, one to read and record the load while the other photographs the specimen.

The data in the appendix are taken from three specimens each of four metals. Their individual true stress-true strain curves are plotted and the average of the curves is the plot of the arithmetical average of the strains at a given stress.

CHAPTER VI

CONCLUSIONS

The straight line relationship of the stress-strain curves in the plastic range is an indication of the reliability of this photo-grid technique. Not only does the data agree with the findings of MacGregor as brought out in Chapter II but this method provides a permanent record of the physical strains and specimen dimensions which can easily and readily be seen and analyzed.

MacGregor plotted data of stress-strain relationships for five materials and obtained straight lines in each case. Three specimens each, of four different materials, were tested by the photo-grid technique and all curves also yielded straight lines in the plastic range. Such agreement between two different methods supports the findings and reliability of each method.

Another factor which indicates the reliability of the method is the repeating results. The deviation is only typical of engineering material properties and is slight, as can be seen by comparing the average stress-strain curve with any single curve of the same material.

CHAPTER VII

RECOMMENDATIONS

The films taken have been preserved. Curves could be plotted by using various size gage lengths, say, 1.0, 0.5, and 0.01 inch, across the necked-down portion of the specimen. These data could be obtained directly from the film. The curves would tend to converge to some configuration of point strain and perhaps reveal needed information. Curves could be plotted of the log of the ratio of areas for another comparison of true strain in the same manner MacGregor made his analysis.

Furthermore, this method of developing a grid on specimens could be extended to flat specimens, and plastic studies of Poisson's ratio could be made since both horizontal and vertical lines are available. If the specimens contained stress raisers, such as holes, increased strains around the hole would indicate the presence of stress concentrations and provide a means for computing stress concentration factors. Also, flat members could be studied in bending and photographed for localized strains in the plastic region.

APPENDIX

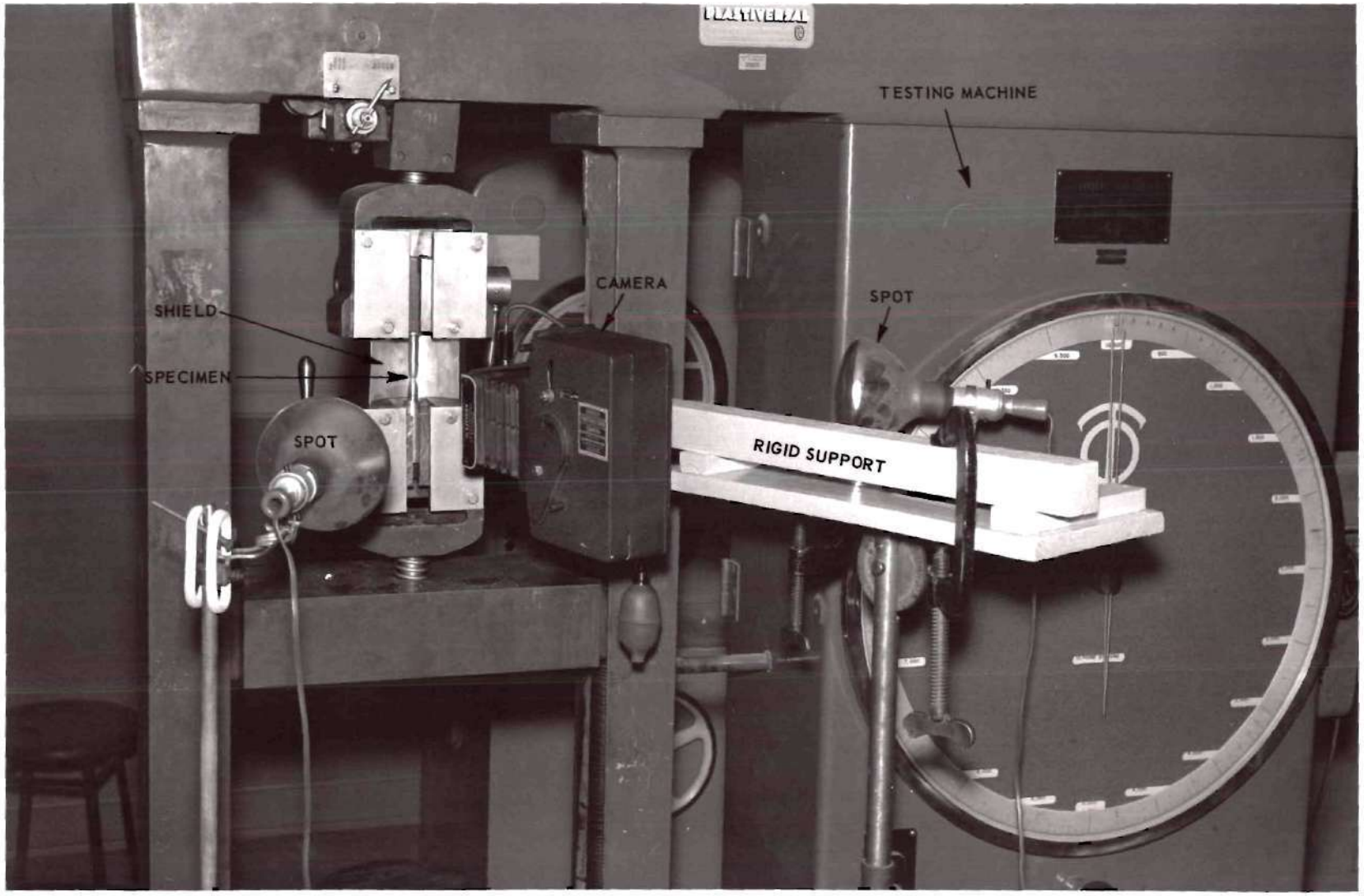
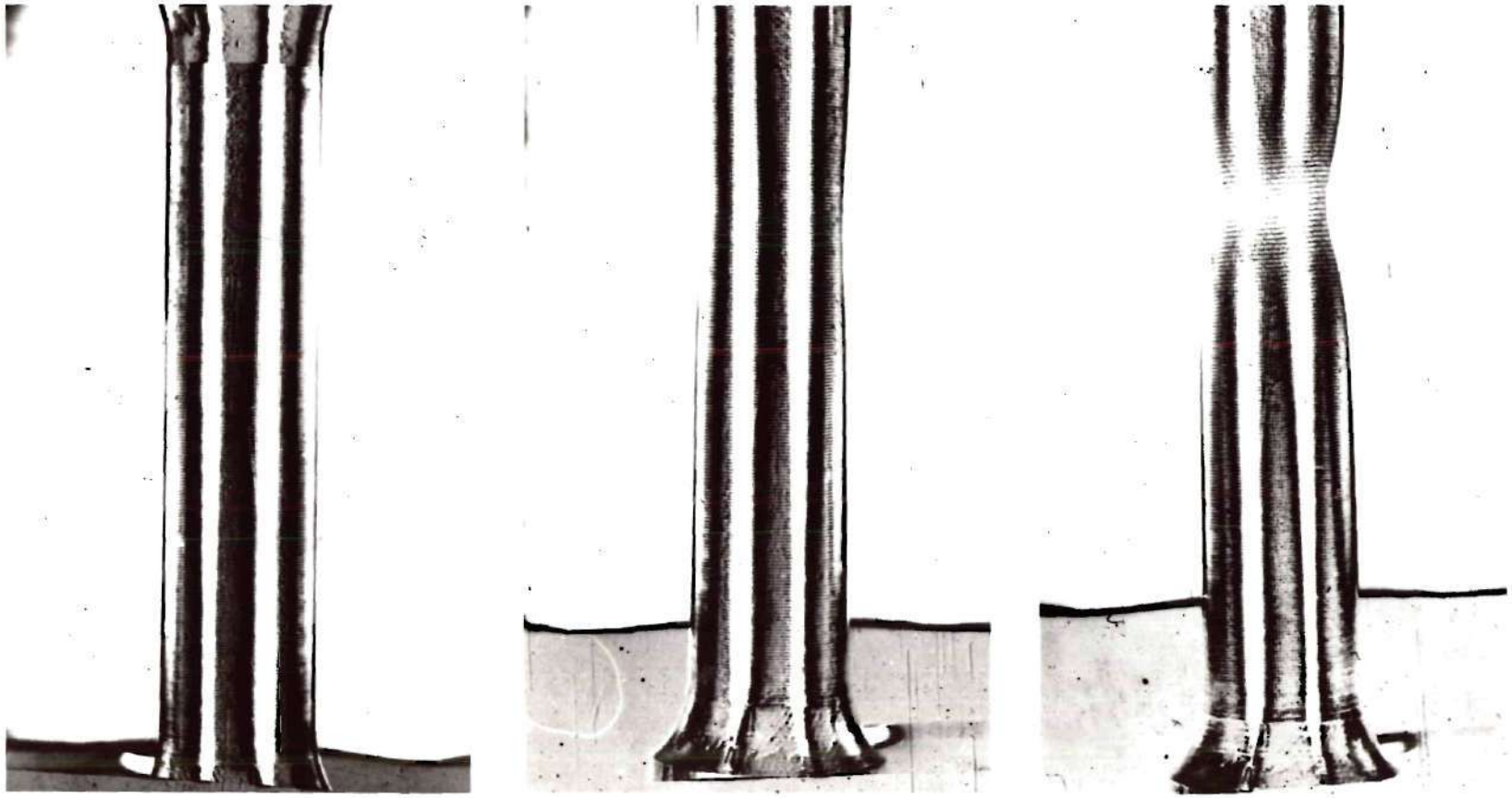


Figure 1. Test Apparatus.



A. UNLOADED SPECIMEN B. AT START OF NECKING C. JUST BEFORE FRACTURE

Figure 2. 1018 Steel Specimen No. 9 at Three Test Stages Showing Typical Grid Elongation.

