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Rolling - titanium

HOT ROLLING OF COMMERCIALLY PURE TITANIUM AND TITANIUM ALLOY Ti-6Al-4V

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By

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TITLE

HOT ROLLING OF COMMERCIALLY PURE TITANIUM AND TITANIUM ALLOY Ti-6Al-4V

ABSTRACT

Rolling forces and torque were experimentally determined in hot rolling commercially pure titanium and titanium 6Al-4V alloy on a 2-high experimental rolling mill with 5-1/4" O. D. rolls. Rolling temperatures were 1400 F, 1600 F, 1800 F, and 2000 F, specimen widths 1", 2", and 4", and specimen thicknesses 1/32", 1/16", and 1/8".

Results are presented in the form of curves showing the effects of reduction, rolling temperature, specimen size, and alloy on roll separating force, specific pressure, horsepower and work, forward slip, lever arm ratio and spread.

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INTRODUCTION

The rolling of metals, one of the most common fabrication processes, has been the subject of considerable research. Theories of rolling have attempted to explain the rolling process; however, the theories are not sufficiently advanced to adequately explain and predict rolling phenomena. There is also a lack of experimental data, particularly in rolling the newer metals such as titanium.

Since titanium, due to its unique characteristics, presents problems in rolling, experimental data relative to force and power requirements would be valuable for use in designing rolling mills, analysis of the rolling process, and for the special case of thin-sheet rolling.

The results presented herein are a continuation of work previously reported[1], in which results were presented for titanium alloys, Ti-75A, RC-130A, Ti-6Al-4V, and RC-130B.

All data presented are for commercially pure titanium and the titanium 6Al-4V alloy. Experimentally measured roll separating force and torque values for varying reductions, specimen widths and thicknesses, and rolling temperatures were used to calculate specific pressure corrected for roll deformation, horsepower, work, forward slip, lever arm ratio, spread, and ratio of final thickness to roll diameter.

MATERIALS AND PROCEDURE

Test Specimens

Test specimens were commercially pure titanium and titanium 6Al-4V alloy, 1", 2", and 4" wide and 1/8", 1/16", and 1/32" thick by 6" long. All specimens were sheared longitudinally from large sheets and the edges surface ground to the specified width.

Mechanical properties and chemical analyses submitted by the producers are shown in Table I.

Some discrepancies may be noted in the mechanical properties, particularly in the thin section. The reason for this is not known. The high hardness of the thin sections may be due to the thinness of the specimen.

TABLE I

Mechanical Properties

	Tensile Strength (psi)	Yield Strength (0.02% Offset) (psi)	Elongation (%)	Hardness R_c
Comm. Pure(0.125")(Trans)	97,800	82,400	24.5	24.5
" " (0.062")(Trans)	95,600	79,600	22.0	23
" " (0.031")(Trans)	96,300	72,700	18.5	22/23
6Al-4V (0.125")(Long)	145,200	121,200	7.5	30.5
" (0.125")(Trans)	150,100	137,500	9.5	32
" (0.062")(Long)	145,200	125,000	5.5	31.5
" (0.062")(Trans)	150,000	142,000	7.5	32
" (0.031")(Long)	127,900	117,000	2.0	39
" (0.031")(Trans)	155,000	145,500	2.5	38

Chemical Analyses

	C	N	Fe	Al	V	H	Mn
Comm. Pure Titanium	0.10	0.016	0.30	--	--	--	--
Ti-6Al-4V	0.01	0.014	0.15	6.2	3.7	0.003	0.04

Equipment and Procedures

The test equipment and procedures are described in a previous report.[1] Briefly, specimens were heated in a muffle-type furnace for one hour, removed with heated tongs and rolled at three-minute intervals through unheated rolls. On leaving the rolls the specimens were guided through a chute into a water-quench tank to retain the as-rolled structure.

