COLD DRAWING OF AUSTENITIC STAINLESS STEEL WIRE

By

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ABSTRACT

The drawing of austenitic stainless steel and brass wire has been studied. Experimental variables were reduction in area, temperature, and draw speed. For stainless steel, the effects of changes in all variables on drawing stress and drawing limit (drawability) were determined; deformation efficiency was measured at room temperature only. Drawing stress, deformation efficiency and drawability were determined for 70-30 brass at room temperature and at one speed.

Values for the coefficient of friction in wire drawing were calculated from experimental data using established wire drawing theories.

Cambridge, Massachusetts
May 25, 1953

Professor Earl B. Millard
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the Degree of Bachelor of Science in Mechanical Engineering, I hereby submit this report, entitled "Cold Drawing of Austenitic Stainless Steel Wire."

Respectfully yours,

Signature redacted

James H. Howard, Jr.

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INTRODUCTION

Much work has been done in the past on the wire drawing process. There are three major wire drawing theories developed by Hill and Tupper, Davis and Dokos, and Sachs. They all agree that when friction work and redundant work are zero the work done in drawing is equal to the work done in tensile stretching.

H. G. Baron and F. C. Thompson (1) in comparing the three theories state that that of Davis and Dokos appears to be the most accurate and will give reliable values of the coefficient of friction if redundant work is small or zero.

G. D. S. MacLellan (2) had adapted this theory to include the effect on draw stress of friction in the bearing section of a die—an important consideration that had been ignored previous to MacLellan's work.

These theories all relate the draw stress to die half-angle, coefficient of friction, reduction in area, and mechanical properties of the material. A simpler tool for analysis of the wire drawing process is the Deformation Efficiency concept. This defines an Efficiency η equal to the ratio of the work done in tensile stretching to the actual work done in the process. The work in tensile stretching is equal to the area under the true stress—true stress curve of the material drawn. The work actually expended in the process can be shown to equal the drawing stress or the drawing load divided by the cross sectional area of the wire after drawing.(3) This gives a reasonably good picture of the process if consistent drawing conditions are maintained.

Limited work has been done on the drawing of stainless steels, which are unique in that cold working induces a transformation of the austenite to martensite. It was the purpose of this thesis to obtain new and additional data pertaining to the martensite transformation and its role in the drawing process.

Since lower temperatures tend to promote the martensite transformation, it was decided to carry out some experiments at sub-zero temperatures.

EXPERIMENTAL MATERIALS, EQUIPMENT, AND PROCEDURES

Materials

The materials used in the experiments were:

1) commercial stainless steel rod-type 304; 0.250 inches in diameter; annealed in a hydrogen atmosphere for fifteen minutes at 1950°F.

Analysis:

Carb.	Mang.	Phos.	Sulphur	Nickel	Chromium	Moly.
.045	.45	.028	.011	8.81	18.50	.14

2) The experimental foundry prepared a melt of stainless steel to the specifications of type 301. This material was hot forged to 5/16 in. round stock, then wire drawn in the laboratory to 0.250 inches in diameter, then anealed in a hydrogen atmosphere for fifteen minutes at 1950°F. No chemical analysis is available for this material.

3) 70-30 Brass--received annealed; 0.250 inch diameter.

Equipment

A simple experimental setup was employed. A testing machine was used to draw the wires through the dies. The pointed end was gripped in the moving head and the wire was pulled through the dies, which sat on a steel block fitted snugly into the stationary head of the machine. The drawing load could then be measured on the balancing arm of the machine.

Two coolant reservoirs consisting of a two-inch diameter steel tubing brazed to an annular section of three-inch steel round were used. These were bolted to the steel die holder and held the coolant used in the low temperature tests around the dies and undrawn portion of the wire. A one-inch layer of asbestos was used to insulate the eight-inch length of tubing.

The following equipment was used:

1) A series of six tungsten carbide dies with diameters of 0.230, 0.212, 0.196, 0.181, 0.167, and 0.154 inches. With a rod of 0.250 initial diameter, these dies give the following respective reductions in area: 15.3%, 28.1%, 38.5%, 47.7%, 55.4%, and 62.1%. The half-die angles and bearing lengths measured with a special profilometer at the American Steel and Wire Works in Worcester, Massachusetts, were found to be:

Red in Area (%)	Die Diameter (in.)	Die Half Angle (degrees)	Bearing Length (in.)
15.3	0.230	7.0	0.101
28.1	0.212	9.6	0.096
38.5	0.196	6.5	0.072
47.7	0.181	7.2	0.058
55.4	0.167	8.0	0.074
62.1	0.154	7.1	0.057

2) A Tinius-Olsen Testing Machine--60,000 pound capacity to apply and measure the drawing load.

The following head speeds were available: 7.0 in./min, 1.12 in./min, and 0.28 in./min.

3) A die holder to position the dies in the testing machine and to keep the drawing load directed along the axis of the rod and perpendicular to the die cross section.

4) Templin grips (8,000 pound capacity) to draw the pointed wire through the dies.

5) Two "coolant reservoirs" to hold the low temperature baths used in some of the experiments.

6) Swaging machine to point the test specimens prior to drawing.

Procedures

The experiments were carried out in the following manner. An approximately 12-inch length of annealed rod was pointed in swaging dies, lubricated with Molykote Z,* and then inserted through the drawing die and fastened in the Templin grip. Load was applied slowly until the grip was taut, so as to eliminate any possible shock effects. Load was then applied at the desired head speed. Load readings were taken at regular intervals (thirty second or one minute).