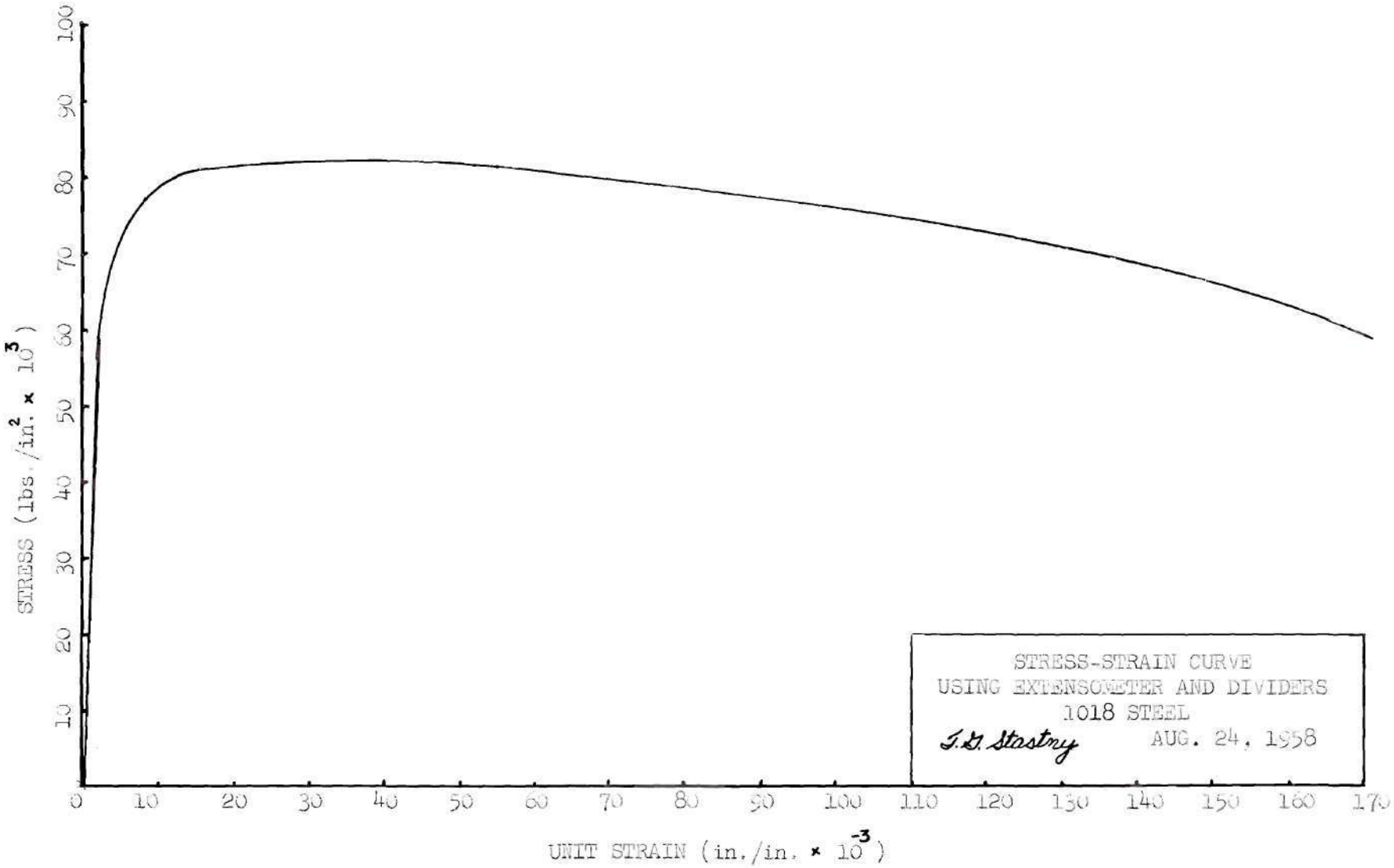

STRESS (lbs./in.^{2} × 10^3)
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
UNIT STRAIN (in./in. × 10^{-3})
STRESS-STRAIN CURVE
USING EXTENSOMETER AND DIVIDERS
1018 STEEL
T.G. Stastny
AUG. 24, 1958

FIGURE 3

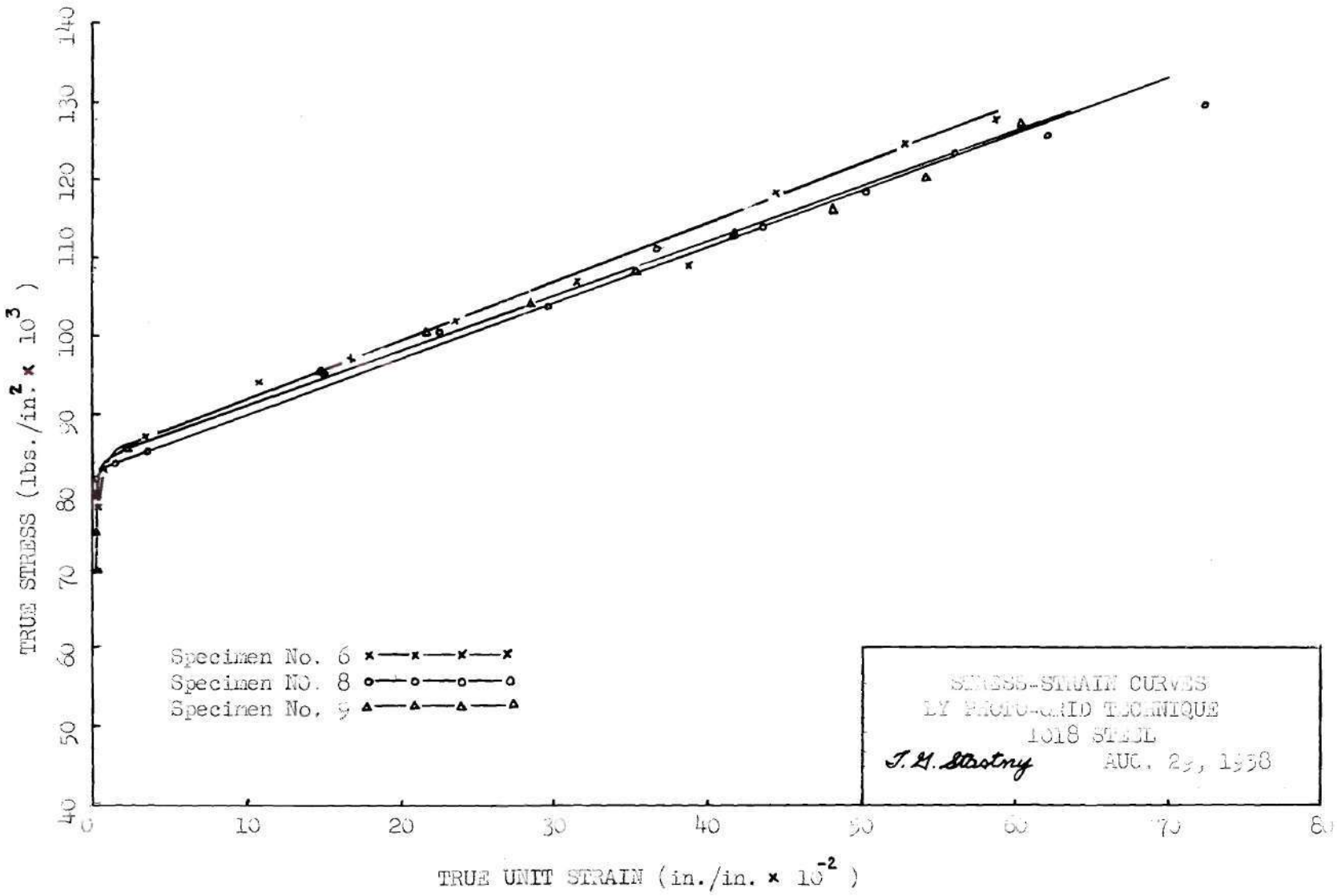

TRUE STRESS (lbs./in.^{2} × 10^3)
TRUE UNIT STRAIN (in./in. × 10^{-2})
Specimen No. 6
Specimen No. 8
Specimen No. 9
STRESS-STRAIN CURVES
BY PHOTO-GRID TECHNIQUE
1018 STEEL
T. G. Slastny
AUG. 29, 1958