The rolling mill was a 2-high/4-high experimental mill used as a 2-high mill, and was equipped with strain gage load cells and torque arms. The load cells are described in Reference 1. The torque arms (Figure 1) replaced the top and bottom drive shafts and utilized a similar amplifier and recorder system.

Specimen thickness and width before and after rolling was measured with a micrometer to 0.001". Forward slip measurements were made to 0.01" with an engineer's scale.

Roll separating force, torque, and slip measurements were used to calculate the data for the curves. Formulae, calculations, and definitions of terms are presented in Appendix A.

RESULTS AND DISCUSSIONS

In rolling sheet material, the initial thickness of the sheet is important. As the thickness decreases the rolling pressure increases and the limit of rollability is approached for a mill of given capacity. This limitation may be expressed by the formula for average rolling pressure

$$P_{avg} = \sigma_y{*}(1 + \frac{\mu L}{2H})$$

wherein it may be seen that P_{avg} is dependent upon the yield strength $\sigma_y{*}$ of the material, coefficient of friction μ, contact length L, and material thickness h. The rolling limit is approached when the average rolling pressure is not great enough to produce further plastic deformation of the material but only deformation of the rolls.

Rolling metals at elevated temperatures permits greater reductions due to the lower yield strength and change in coefficient of friction between the sheet and the rolls. This is also true for titanium; however, high temperature rolling of titanium also introduces the problem of surface contamination and size and flatness variations. When rolling titanium, these and other factors must be considered; however, these problems are not pertinent to this work.

In addition to the above, the power consumption is an important consideration. The power required for rolling is dependent upon the magnitude and location of the vertical resultant of the applied rolling load. These are determined by several interdependent factors including roll diameter, material size, angle of contact, specimen resistance to deformation, and friction conditions within the roll gap. There is an increase in power consumption with increasing roll diameter for a constant reduction due to an increase in the contact area, friction, and length of the lever arm.

Friction conditions, due to the surface condition of the rolls and sheet materials, and the use of a lubricant influence the height of the friction hill and the length of the lever arm, hence the power consumption.

Thus it is apparent that cold rolling an unlubricated, wide, thin sheet of metal with large diameter rolls will require more power than hot rolling a narrow, thicker strip of the same material with smaller diameter rolls.

Power requirements in rolling may be measured by determining the electrical power input to the drive motor; however, the method is somewhat inaccurate as the actual power expended at the rolls must be calculated based on the efficiency of the motor and several drive components. A more accurate method is to measure the torque required at the drive shaft by means of electrical strain gages, and from this to calculate the horsepower. Only the loss at the roll bearings is neglected. This latter method was used for the work reported herein.

In the following sections, experimental data pertaining to the above factors in rolling titanium are presented and briefly discussed. First, the rolling load data is presented together with curves of specific pressure. Then power data is presented in one set of curves showing total power consumption and another showing work per unit volume of metal rolled, indicating the effects of several variables. The remaining sections, covering forward slip, lever arm ratio, and spread, are important as they indicate the frictional conditions within the roll gap.

Roll Separating Force and Specific Pressure

1. Reduction

The rate of increase in roll separating force was greatest for the highest reductions due to an increase in resistance to deformation by the titanium and to roll flattening, see Figures 2 through 7.

The curves of specific pressure versus reduction are presented in Figures 8 through 13. By comparing the curves on the basis of unit widths, specimen width is seen to have no effect on the roll separating force. An exception may be noted for the 1/32"-thick specimens rolled at the highest temperatures. This may be due to inaccuracies in measurements caused by the low reductions and scale on the surface of the specimens, and to roll quenching.

2. Temperatures

Rolling temperatures between 1400 F and 2000 F were selected in order to roll specimens with microstructures ranging from all-alpha to all-beta. It is evident in Figures 14 and 15 that the magnitude of the roll separating force decreased rapidly with increasing temperatures up to about 1800 F. In the all-beta range (above 1800 F), the effect of temperature is comparatively minor for all thicknesses in the commercially pure metal; however, roll separating forces for the thicker sections of the 6Al-4V alloy continued to decrease.