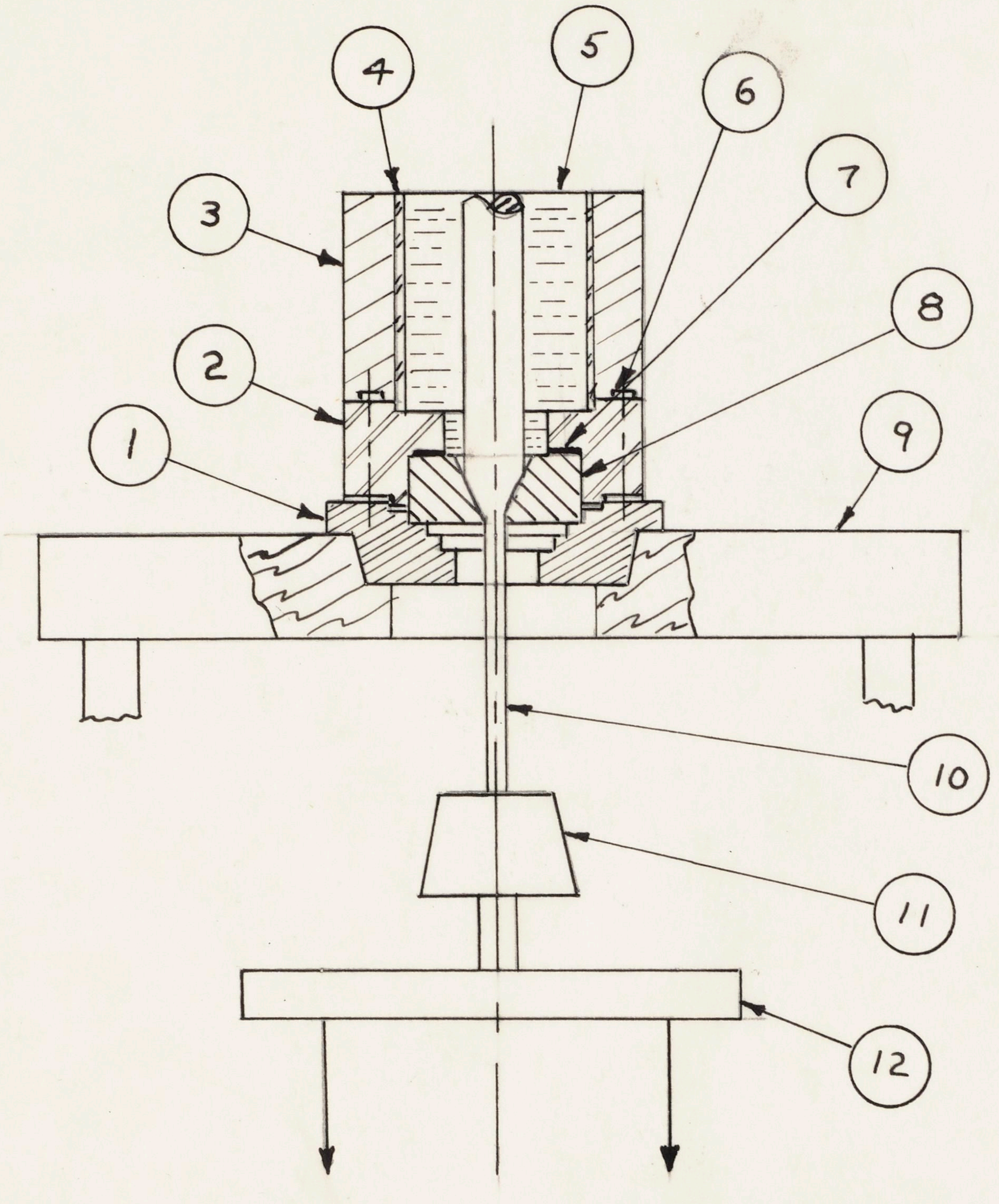
In the large reductions it was necessary to put a point of two diameters on the specimen, one slightly smaller than the exit diameter of the die and the other slightly larger. The larger section of the point was drawn through the die and the test stopped. The small diameter was then cut off and a grip secured on the newly-drawn section. The test was then continued. This procedure was necessary because the stress of the material and a drawing limit would be indicated of smaller magnitude than the actual value.

Two series of low temperature tests were run on the stainless steels, one with dry ice and acetone for a coolant, and the other with liquid notrogen as a coolant. The steady state temperatures reached were -75°C and -185°C respectively as measured with a pentane thermometer. Each specimen was pulled through the die for a short distance to seal the opening. The coolant reservoir was then fastened to the die holder and the appropriate coolant added. When the coolant and specimen reached an equilibrium temperature, the test was resumed. Temperature measurements

*Molykote Z, a commercial lubricant for working of stainless steel, manufactured by the Alpha Corporation of Greenwich, Connecticut, was used on all of the tests.

were made simultaneously with load measurements. Coolant was added as needed during the test to maintain the required temperature. The liquid nitrogen had to be poured very steadily or large fluctuations in load were evidenced.

Tensile tests on the 304, 301, and brass were performed to obtain the true stress—true strain relationships. These curves were graphically integrated to get the relationship between the minimum work to bring about a given change in volume in tensile stretching and the true strain. These values were used in the calculations to obtain the efficiencies and coefficient of friction in wire drawing.



Schematic Diagram
of Apparatus

KEY TO SCHEMATIC DIAGRAM

1) Die holder
2) Base of coolant reservoir
3) Insulation around coolant reservoir
4) Tube of coolant reservoir
5) Coolant
6) Bolt
7) Lead gasket
8) Die
9) Stationary head of testing machine
10) Pointed end of specimen
11) Templin grips
12) Moving head of testing machine

RESULTS

Effect of Reduction in Area on Efficiency

The deformation efficiency increases as the reduction in area increases. This is due to a smaller percentage of friction work being wasted in the process. Thus, a heavy pass will be more efficient from the point of energy expended, than a series of lighter passes which give the same final diameter.

Figure 1 shows the relationship between Deformation Efficiency and Reduction in Area and also Natural Strain for 304, 301, and Brass.

Figure 2 shows the True Stress--True Strain relationship of 304, the Minimum Work--True Strain relationship and the Drawing Stress--True Strain relationship.

The inner section of the extrapolated Drawing Stress curve and the True Stress--True Strain curve should give the drawing limit of the material, for the drawing stress cannot exceed the tensile stress without fracture taking place. The intersection for 304 is at a strain of about 1.0 or a reduction in area of 63.2%. In Figures 3 and 4 which are the corresponding curves for 301 and Brass, we get drawing limits upon extrapolation of 62% for the 301, and 67% for the Brass.

However, in our wire drawing experiments we found that we could draw successfully all these materials through the 55.4% die, and that they would fracture if we attempted to bring about a 62.1% reduction in area. Thus, the drawing limit at room temperature for these materials is somewhere between 55.4% and 62.1%.

We can explain this seeming discrepancy in the following way:

1) Our values of drawing stress are computed by using the Average Drawing Load. While the Average Per Cent deviations are small, an

occasional load reading would exceed the average load by a considerable amount. Also, higher values than the average load were recorded at the start of many of the tests. This was probably due to the fact that sliding friction is less than static friction, and an increase in temperature in the die due to deformation and friction occurs as the test proceeds, and less martensite is formed. These values were discounted when computing the average drawing load, the average per cent deviation, and the average drawing stress (average drawing load/final area of wire).

2) A uniform stress distribution across the drawn cross section has been assumed. It is suspected that this may not be true, and therefore, a higher stress than that actually calculated is experienced in the wire and fracture occurs before our estimated drawing limit is reached.

3) It is difficult to extrapolate the drawing stress curve with much preciseness.