FIGURE 4

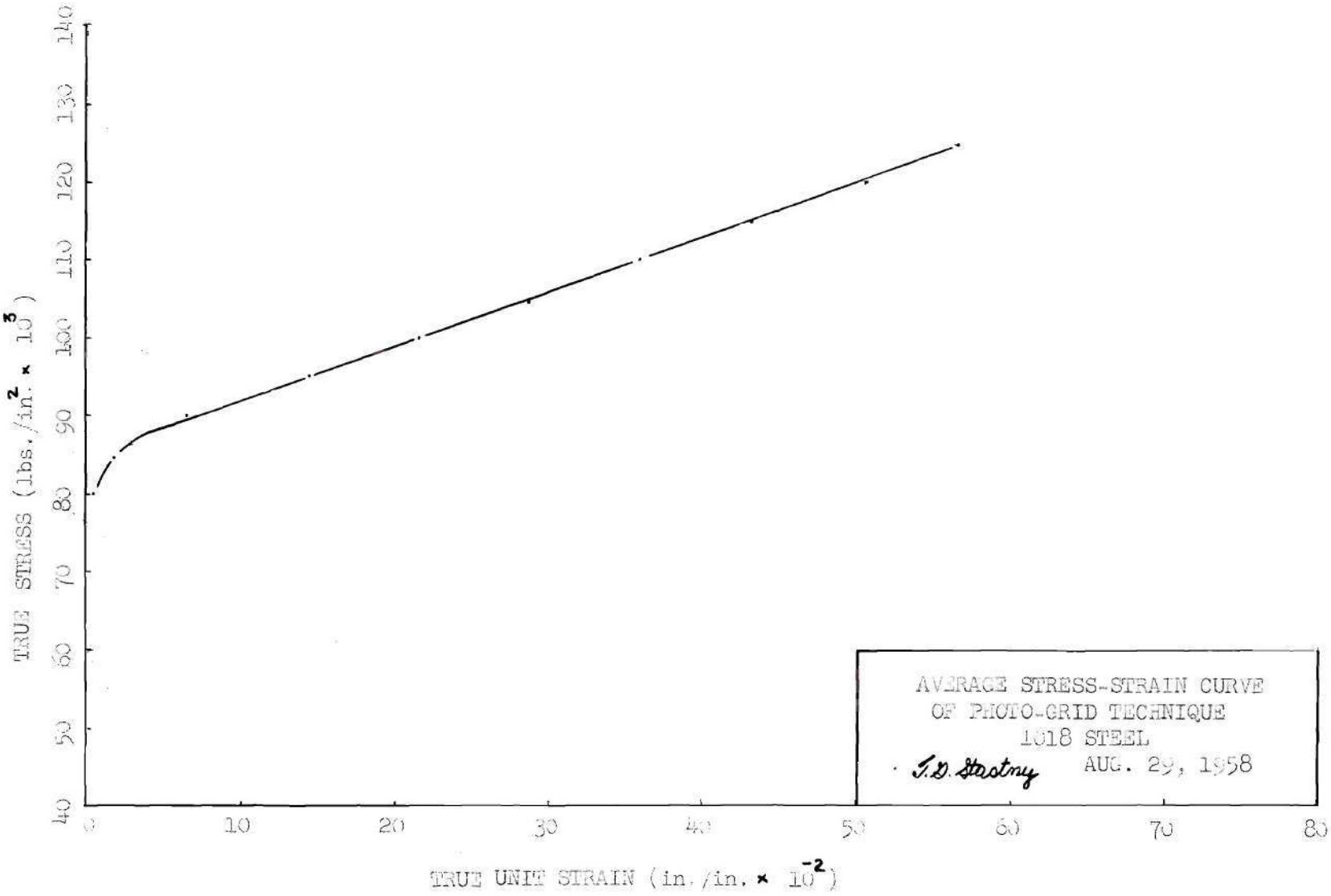

TRUE STRESS (lbs./in.^{2} × 10^3)
40
50
60
70
80
90
100
110
120
130
140
0
10
20
30
40
50
60
70
80
TRUE UNIT STRAIN (in./in. × 10^{-2})
AVERAGE STRESS-STRAIN CURVE
OF PHOTO-GRID TECHNIQUE
1018 STEEL
T.D. Starstny
AUG. 29, 1958

FIGURE 5

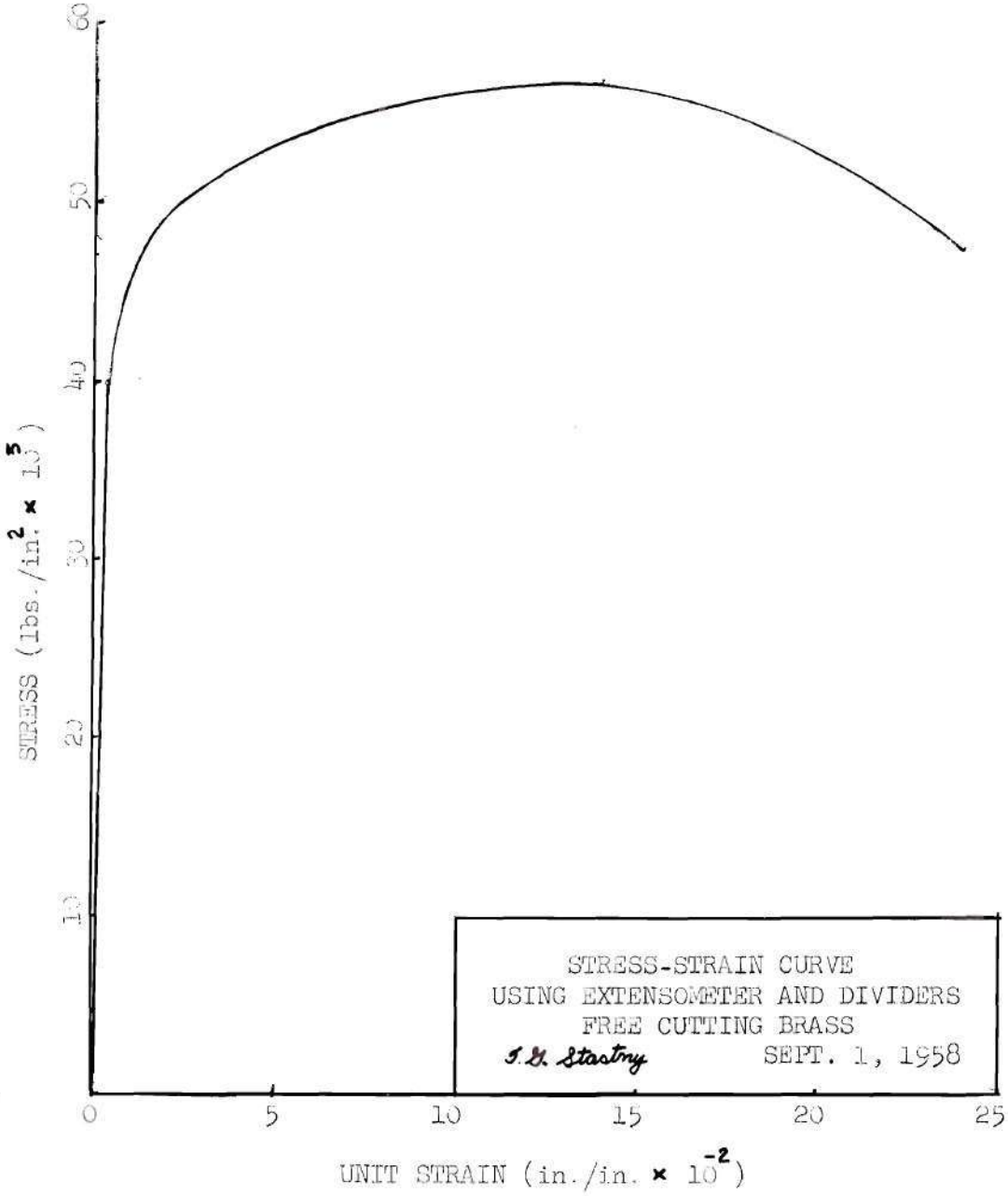

STRESS-STRAIN CURVE
USING EXTENSOMETER AND DIVIDERS
FREE CUTTING BRASS
J. G. Stastny
SEPT. 1, 1958
STRESS (lbs./in.^{2} × 10^3)
UNIT STRAIN (in./in. × 10^{-2})
0
5
10
15
20
25
10
20
30
40
50
60

FIGURE 6

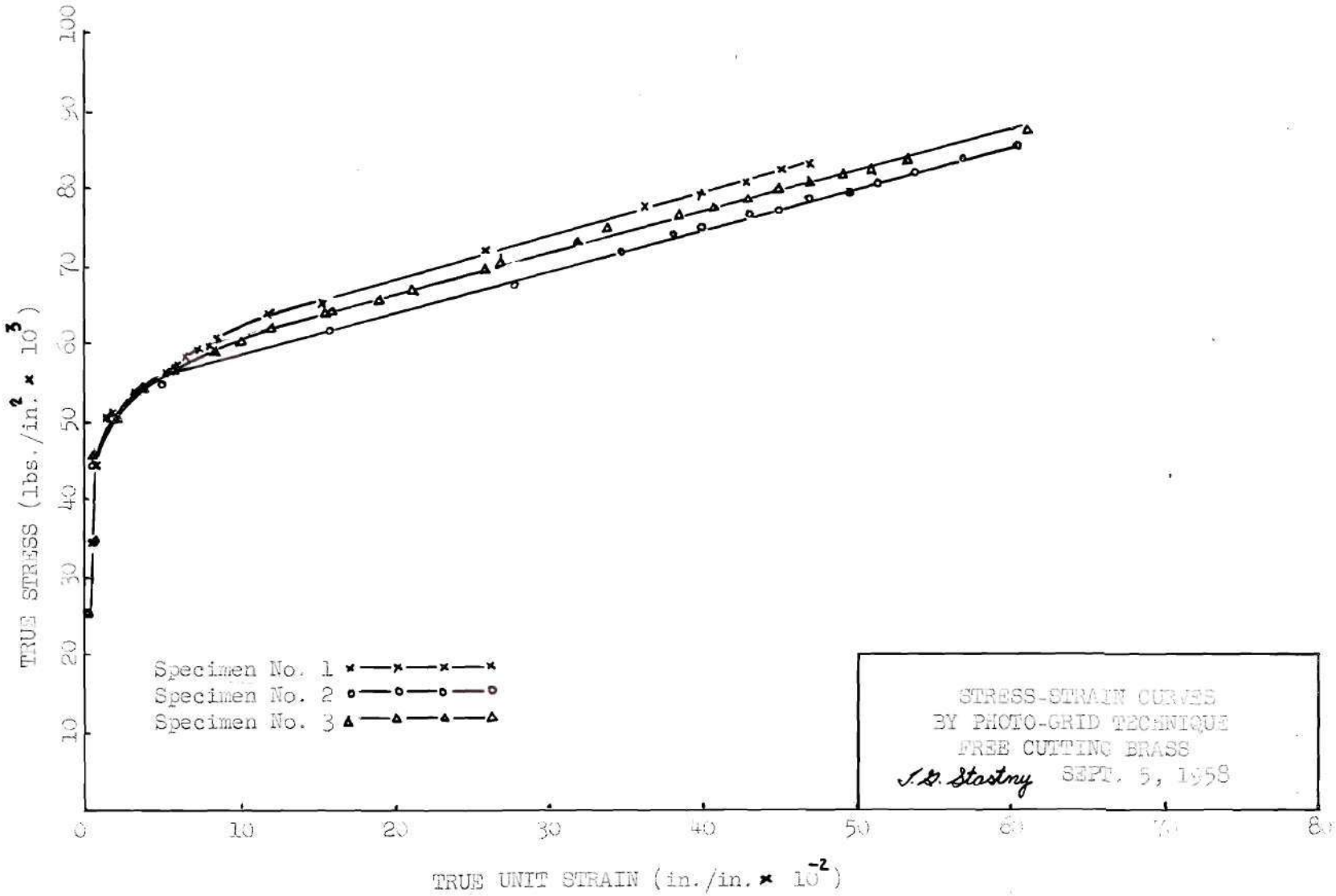

TRUE STRESS (lbs./in.^{2} × 10^3)
TRUE UNIT STRAIN (in./in. × 10^{-2})
Specimen No. 1
Specimen No. 2
Specimen No. 3
STRESS-STRAIN CURVES
BY PHOTO-GRID TECHNIQUE
FREE CUTTING BRASS
S.D. Stastny SEPT. 5, 1958