The effect of roll quenching is apparent in the thin and narrow specimens, some of which actually require higher forces at the higher temperature. This indicates a drop in the specimen temperature due to rapid cooling of the thin cross section. Data for the thinnest sections may be somewhat inaccurate due to the small reductions, scale, and the difficulty of obtaining accurate thickness measurements.

An interesting indication of the effect of temperature and roll quenching may be seen in the curves of reduction versus temperature for a constant roll separating force, Figures 16 and 17. It is apparent from the curves that hot rolling thin sections is not advantageous with respect to power requirements as the thinnest sections showed little change in reduction with increasing temperature. In addition, surface contamination, size and flatness control, grain growth, and temperature control are factors which make hot rolling of thin sections unattractive and suggest why cold rolling is normally used.

The appearance of the specific pressure curves is comparable to that of the roll separating force curves. Of particular interest in Figure 18 is the appreciable drop in specific pressure with increasing temperature for a 15% reduction. Exceptions are the curves for narrow 1/32"-thick specimens which indicate an increase in specific pressure for these specimens at the high temperatures.

3. Specimen Thickness

The curves of Figure 19 of roll separating force versus specimen thickness for a 15% reduction are interesting because they indicate the effect of roll quenching on thin sections. Roll separating forces for a 15% reduction are comparable for all widths of the 1/8"- and 1/16"-thick specimens, but increase appreciably in magnitude for the 1/32"-thick specimens. This is most apparent at high temperatures where the effect of roll quenching is greatest.

In Figure 18, comparison of the specific pressure curves also shows an increase in magnitude of the specific pressure with decreasing specimen thickness. This is due primarily to increased roll deformation caused by a smaller contact area on the rolls and to an increase in deformation resistance of the thinner section.

4. Specimen Width

In Figure 20, the effect of specimen width on reduction is shown for several thicknesses at a constant roll separating force. In Figures 21 and 22, the roll separating force is seen to increase linearly with the width of the strip, with the slope varying with microstructure and alloy.

The curves of specific pressure shown in Figures 8 through 13, based on a unit width, are essentially identical for all widths with the exception of the 1/32"-thick specimens of commercially pure titanium rolled at 1800 F and 2000 F. As noted in paragraph 2, above, on Temperatures, this may be due to roll quenching and inaccurate thickness measurements resulting from small reductions, scale on the specimens, and variations in final thickness within the specimens.

5. Alloy

Roll separating forces for the titanium alloy 6Al-4V are generally higher than for the commercially pure titanium due to the higher yield strength of the former.

Higher specific pressures for the alloy titanium are in agreement with the rolling load curves. An appreciable reduction in specific pressure, for the thicker sections of alloy titanium, results from increasing rolling temperatures.

Horsepower and Work

1. Reduction

The curves of Figures 23 through 26 show that horsepower consumption increases moderately while work per unit volume of rolled metal increases sharply as the maximum reduction is approached. The difference is due to the work expended in deforming the rolls, resulting in less reduction of the specimen per horsepower input.

The rate of increase in work for the 1/8"-thick specimens also shows the effect of roll quenching and resistance to deformation. At the higher reductions and temperatures the slopes of the curves increase rapidly, and are comparable to the slopes for the thinner specimens. For low reductions and temperatures, roll quenching is less effective due to the smaller contact area between the specimen and the rolls. Resistance to deformation is also lower, due to the lesser reductions.

2. Temperature and Specimen Thickness

The curves in Figures 27 and 28 show that horsepower requirements for a given reduction were generally lower with increasing temperature and that work per unit volume showed a similar trend in the thicker sections. For comparable reductions there is little difference in horsepower with decreasing specimen thickness as contrasted to the effect on work. Work shows an appreciable increase per unit volume at all temperatures, Figures 23 through 26. This is due to the approaching limit of rollability, with an increased proportion of the work going into deformation of the rolls and less into deformation of the metal being rolled.