The most we can say on the drawability of these materials is that it is bracketed somewhere between 55.4% and 62.1%, perhaps in the order of increasing drawability: 301, 304, and Brass.

Effect of Head Speed on Efficiency

Figure 5 shows the relationship between Deformation Efficiency and Reduction in Area for 304 measured at three different head speeds. The fact that these curves cross would seem to indicate that the material is rate sensitive; rather than a trend in efficiency versus head speed being indicated, it is more likely that the mechanical properties of the material are changing with changing head speed.

Effect of Low Temperature on Efficiency

The drawing stresses increase for the same reduction as the temperature decreases.

Figure 6 shows the affect of low temperatures on the drawing stresses for 304.

Figure 7 shows the affect of low temperatures on the drawing stresses for 301.

In our wire drawing experiments at the dry ice and acetone Temperature and at the nitrogen temperature, we found that we could draw both stainless steels through the 38.5% die and that they would fracture if we attempted to bring about a 47.7% reduction in area. However, these values present a fictitious picture of the drawing limit of stainless steel at low temperatures. It was impossible to maintain the drawn portion at the temperature of the die and undrawn portion in the coolant reservoir. The material fractured at a point which was at a higher temperature than that at which the wire drawing process was being carried out. At room temperature the fracture would normally occur at a point just outside the die exit. At dry ice and acetone temperatures the fracture occurred at a point approximately four inches from the die, and at the liquid nitrogen temperature the fracture occurred at a point just outside the grips. Since stainless steel is much stronger at lower temperatures than at room temperature, the drawing limit realized is less than that expected if low temperature could be maintained throughout the specimen.

The 304 specimens drawn at liquid nitrogen temperature are much more magnetic than any of the other specimens. This indicates a larger degree of martensite transformation. The 301 specimens drawn at liquid nitrogen temperature show very little magnetism and thus a smaller degree of transformation has taken place. The effect of this martensite transformation can be seen by comparing the drawing stress curves for the two materials at liquid nitrogen temperature.

Values of deformation efficiency cannot be given because no information on the true stress--true strain characteristics of the materials is available for the low temperatures at which the tests were performed.

Values of the Coefficient of Friction in Wire Drawing

Symbols used

A . . .	Cross-sectional area of wire
L . . .	Length of bearing section
a . . .	Die semi-angle
Wt . . .	Draw stress (work done per unit volume)
Y1 . . .	Initial yield stress in Davis and Dokos approximation to the tensile true stress--true strain curve
K . . .	Slope of above relation
μ . . .	Coefficient of friction
P . . .	Drawing load without considering bearing length
P . . .	Drawing load taking bearing load into consideration
D . . .	Diameter
l . . .	L/D
Y . . .	Yield stress
Suffix 1 .	Before deformation
Suffix 2 .	After deformation

Davis and Dokos theory is

$$P = \left(1+\frac{1}{\mu\cot\alpha}\right)\left\{\left[1-\left(\frac{A_2}{A_1}\right)^{\mu\cot\alpha}\right]\left(Y_1-\frac{K}{\mu\cot\alpha}\right)+K\log_e\frac{A_1}{A_2}\right\}$$

assuming that Y is a linear function of natural strain

$$Y = Y_1 + K\log_e\frac{A_1}{A_2}$$

MacLellan takes into consideration the bearing length and his equation is

$$P_t = A_2 Y_2\left(1-e^{-4\mu l}\right) + P\cdot e^{-4\mu l}$$

Upon examination of these theories we find that the only quantity which we cannot measure is the coefficient of friction. The drawing load is known. The initial and final areas can be measured, and the die angle and length of bearing section can be gotten from the profilometer information. The values of Y_1, and Y_2, and K can be taken from the true stress--true strain relations for the respective materials.

Using a solution involving successive approximations by trial and error insertion of values for the coefficient of friction until the calculated drawing load equals the measured drawing load gives the following values:

	Coefficient of friction			
Red in Area	Davis and Dokos		MacLellan	
	Brass	304	Brass	304
15.3	0.21	0.31	----	----
38.5	0.10	0.18	----	0.12
55.4	0.08	0.25	0.05	0.20

It can be seen that the effect of the bearing length on the value of the coefficient of friction is appreciable.