FIGURE 7

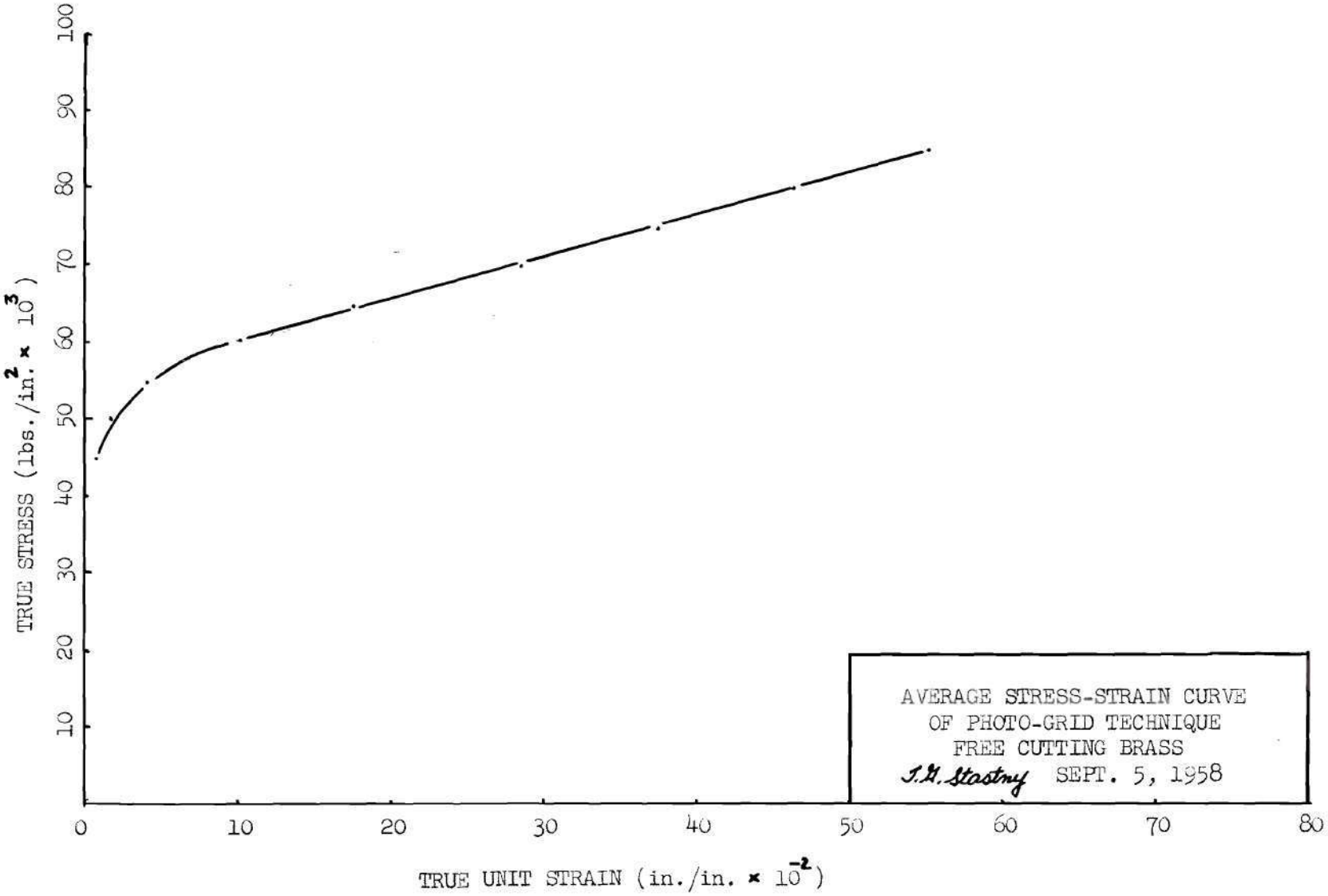

TRUE STRESS (lbs./in.^{2} × 10^3)
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
TRUE UNIT STRAIN (in./in. × 10^{-2})
AVERAGE STRESS-STRAIN CURVE
OF PHOTO-GRID TECHNIQUE
FREE CUTTING BRASS
T.H. Stastny SEPT. 5, 1958

FIGURE 8

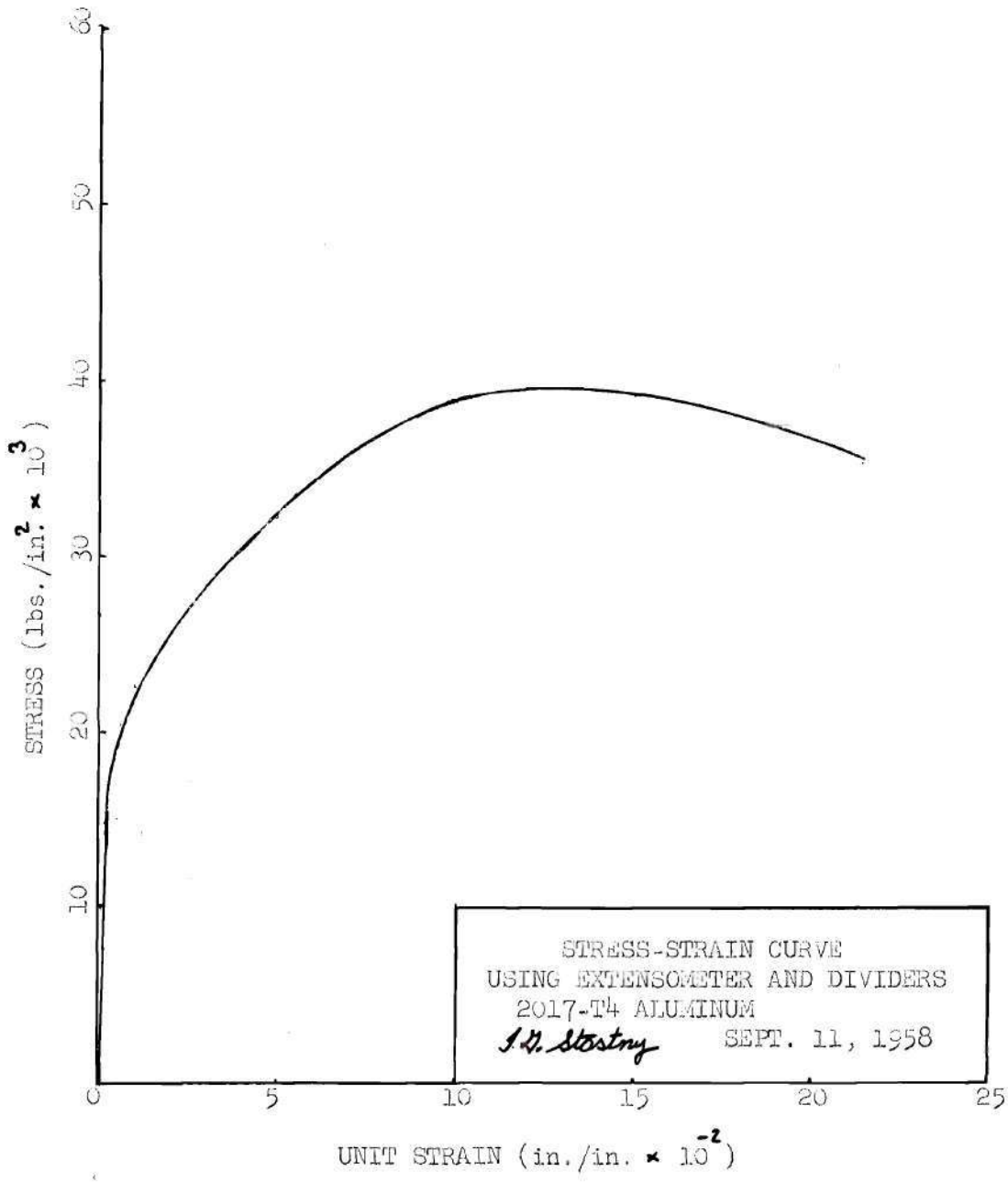
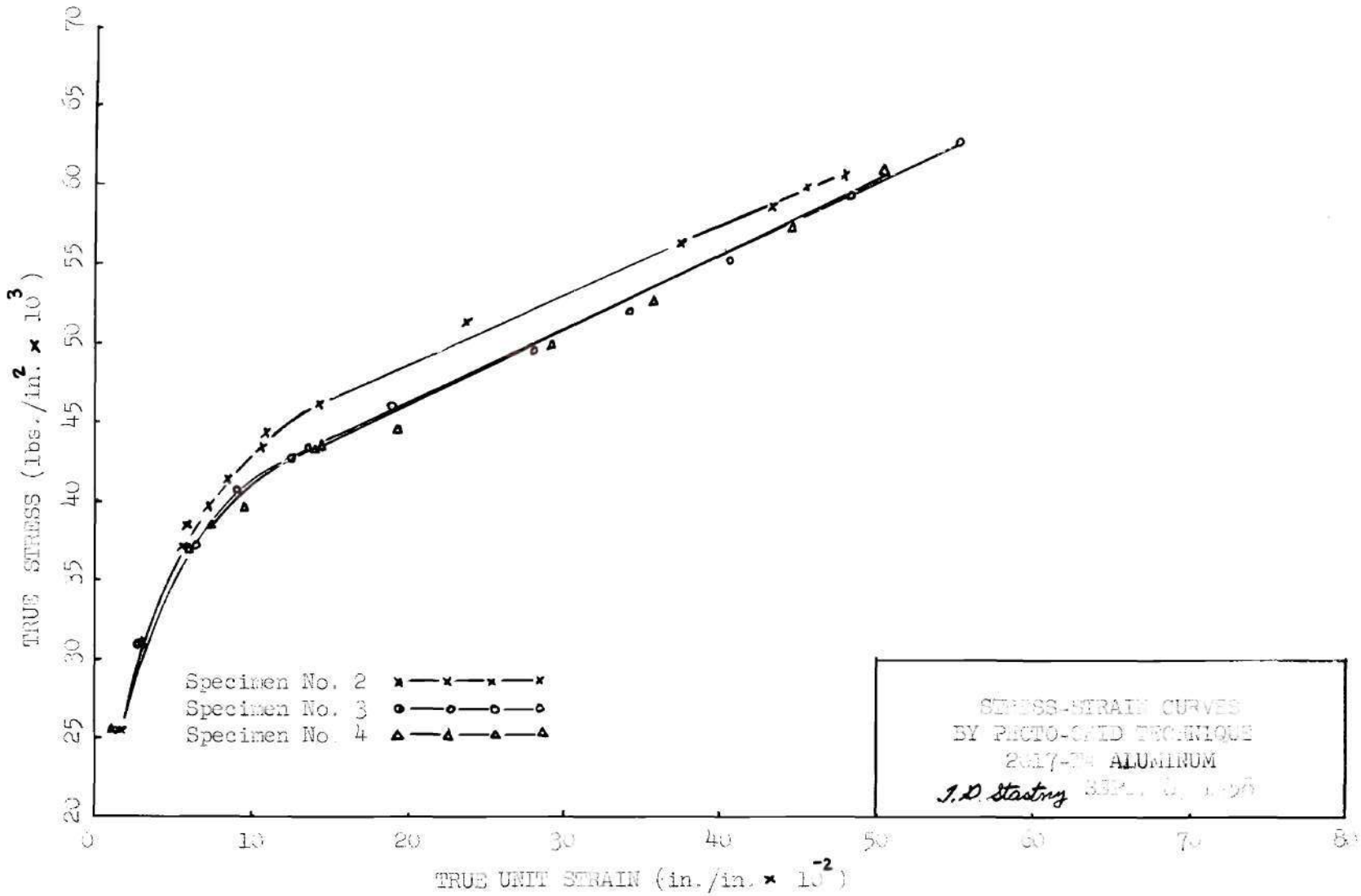