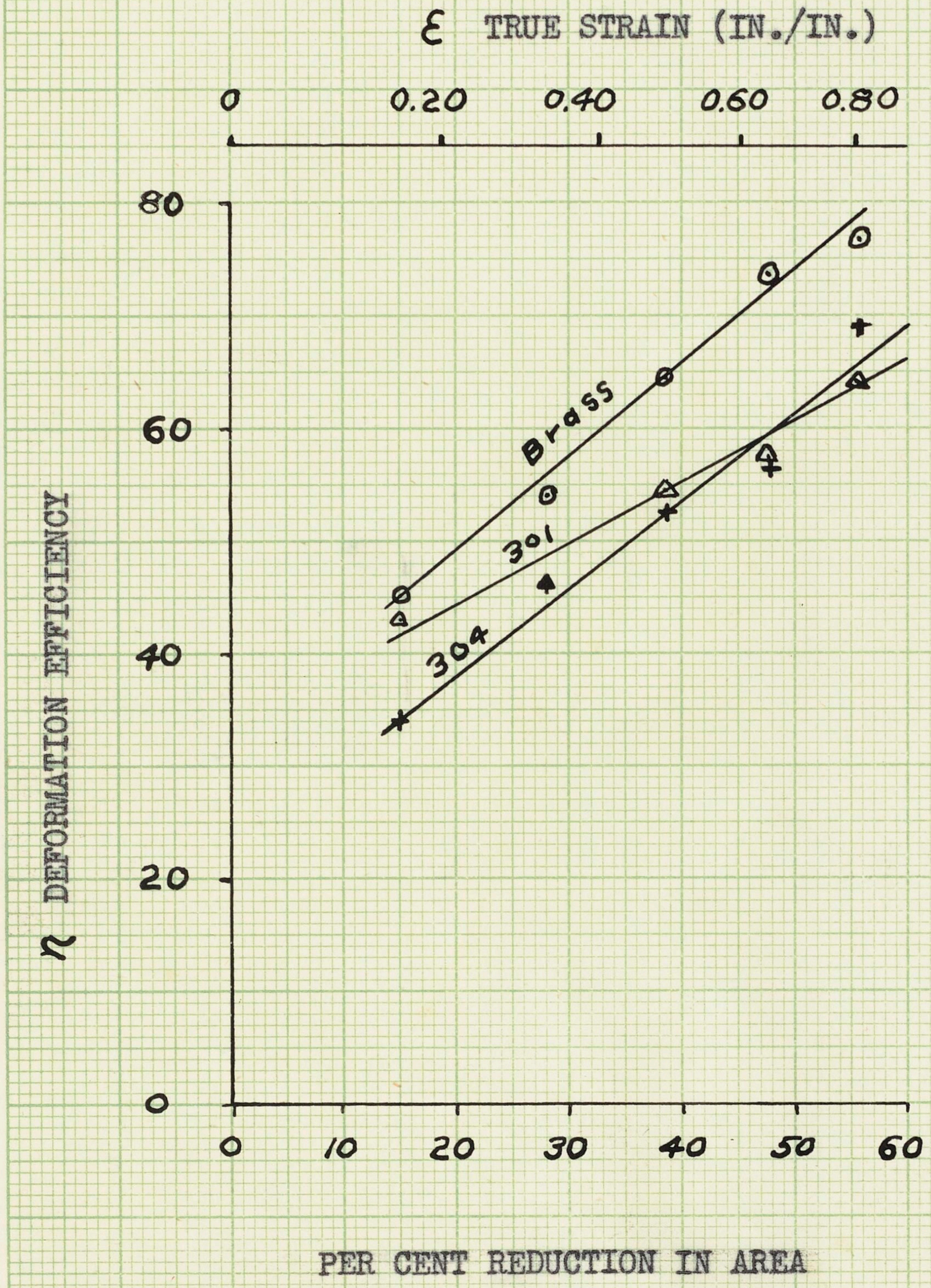

ε TRUE STRAIN (IN./IN.)
0
0.20
0.40
0.60
0.80
80
60
40
20
0
η DEFORMATION EFFICIENCY
Brass
301
304
0
10
20
30
40
50
60
PER CENT REDUCTION IN AREA

Fig. 1

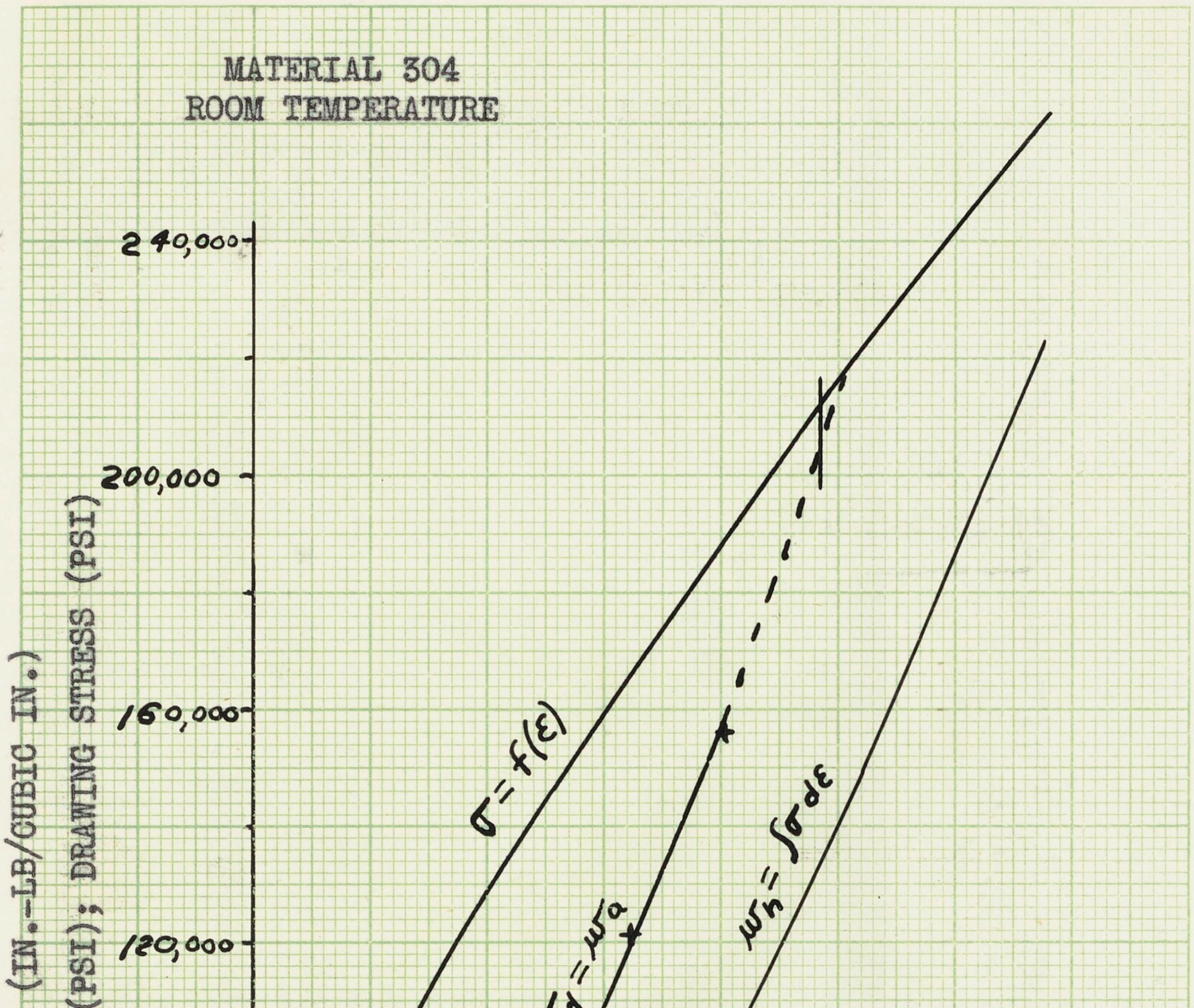

MATERIAL 304
ROOM TEMPERATURE
w MINIMUM WORK (IN.-LB/CUBIC IN.)
σ TRUE STRESS (PSI); DRAWING STRESS (PSI)
240,000
200,000
160,000
120,000
80,000
40,000
0
0
0.4
0.8
1.2
1.6
ε TRUE STRAIN (IN./IN.)
$\sigma = f(\varepsilon)$
$\sigma_d = w_a$
$w_h = \int \sigma d\varepsilon$

Fig. 2

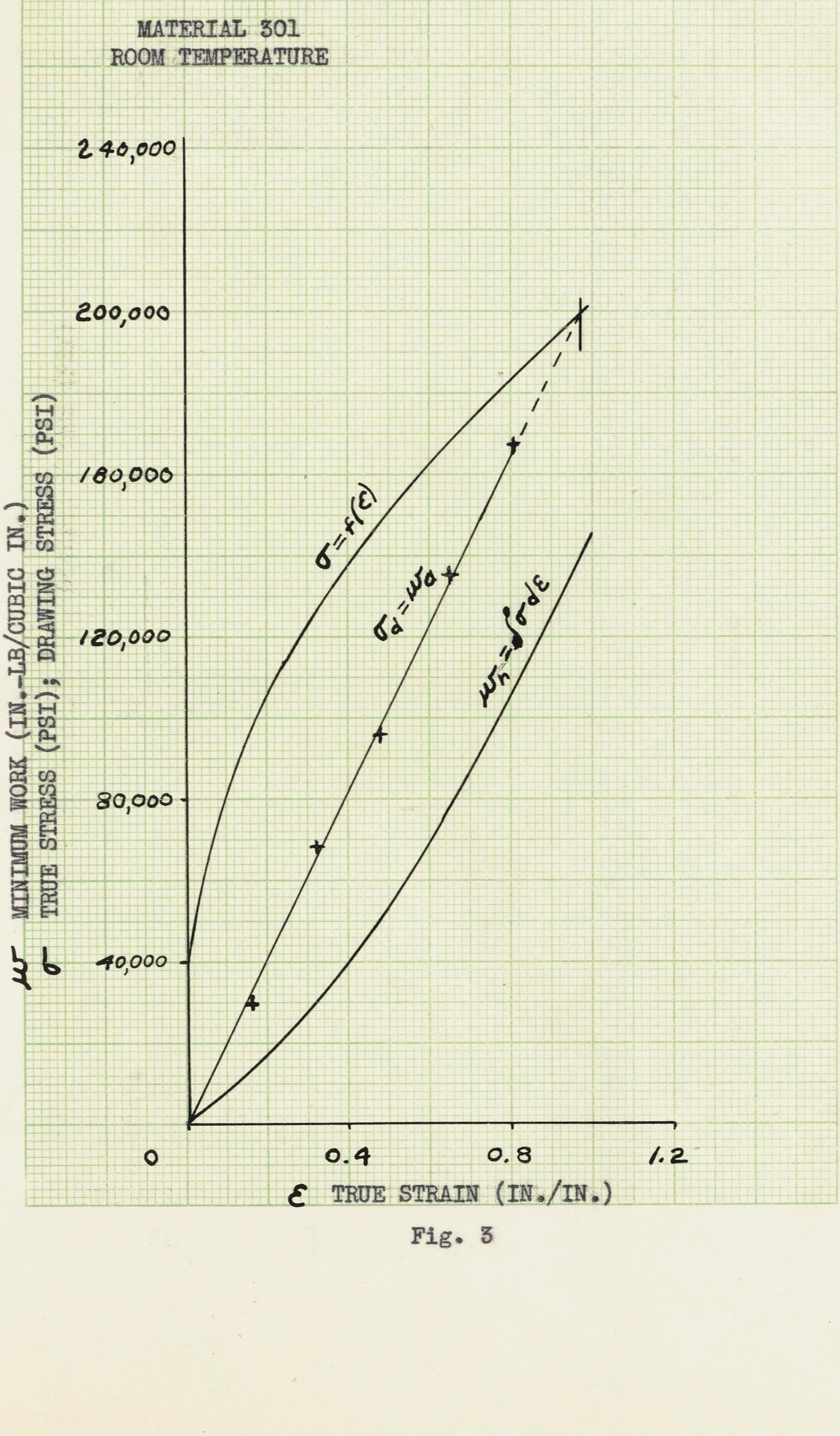

MATERIAL 301
ROOM TEMPERATURE
240,000
200,000
160,000
120,000
80,000
40,000
0
0.4
0.8
1.2
w σ MINIMUM WORK (IN.-LB/CUBIC IN.)
TRUE STRESS (PSI); DRAWING STRESS (PSI)
ε TRUE STRAIN (IN./IN.)
σ = f(ε)
σd = wa
wn = ∫σ dε