STRESS (lbs./in.^{2} × 10^3)
60
50
40
30
20
10
0
5
10
15
20
25
UNIT STRAIN (in./in. × 10^{-2})
STRESS-STRAIN CURVE
USING EXTENSOMETER AND DIVIDERS
2017-T4 ALUMINUM
I. D. Stostny
SEPT. 11, 1958

FIGURE 9


TRUE STRESS (lbs./in.^{2} x 10^3)
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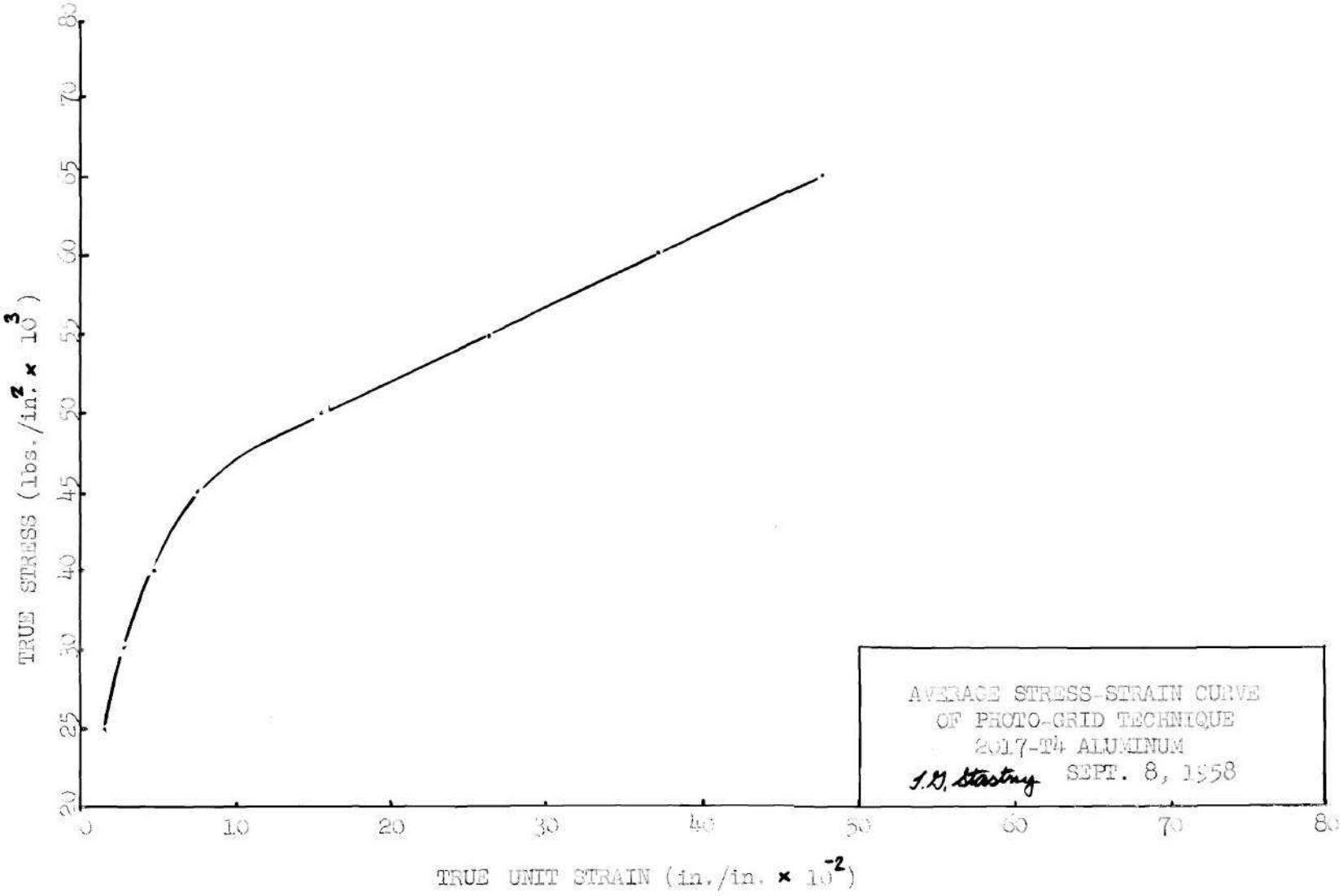
25
30
35
40
45
50
55
60
65
70
0
10
20
30
40
50
60
70
80
TRUE UNIT STRAIN (in./in. x 10^{-2})
Specimen No. 2
Specimen No. 3
Specimen No. 4
STRESS-STRAIN CURVES
BY PHOTO-GRID TECHNIQUE
2017-T4 ALUMINUM
J. D. Stastny

FIGURE 10


TRUE STRESS (lbs./in.^{2} × 10^3)
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25
30
35
40
45
50
55
60
65
70
75
80
0
10
20
30
40
50
60
70
80
TRUE UNIT STRAIN (in./in. × 10^{-2})
AVERAGE STRESS-STRAIN CURVE
OF PHOTO-GRID TECHNIQUE
2017-T4 ALUMINUM
SEPT. 8, 1958

FIGURE 11

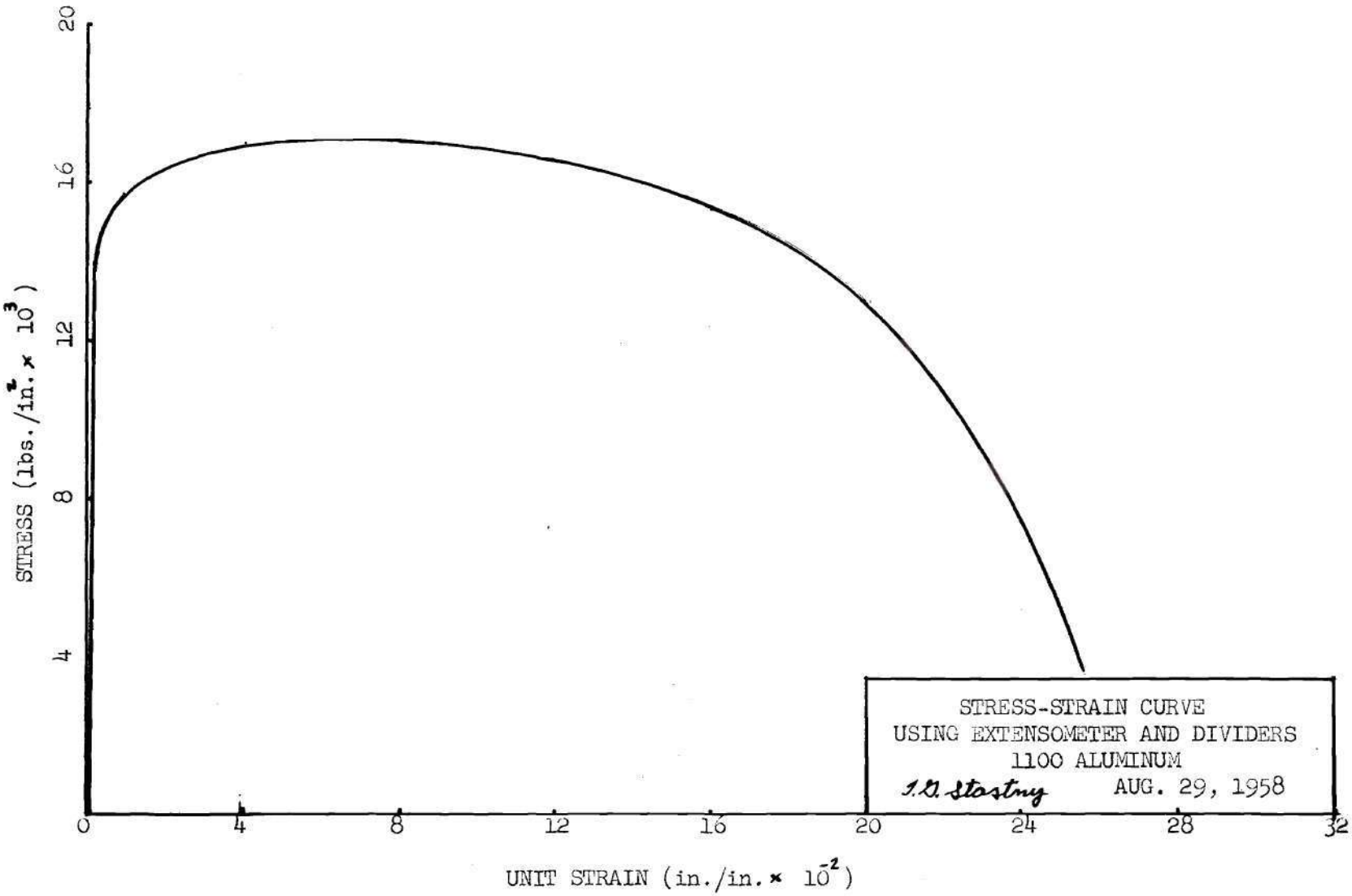
STRESS (lbs./in.² × 10³)
20
16
12
8
4
0
4
8
12
16
20
24
28
32
UNIT STRAIN (in./in. × 10⁻²)
STRESS-STRAIN CURVE
USING EXTENSOMETER AND DIVIDERS
1100 ALUMINUM
J.D. Stastny
AUG. 29, 1958