Fig. 3

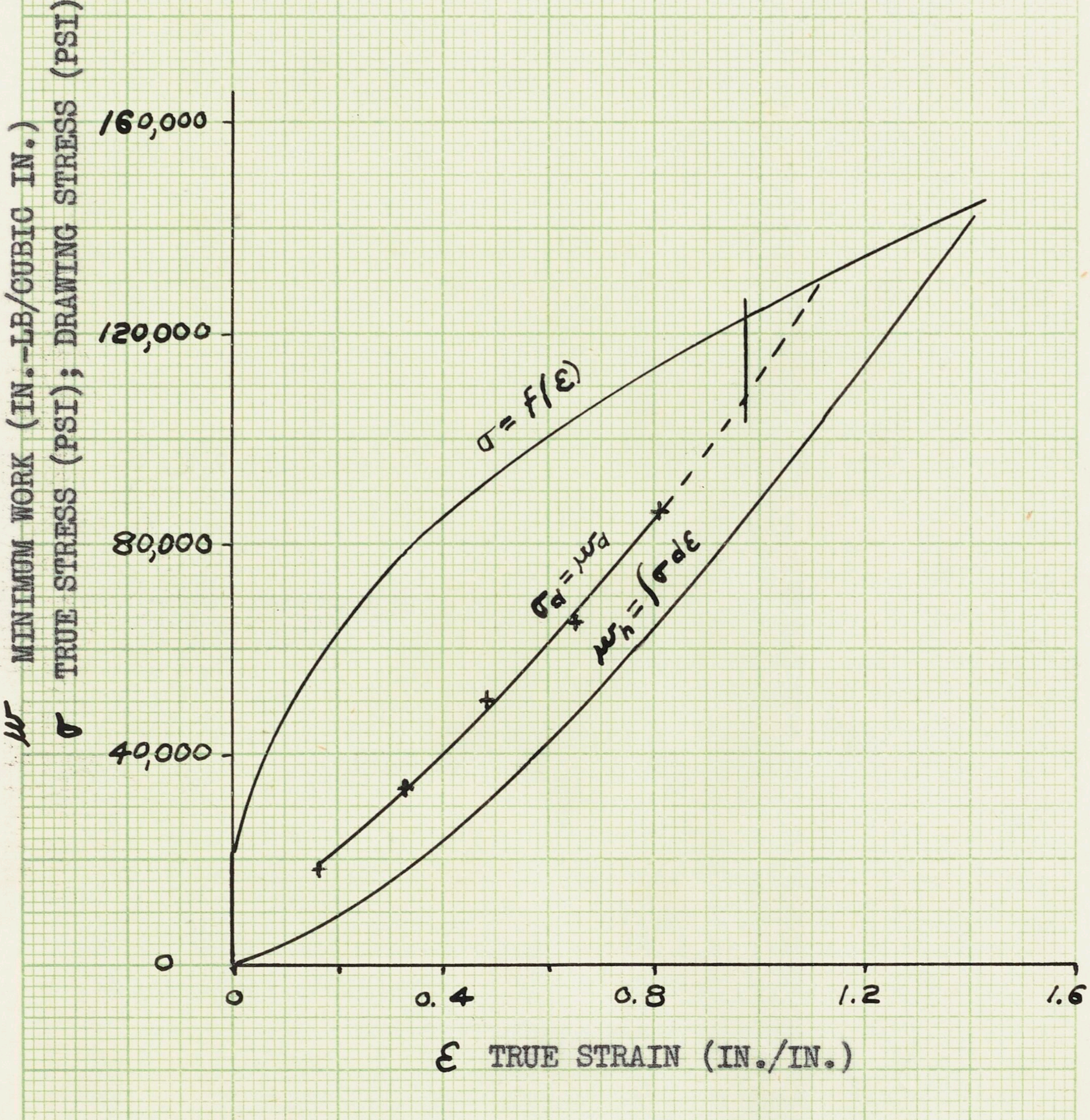

MATERIAL 70-30 BRASS
ROOM TEMPERATURE
w MINIMUM WORK (IN.-LB/CUBIC IN.)
σ TRUE STRESS (PSI); DRAWING STRESS (PSI)
160,000
120,000
80,000
40,000
0
0
0.4
0.8
1.2
1.6
ε TRUE STRAIN (IN./IN.)
$\sigma = f(\varepsilon)$
$\sigma_d = w_d$
$w_h = \int \sigma d\varepsilon$

Fig. 4

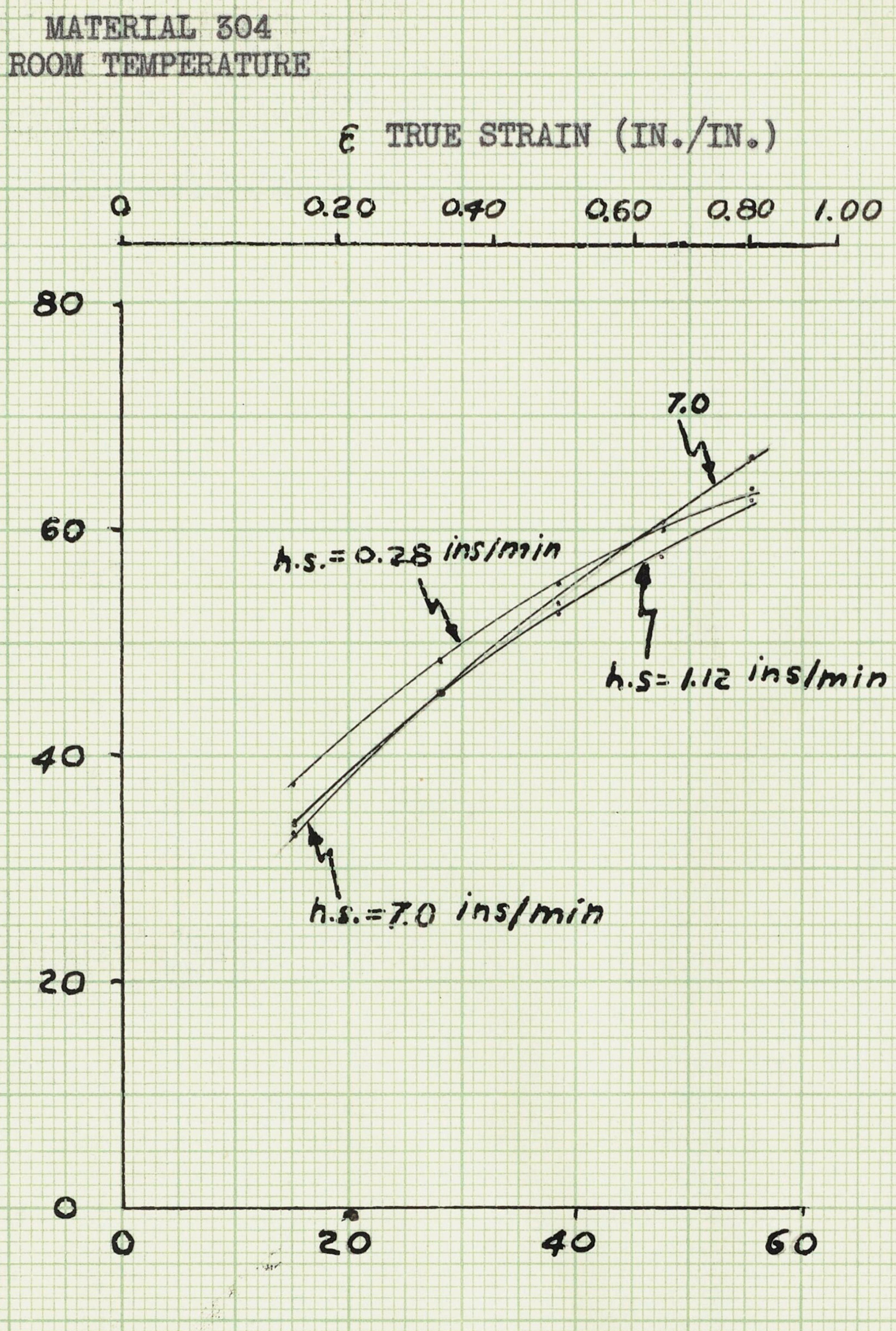
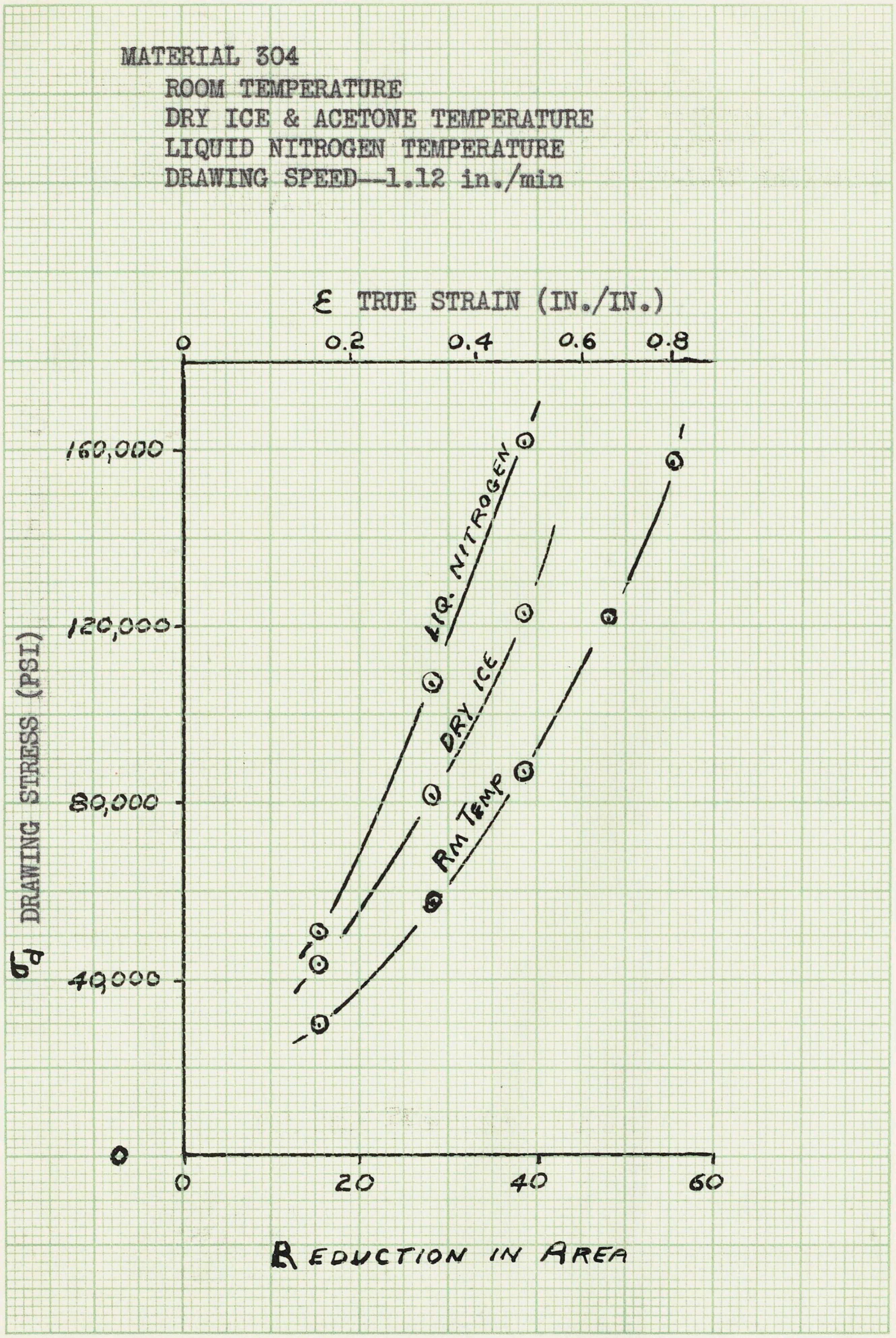