FIGURE 12

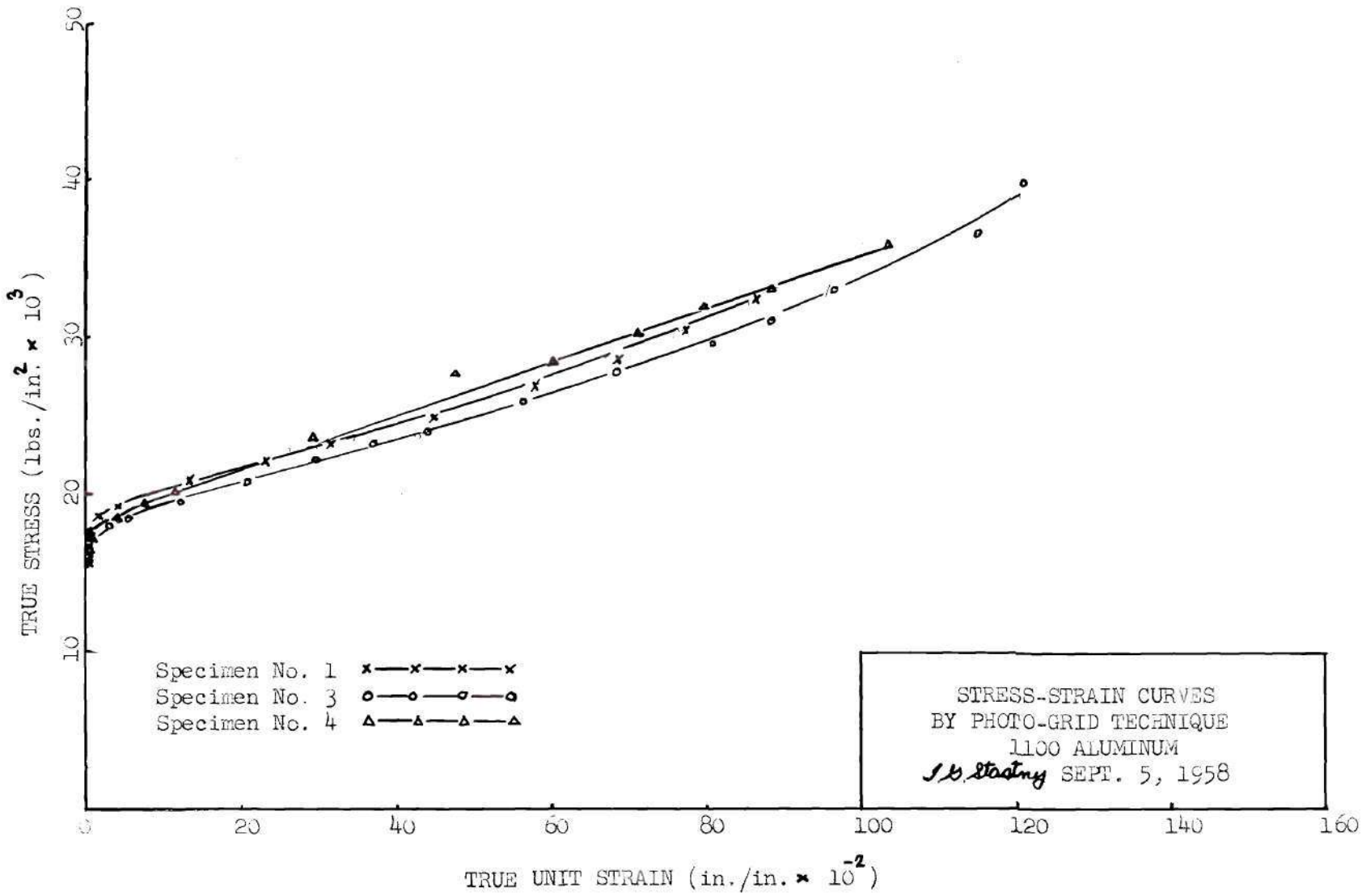
TRUE STRESS (lbs./in.^{2} × 10^3)
50
40
30
20
10
0
20
40
60
80
100
120
140
160
TRUE UNIT STRAIN (in./in. × 10^{-2})
Specimen No. 1
Specimen No. 3
Specimen No. 4
STRESS-STRAIN CURVES
BY PHOTO-GRID TECHNIQUE
1100 ALUMINUM
S.B. Stastny SEPT. 5, 1958

FIGURE 13

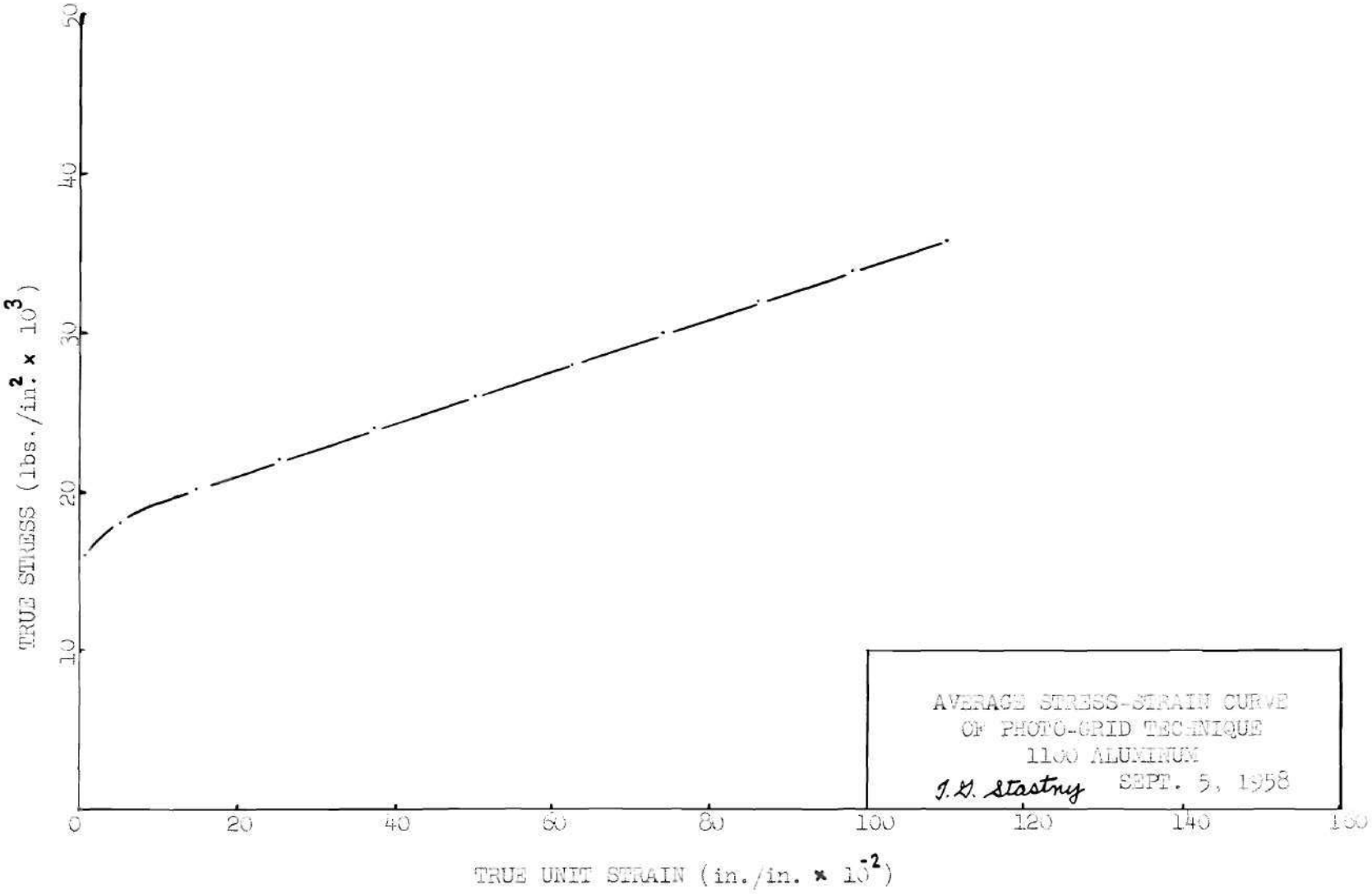
TRUE STRESS (lbs./in.^{2} x 10^3)
10
20
30
40
50
0
20
40
60
80
100
120
140
160
TRUE UNIT STRAIN (in./in. x 10^{-2})
AVERAGE STRESS-STRAIN CURVE
OF PHOTO-GRID TECHNIQUE
1100 ALUMINUM
J. D. Stastny
SEPT. 5, 1958

FIGURE 14

Table 1. Photo-Grid Data for Stress-Strain Relations

Specimen No. 6 Type Material: 1018 Steel

Initial Diameter = 0.4980 inch

5.270 K = 0.4980

K = 0.094497

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.270	0.1947	0	2.738	0
3	1,000	5.264	0.1947	5,136	---	---
4	5,000	5.274	0.1947	25,681	---	---
5	10,000	5.244	0.1947	51,361	---	---
6	12,000	5.257	0.1947	61,633	---	---
7	13,000	5.262	0.1947	66,769	2.739	---
8	14,000	5.248	0.1947	71,905	2.735	---
9	15,000	5.241	0.1924	77,963	2.745	0.00256
10	16,000	5.241	0.1924	83,160	2.751	0.00475
11	16,440	5.210	0.1901	86,481	2.787	0.01789
12	16,550	5.187	0.1886	87,168	2.821	0.03031
13	16,000	4.930	0.1703	93,952	3.027	0.10555
14	15,500	4.776	0.1598	96,996	3.193	0.16617
15	15,000	4.583	0.1473	101,833	3.370	0.23082
16	14,500	4.387	0.1352	107,249	3.603	0.31592
17	14,000	4.291	0.1391	108,443	3.810	0.39153
18	13,500	4.030	0.1140	118,421	3.995	0.44444
19	13,000	3.869	0.1049	123,928	4.188	0.52958
20	12,500	3.728	0.0973	128,469	4.348	0.58802
	12,000	(Fracture)				

Table 2. Photo-Grid Data for Stress-Strain Relations

Specimen No. 8 Type Material: 1018 Steel

Initial Diameter = 0.5005 inch

5.260 K = 0.5005

K = 0.095152

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.260	0.1967	0	2.734	0
3	1,000	5.258	0.1967	5,084	---	---
4	3,000	5.143	0.1967	15,252	---	---
5	7,000	5.249	0.1967	35,587	---	---
6	10,000	5.262	0.1967	50,839	2.734	---
7	12,000	5.261	0.1967	61,007	2.728	---
8	13,000	5.257	0.1967	66,090	2.725	---
9	14,000	5.258	0.1967	71,174	2.731	---
10	15,000	5.254	0.1967	76,258	2.733	---
11	16,000	5.238	0.1952	81,967	2.740	0.00219
12	16,290	5.216	0.1932	84,317	2.773	0.01426
13	16,320	5.172	0.1901	85,850	2.830	0.03511
14	16,000	4.851	0.1672	95,694	3.141	0.14886
15	15,500	4.662	0.1545	100,324	3.348	0.22457
16	15,000	4.502	0.1439	104,239	3.547	0.29736
17	14,500	4.284	0.1304	111,196	3.741	0.36832
18	14,000	4.151	0.1225	114,286	3.929	0.43708
19	13,500	3.994	0.1134	119,048	4.113	0.50438
20	13,000	3.842	0.1049	123,928	4.272	0.56254
21	12,500	3.730	0.0989	126,390	4.432	0.62106
22	12,000	3.609	0.0924	129,870	4.727	0.72896
	11,800	(Fractured)				

Table 3. Photo-Grid Data for Stress-Strain Relations

Specimen No. 9 Type Material: 1018 Steel

Initial Diameter = 0.5051 inch

K 5.269 = 0.5051

K = 0.095862

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.269	0.2003	0	2.713	0
3	1,000	5.261	0.2003	4,993	---	---
4	3,000	5.264	0.2003	14,978	---	---
5	7,000	5.267	0.2003	34,948	---	---
6	10,000	5.258	0.2003	49,925	---	---
7	12,000	5.264	0.2003	59,910	---	---
8	13,000	5.262	0.2003	64,903	---	---
9	14,000	5.253	0.2003	69,895	2.717	0.00147
10	15,000	5.261	0.2003	74,888	2.718	0.00184
11	16,000	5.265	0.2003	79,880	2.725	0.00442
12	16,880	5.215	0.1963	85,990	2.768	0.01953
13	16,500	4.869	0.1710	96,491	3.113	0.1474
14	16,000	4.685	0.1583	101,074	3.296	0.2148
15	15,500	4.513	0.1469	105,514	3.491	0.2867
16	15,000	4.378	0.1381	108,617	3.668	0.3520
17	14,500	4.209	0.1278	113,459	3.845	0.4172
18	14,000	4.082	0.1200	116,667	4.020	0.4817
19	13,500	3.946	0.1122	120,321	4.183	0.5418
20	13,000	3.759	0.1017	127,827	4.350	0.6033
	12,500	(Fracture)				

Table 4. Photo-Grid Data for Stress-Strain Relations

Specimen No. 1

Type Material: Free Cutting Brass

Initial Diameter = 0.5080 inch

K 5.736 = 0.5080

K = 0.088563

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.736	0.2027	0	2.928	0
3	1,000	5.733	0.2023	4,943	2.930	---
4	3,000	5.734	0.2023	14,829	2.928	---
5	5,000	5.727	0.2019	24,767	2.933	0.00171
6	7,000	5.729	0.2019	34,671	2.941	0.00444
7	9,000	5.725	0.2018	44,599	2.954	0.00888
8	10,000	5.695	0.1995	50,125	2.969	0.01400
9	10,300	5.644	0.1995	51,629	2.983	0.01878
10	10,600	5.653	0.1968	53,862	3.021	0.03176
11	10,900	5.590	0.1924	56,653	3.079	0.05157
12	11,000	5.573	0.1912	57,531	3.100	0.05874
13	11,000	5.556	0.1901	57,864	3.117	0.06454
14	11,080	5.524	0.1878	58,999	3.147	0.07479
15	11,140	5.506	0.1867	59,668	3.158	0.07855
16	11,200	5.482	0.1852	60,475	3.190	0.08948
17	11,300	5.414	0.1805	62,604	3.281	0.12056
18	11,400	5.347	0.1760	64,773	3.382	0.15505
19	11,400	5.120	0.1612	70,720	3.695	0.26195
20	11,200	4.870	0.1459	76,765	4.001	0.36646
21	11,100	4.798	0.1418	78,279	4.110	0.40368
22	11,000	4.732	0.1379	79,768	4.191	0.43135
23	10,900	4.648	0.1330	81,955	4.259	0.45457
24	10,800 (Fracture)	4.617	0.1312	82,317	4.321	0.47575

Table 5. Photo-Grid Data for Stress-Strain Relations

Specimen No. 2 Type Material: Free Cutting Brass

Initial Diameter = 0.5055 inch

K 5.710 = 0.5055

K = 0.088529

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.710	0.2006	0	2.905	0
3	1,000	5.710	0.2006	4,985	2.901	---
4	3,000	5.698	0.2006	14,955	2.907	---
5	5,000	5.698	0.2006	24,925	2.911	0.00206
6	7,000	5.704	0.2006	34,895	2.922	0.00585
7	9,000	5.691	0.2006	44,865	2.923	0.00620
8	10,000	5.645	0.1961	50,994	2.962	0.01962
9	10,500	5.573	0.1911	54,945	3.050	0.04991
10	10,920	5.362	0.1769	61,730	3.382	0.16420
11	10,900	5.106	0.1605	67,913	3.720	0.28055
12	10,800	4.933	0.1497	72,144	3.916	0.34802
13	10,700	4.833	0.1437	74,461	4.010	0.38038
14	10,600	4.788	0.1410	75,177	4.071	0.40138
15	10,500	4.721	0.1372	76,531	4.158	0.43133
16	10,400	4.679	0.1347	77,208	4.222	0.45386
17	10,300	4.600	0.1302	79,109	4.280	0.47332
18	10,200	4.566	0.1283	79,501	4.347	0.49639
19	10,100	4.499	0.1245	81,124	4.406	0.51670
20	10,000	4.447	0.1217	82,169	4.470	0.53873
21	9,900	4.362	0.1170	83,760	4.566	0.57177
22	9,600	4.268	0.1121	85,638	4.667	0.60654
	9,300	(Fracture)				

Table 6. Photo-Grid Data for Stress-Strain Relations

Specimen No. 3 Type Material: Free Cutting Brass

Initial Diameter = 0.5040 inch

K 5.714 = 0.5040

K = 0.088204

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.714	0.1995	0	2.955	0
3	1,000	5.689	0.1995	5,115	2.950	---
4	3,000	5.689	0.1995	15,345	2.957	---
5	5,000	5.684	0.1995	25,575	2.961	---
6	7,000	5.682	0.1995	35,806	2.961	---
7	9,000	5.664	0.1960	45,918	2.972	0.00575
8	10,000	5.644	0.1946	51,387	2.996	0.01387
9	10,500	5.593	0.1909	55,003	3.066	0.03756
10	10,750	5.545	0.1878	57,242	3.138	0.06193
11	10,880	5.495	0.1844	59,002	3.201	0.08325
12	11,000	5.420	0.1794	61,315	3.255	0.10152
13	11,100	5.402	0.1783	62,255	3.321	0.12386
14	11,120	5.315	0.1726	64,426	3.411	0.15431
15	11,130	5.312	0.1723	64,597	3.423	0.15838
16	11,130	5.250	0.1684	66,093	3.519	0.19086
17	11,100	5.194	0.1647	67,395	3.577	0.21049
18	11,000	5.097	0.1586	69,357	3.728	0.26159
19	10,900	4.995	0.1524	71,522	3.746	0.26768
20	10,800	4.913	0.1475	73,220	3.922	0.32724
21	10,700	4.826	0.1422	75,246	3.995	0.33840
22	10,600	4.776	0.1393	76,095	4.091	0.38443
23	10,500	4.725	0.1363	77,036	4.164	0.40914
24	10,400	4.654	0.1323	78,609	4.227	0.43046
25	10,300	4.589	0.1286	80,093	4.290	0.45178
26	10,200	4.567	0.1272	80,189	4.346	0.47073
27	10,100	4.495	0.1233	81,914	4.410	0.49239
28	10,000	4.469	0.1219	82,034	4.477	0.51506
29	9,900	4.419	0.1193	82,984	4.540	0.53638
30	9,500	4.219	0.1087	87,397	4.766	0.61286
	9,300	(Fracture)				

Table 7. Photo-Grid Data for Stress-Strain Relations

Specimen No. 2 Type Material: 2017-T4 Aluminum

Initial Diameter = 0.5020 inch

K 5.738 = 0.5020

K = 0.08748

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.738	0.1979	0	2.929	0
3	1,000	5.731	0.1979	5,053	2.931	0.00068
4	3,000	5.740	0.1979	15,159	2.932	0.00102
5	5,000	5.702	0.1953	25,603	2.983	0.01844
6	7,000	5.608	0.1889	37,057	3.090	0.05497
7	7,200	5.582	0.1872	38,462	3.097	0.05736
8	7,400	5.561	0.1858	39,828	2.137	0.07101
9	7,600	5.522	0.1832	41,485	3.182	0.08638
10	7,800	5.465	0.1795	43,454	3.243	0.10720
11	8,000	5.467	0.1795	44,568	3.246	0.10823
12	8,100	5.407	0.1757	46,103	3.349	0.14339
13	8,070	5.122	0.1576	51,206	3.628	0.23865
14	7,750	4.791	0.1379	56,200	4.027	0.37487
15	7,600	4.652	0.1301	58,417	4.198	0.43325
16	7,500	4.581	0.1256	59,713	4.268	0.45715
17	7,400	4.522	0.1228	60,261	4.337	0.48071
	7,300	(Fracture)				