MATERIAL 304
ROOM TEMPERATURE
ε TRUE STRAIN (IN./IN.)
0
0.20
0.40
0.60
0.80
1.00
80
60
40
20
0
0
20
40
60
7.0
h.s.= 0.28 ins/min
h.s= 1.12 ins/min
h.s.=7.0 ins/min
η DEFORMATION EFFICIENCY (%)
PER CENT REDUCTION IN AREA

Fig. 5



MATERIAL 304
ROOM TEMPERATURE
DRY ICE & ACETONE TEMPERATURE
LIQUID NITROGEN TEMPERATURE
DRAWING SPEED--1.12 in./min

Fig. 6

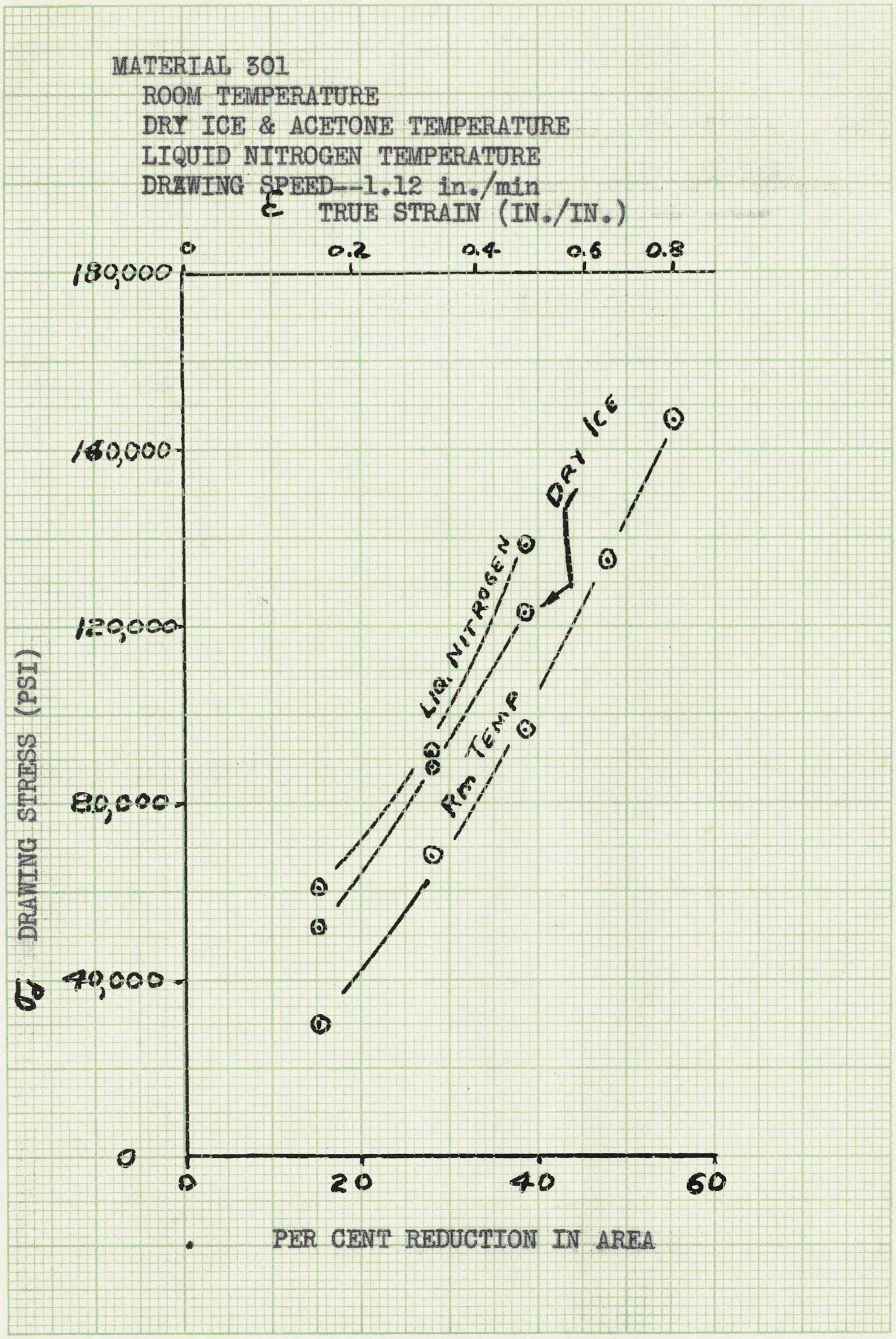

MATERIAL 301
ROOM TEMPERATURE
DRY ICE & ACETONE TEMPERATURE
LIQUID NITROGEN TEMPERATURE
DRAWING SPEED--1.12 in./min
ε TRUE STRAIN (IN./IN.)
0
0.2
0.4
0.6
0.8
180,000
160,000
120,000
80,000
40,000
0
σd DRAWING STRESS (PSI)
LIQ. NITROGEN
DRY ICE
Rm TEMP
0
20
40
60
PER CENT REDUCTION IN AREA

Fig. 7

CONCLUSIONS

1) Deformation Efficiency increases with reduction in area.
2) Drawing speed has a very slight effect on drawing stress and may have an effect on deformation efficiency.
3) Drawing stress increases with decreasing temperature for a given reduction in area.
4) The drawing limit at room temperature for 304, 301, and brass lies between 55.4% and 62.1%.
5) By the use of established wire drawing theories we can calculate the coefficients of friction in drawing of stainless steel and brass to be in the range of = 0.05 to 0.20.
6) Molykote Z is a satisfactory lubricant for drawing stainless steel wire at the head speeds used in these experiments.

SUGGESTIONS FOR FURTHER WORK

The following problems would be a logical extension of this work:

1) Investigation of the relation of the amount of martensite transformation as a function of reduction in area and its effect on the drawing process by X-ray or magnetic techniques.

2) The effect that working stainless steel at low temperature has on its material properties at room temperature.

3) Investigation of the true stress--true strain relationships at low temperatures and the affect of temperature on the deformation efficiency.

4) Investigation of the effect that prestraining the test specimens has on the drawing process, i.e., making successive reductions on the same wire.

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MATERIAL 304

Room Temperature
Tungsten Carbide Dies
Lubricant--Molykote Z

Head Speed	7.0 ins/min				1.12 ins/min				0.28 ins/min			
Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)
15.3	1253	1.55	30,100	33.2	1232	0.68	29,600	33.8	1110	1.92	26,700	37.4
28.1	2007	0.91	57,000	45.6	2014	0.36	57,100	45.6	1895	0.57	53,700	48.4
38.5	2614	0.26	86,500	53.2	2627	0.64	87,200	53.2	2516	0.49	83,300	85.2
47.7	2955	1.37	115,000	60.8	3125	1.21	122,000	60.8	2998	0.48	116,700	60.0
55.4	3228	0.71	148,000	66.2	3437	0.58	157,000	66.2	3402	0.30	155,000	63.2
62.1		FRACTURE				FRACTURE				FRACTURE		

MATERIAL 304

Temperature--Dry Ice & Acetone (-77°C)
Tungsten Carbide Dies
Lubricant--Molykote Z

Head Speed	7.0 ins/min			1.12 ins/min			0.28 ins/min		
Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)
15.3	---	---	---	1809	1.47	43,500	1689	1.29	40,700
28.1	---	---	---	2881	3.61	81,600	2925	0.64	82,900
38.5	3519	1.71	116,500	3721	0.83	123,200	3760	1.06	124,500
47.7		FRACTURE			FRACTURE			FRACTURE	

Temperature--Liquid Nitrogen (-189°C)
Tungsten Carbide Dies
Lubricant--Molykote Z

1.12 ins/min

Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)
15.3	2110	3.37	50,700
28.1	3765	4.02	107,000
38.5	4888	1.50	162,000
47.7		FRACTURE	

MATERIAL 301

Room Temperature
Tungsten Carbide Dies
Lubricant—Molykote Z

Head Speed	7.0 ins/min				1.12 ins/min				0.28 ins/min			
Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)
15.3	1478	4.06	35,500	36.6	1256	1.87	30,200	43.1	1483	1.27	35,600	36.5
28.1	——	——	——	——	2372	1.49	68,100	45.6	2173	2.69	61,400	50.5
38.5	3075	0.89	102,000	51.0	2906	1.05	96,400	53.9	2839	0.72	94,000	55.3
47.7	——	——	——	——	3480	0.84	135,400	57.7	——	——	——	——
55.4	3739	0.90	171,000	62.5	3664	0.19	167,300	63.9	——	——	——	——
62.1		FRACTURE				FRACTURE				FRACTURE		

Temperature--Liquid Nitrogen (-189°C)
Tungsten Carbide Dies
Lubricant--Molykote Z

Head Speed 1.12 ins/min

Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)
15.3	2506	1.45	60,300
28.1	3189	3.45	90,600
38.5	4167	3.12	138,000
47.7		FRACTURE	

Temperature--Dry Ice & Acetone (-77°C)
Tungsten Carbide Dies
Lubricant--Molykote Z

Head Speed 1.12 ins/min

Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)
15.3	2148	3.00	51,700
28.1	3105	2.28	88,000
38.5	3718	0.83	123,000
47.7		FRACTURE	

MATERIAL 70-30 BRASS

Room Temperature
Tungsten Carbide Dies
Lubricant--Molykote Z

Head Speed 1.12 ins/min

Red in Area (%)	Average Draw Force (lbs)	Average Deviation (%)	Average Draw Stress (psi)	Deformation Efficiency (%)
15.3	742	0.42	17,800	44.9
28.1	1173	1.50	33,200	54.2
38.5	1498	0.57	49,600	64.5
47.7	1677	0.50	65,300	73.5
55.4	1891	0.33	86,300	76.4
62.1		FRACTURE		

VALUES USED IN CALCULATIONS OF DRAW STRESSES AND DEFORMATION EFFICIENCIES

Red in Area* (%)	Area After Draw (sq. ins)	Natural Strain (in/in)	Energy/Vol. in "Homogeneous" Deformation (in.—lbs/cu. in.)		
			304	301	Brass
15.3	.04.6	0.166	10,000	13,000	8,000
28.1	.0353	0.329	26,000	31,000	18,000
38.5	.0302	0.485	46,000	52,000	32,000
47.7	.0257	0.647	70,000	78,000	48,000
55.4	.0219	0.806	98,000	107,000	66,000

*Initial Area = .0491 sq. ins.