Table 8. Photo-Grid Data for Stress-Strain Relations

Specimen No. 3 Type Material: 2017-T4 Aluminum

Initial Diameter = 0.5040 inch

$K\ 5.798 = 0.5040$

$K = 0.086927$

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.798	0.1995	0	2.914	0
3	1,000	5.790	0.1995	5,013	2.899	---
4	3,000	5.793	0.1995	15,038	2.913	---
5	5,000	5.758	0.1967	25,419	2.963	0.01682
6	6,000	5.711	0.1935	31,008	2.997	0.02848
7	7,000	5.628	0.1880	37,234	3.102	0.06452
8	7,400	5.548	0.1826	40,526	3.179	0.09094
9	7,600	5.489	0.1788	42,506	3.274	0.12354
10	7,620	5.458	0.1767	43,124	3.307	0.13487
11	7,630	5.314	0.1676	45,525	3.469	0.19046
12	7,600	5.095	0.1541	49,319	3.727	0.27900
13	7,550	4.949	0.1453	51,961	3.911	0.34214
14	7,500	4.787	0.1359	55,188	4.098	0.40631
15	7,400	4.584	0.1247	59,342	4.323	0.48353
16	7,300	4.416	0.1157	63,094	4.525	0.55285
	7,200	(Fracture)				

Table 9. Photo-Grid Data for Stress-Strain Relations

Specimen No. 4 Type Material: 2017-T4 Aluminum

Initial Diameter = 0.5035 inch

K 5.720 = 0.5035

K = 0.088025

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.720	0.1991	0	2.932	0
3	1,000	5.721	0.1991	5,023	2.929	---
4	3,000	5.710	0.1984	15,121	2.935	---
5	5,000	5.673	0.1958	25,536	2.973	0.01398
6	6,000	5.646	0.1940	30,928	3.022	0.03070
7	7,000	5.566	0.1885	37,135	3.114	0.06207
8	7,200	5.550	0.1874	38,420	3.157	0.07674
9	7,400	5.533	0.1862	39,742	3.214	0.09618
10	7,610	5.394	0.1770	42,994	3.340	0.13915
11	7,680	5.384	0.1764	43,537	3.353	0.14359
12	7,680	5.312	0.1717	44,729	3.497	0.19270
13	7,650	5.020	0.1533	49,902	3.790	0.29263
14	7,600	4.857	0.1435	52,962	3.979	0.35709
15	7,500	4.619	0.1298	57,781	4.239	0.44577
16	7,400	4.458	0.1209	61,208	4.412	0.50477
	7,300	(Fracture)				

Table 10. Photo-Grid Data for Stress-Strain Relations

Specimen No. 1 Type Material: 1100 Aluminum

Initial Diameter = 0.5035 inch

K 5.736 = 0.5035

K = 0.087779

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.736	0.1991	0	2.980	0
3	500	5.736	0.1991	2,511	2.980	---
4	1,000	5.736	0.1991	5,023	2.982	---
5	1,500	5.736	0.1991	7,534	2.985	---
6	2,000	5.741	0.1991	10,045	2.978	---
7	2,500	5.741	0.1991	12,557	2.982	---
8	3,000	5.741	0.1991	15,068	2.981	---
9	3,100	5.741	0.1991	15,570	2.986	0.00201
10	3,200	5.740	0.1991	16,072	2.990	0.00335
11	3,300	5.742	0.1991	16,575	2.992	0.00403
12	3,400	5.716	0.1977	17,198	2.994	0.00470
13	3,500	5.709	0.1971	17,757	3.005	0.00839
14	3,600	5.681	0.1953	18,433	3.040	0.02013
15	3,630	5.601	0.1898	19,125	3.107	0.04261
16	3,600	5.357	0.1735	20,749	3.380	0.13422
17	3,500	5.124	0.1589	22,026	3.666	0.23020
18	3,400	4.922	0.1466	23,192	3.904	0.31006
19	3,200	4.613	0.1288	24.845	4.321	0.45000
20	3,000	4.262	0.1099	27,298	4.713	0.58154
21	2,800	4.011	0.0973	28,777	5.019	0.68422
22	2,600	3.754	0.0852	30,516	5.297	0.77751
23	2,400	3.512	0.0745	32,215	5.564	0.86711
	1,000	(Fracture)				

Table 11. Photo-Grid Data for Stress-Strain Relations

Specimen No. 3 Type Material: 1100 Aluminum

Initial Diameter = 0.4975 inch

K 5.640 = 0.4975

K = 0.088209

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.640	0.1944	0	2.940	0
3	500	5.637	0.1944	2,527	2.943	---
4	1,000	5.640	0.1944	5,144	2.946	---
5	1,500	5.644	0.1944	7,716	2.948	---
6	2,000	5.650	0.1944	10,288	2.949	---
7	2,500	5.632	0.1944	12,860	2.950	---
8	3,000	5.637	0.1944	15,432	2.952	0.00408
9	3,200	5.632	0.1944	16,460	2.962	0.00748
10	3,300	5.603	0.1918	17,205	2.970	0.01020
11	3,380	5.540	0.1876	18,017	3.045	0.03571
12	3,380	5.475	0.1832	18,450	3.105	0.05612
13	3,380	5.329	0.1735	19,481	3.291	0.11939
14	3,300	5.089	0.1583	20,846	3.558	0.21020
15	3,200	4.868	0.1448	22,099	3.817	0.29830
16	3,100	4.661	0.1327	23.361	4.046	0.37619
17	3,000	4.519	0.1248	24,038	4.236	0.44082
18	2,800	4.196	0.1075	26,047	4.600	0.56463
19	2,600	3.899	0.0929	27,987	4.957	0.68605
20	2,400	3.644	0.0811	29,593	5.327	0.81190
21	2,200	3.394	0.0704	31,250	5.537	0.88333
22	2,000	3.154	0.0607	32,949	5.781	0.96633
23	1,500	2.587	0.0408	36,765	6.314	1.14762
	≈ 1,400 (Fracture)	2.391	0.0349	40,115	6.483	1.20510

Table 12. Photo-Grid Data for Stress-Strain Relations

Specimen No. 4 Type Material: 1100 Aluminum

Initial Diameter = 0.5015 inch

K 5.727 = 0.5015

K = 0.087568

Fr. No.	Load lbs.	Diam. mm.	Area sq. in.	Stress lbs./sq. in.	25 Lines mm.	Strain MM./mm.
1	Identification					
2	0	5.727	0.1975	0	2.964	0
3	500	5.726	0.1975	2,532	2.967	---
4	1,000	5.712	0.1975	5,063	2.961	---
5	1,500	5.705	0.1975	7,595	2.961	---
6	2,000	5.715	0.1975	10,127	2.966	---
7	2,500	5.715	0.1975	12,658	2.967	---
8	3,000	5.704	0.1975	15,190	2.973	0.00304
9	3,200	5.694	0.1975	16,203	2.974	0.00337
10	3,300	5.695	0.1975	16,709	2.978	0.00472
11	3,400	5.676	0.1940	17,526	2.992	0.00945
12	3,500	5.610	0.1894	18,479	3.084	0.04049
13	3,500	5.482	0.1810	19,337	3.184	0.07422
14	3,500	5.366	0.1734	20,185	3.309	1.11640
15	3,400	4.904	0.1448	23,481	3.830	0.29217
16	3,200	4.446	0.1190	26,891	4.775	0.47605
17	3,000	4.171	0.1047	28,653	4.745	0.60088
18	2,800	3.911	0.0920	30,435	5.066	0.70918
19	2,600	3.669	0.0810	32,099	5.327	0.79723
20	2,400	3.459	0.0721	33,287	5.587	0.88495
21	2,000	3.052	0.0560	35,714	6.027	1.03340
22	1,500	2.763	0.0459	32,680	6.261	1.11235
	1,000	(Fracture)				

Table 13. Arithmetic Average of Photo-Grid Technique

1018 Steel		Free Cutting Brass		2017-T4 Aluminum		1100 Aluminum	
Stress lbs/in^2	Strain in/in	Stress lbs/in^2	Strain in/in	Stress lbs/in^2	Strain in/in	Stress lbs/in^2	Strain in/in
80,000	0.003	45,000	0.007	20,000	0.008	16,000	0.005
85,000	0.019	50,000	0.015	25,000	0.016	18,000	0.050
90,000	0.063	55,000	0.040	30,000	0.028	20,000	0.145
95,000	0.143	60,000	0.110	35,000	0.046	22,000	0.255
100,000	0.215	65,000	0.176	40,000	0.074	24,000	0.375
105,000	0.287	70,000	0.285	45,000	0.154	26,000	0.500
110,000	0.360	75,000	0.373	50,000	0.262	28,000	0.625
115,000	0.431	80,000	0.462	55,000	0.370	30,000	0.740
120,000	0.506	85,000	0.550	60,000	0.476	32,000	0.860
125,000	0.567					34,000	0.980
						36,000	1.100

BIBLIOGRAPHY

1. MacGregor, C. W., "The Tension Test," Proceedings of the American Society for Testing Metals, v40, 1940, pp. 508-534.

2. Ludwik, P., "Elemente der technologischen Mekanik," Julius Springer, Berlin (1909).

3. Haskell, R. K., "True Stress-Strain Curves for Polycrystalline Material," Journal of Applied Physics, v9, January 1938, pp. 30-33.

4. Hencky, H., "The Elastic Behavior of Vulcanized Rubber," Journal of Applied Mechanics, June 1933, pp. 45-53.

5. Stead, J., "The Cold Working of Steel with Reference to the Tensile Test," Journal of the Iron and Steel Institute, v107, 1923, pp. 377-416.

6. Norris, E. B., "The Plastic Flow of Metals," No. 27, Engineering Station Series, Virginia Polytechnic Institute, 1936.

7. MacGregor, C. W., "Relations between Stress and Reduction of Area for Tensile Tests of Metals," Technical Publication 805, Metals Technology, April 1937.

8. Miller, J. A., "Improved Photogrid Techniques for Determination of Strain over Short Gage Lengths," Proceedings of the Society for Experimental Stress Analysis, v10, No. 1, 1952, pp. 29-34.

9. Davidson, W. J., Reproduction of Grids on Metals for Use in High Temperature and Stress Tests, Unpublished paper of The Lockheed Aircraft Corporation, Georgia Division, November 1957.