In Figure 29 the curves of reduction versus temperature for a constant value of work of 55,000 $\frac{\text{in-lb}}{\text{in}^3}$ are interesting. These indicate an increased reduction in the thicker specimens, resulting from an increase in rolling temperature, as contrasted to a small decrease in reduction for the 1/32"-thick specimens. This is due to roll quenching and the higher resistance to deformation of the thin specimens. This effect is also apparent in the curves of Figure 28 which show a substantial increase in work required for the 1/32"-thick specimens as compared to a decrease for the thicker specimens with increasing temperature.

3. Specimen Width

Figures 23 through 26 indicate that horsepower requirements increase approximately linearly with increasing specimen width, while work, based on unit volume, is comparable for all widths of specimens.

4. Alloy

Both horsepower and work per unit volume are greater in magnitude for the titanium alloy due to the higher yield strength of the alloy.

Forward Slip

1. Reduction

An indication of one of the important factors in the roll gap, the coefficient of external friction, is given by forward slip measurements, a high forward slip indicating a high coefficient of friction. As noted earlier, friction helps determine the rolling load and power requirements in rolling.

In Figures 30 and 31 forward slip increases with reduction, the rate of increase being greater at high reductions. The accuracy of forward slip measurements was influenced by scale and distortion on the specimen so that scatter is noted in the data.

2. Temperature

For a constant reduction, Figure 32 shows that forward slip generally decreases with increasing temperature, indicating a decreasing coefficient of friction.

3. Specimen Thickness

Figure 32 shows that the forward slip increases with decreasing initial specimen thickness.

4. Specimen Width

The effect of specimen width on forward slip is negligible.

5. Alloy

Forward slip is comparable for both groups, indicating the coefficient of friction is essentially the same for the commercially pure titanium and the 6Al-4V alloy.

Lever Arm Ratio

1. Reduction

The lever arm ratio is the ratio of the distance at which the rolling load acts to the length of the contact arc. It is an indication of the no-slip point or zone and the point at which the resultant of the rolling load acts, and is usually below 0.5. The lever arm and the rolling load determine power consumption in rolling. Figures 33 and 34 show a decrease in lever arm ratio with increasing reduction.

2. Other Variables

a. The magnitude of the lever arm ratio is essentially unaffected by the rolling temperature.

b. The lever arm ratio is generally lower with decreasing specimen thickness.

c. Specimen width does not affect the lever arm ratio.

d. The lever arm ratio is comparable for both the alloy and the commercially pure specimens.

Spread

Curves showing the increase in specimen width, or spread, with reduction are presented in Figure 35. These show that spread increases with increasing reduction, rolling temperature and specimen thickness and decreases with increasing specimen width. This is due to the decrease in resistance to metal flow offered by the thick, narrow specimens at elevated temperatures. The spread is comparable in magnitude for both the alloy and the commercially pure titanium.

CONCLUSIONS

1. Roll separating forces and specific pressures -

a. increase with reduction. The former increases nonlinearly, with the greatest increase at the high reductions. The increase is generally linear for specific pressures.

b. decrease with increasing rolling temperature, generally most rapidly for temperatures below the all-beta range of approximately 1800 F. However, roll quenching results in higher roll separating forces for the thin, narrow specimens at high temperatures.

c. are higher for the alloy titanium due to the higher yield strength.

2. Horsepower and work per unit volume -

a. increase with reduction. The latter increases at the higher rate due to an increase in work expended in roll deformation.

b. increase with decreasing specimen thickness. The latter increases at the higher rate.

c. decrease with increasing rolling temperature for the 1/8"- and 1/16"-thick specimens but increase for the 1/32"-thick specimens due to roll quenching.

d. are greater for the alloy than for the commercially pure titanium.

3. <u>Forward slip</u> -

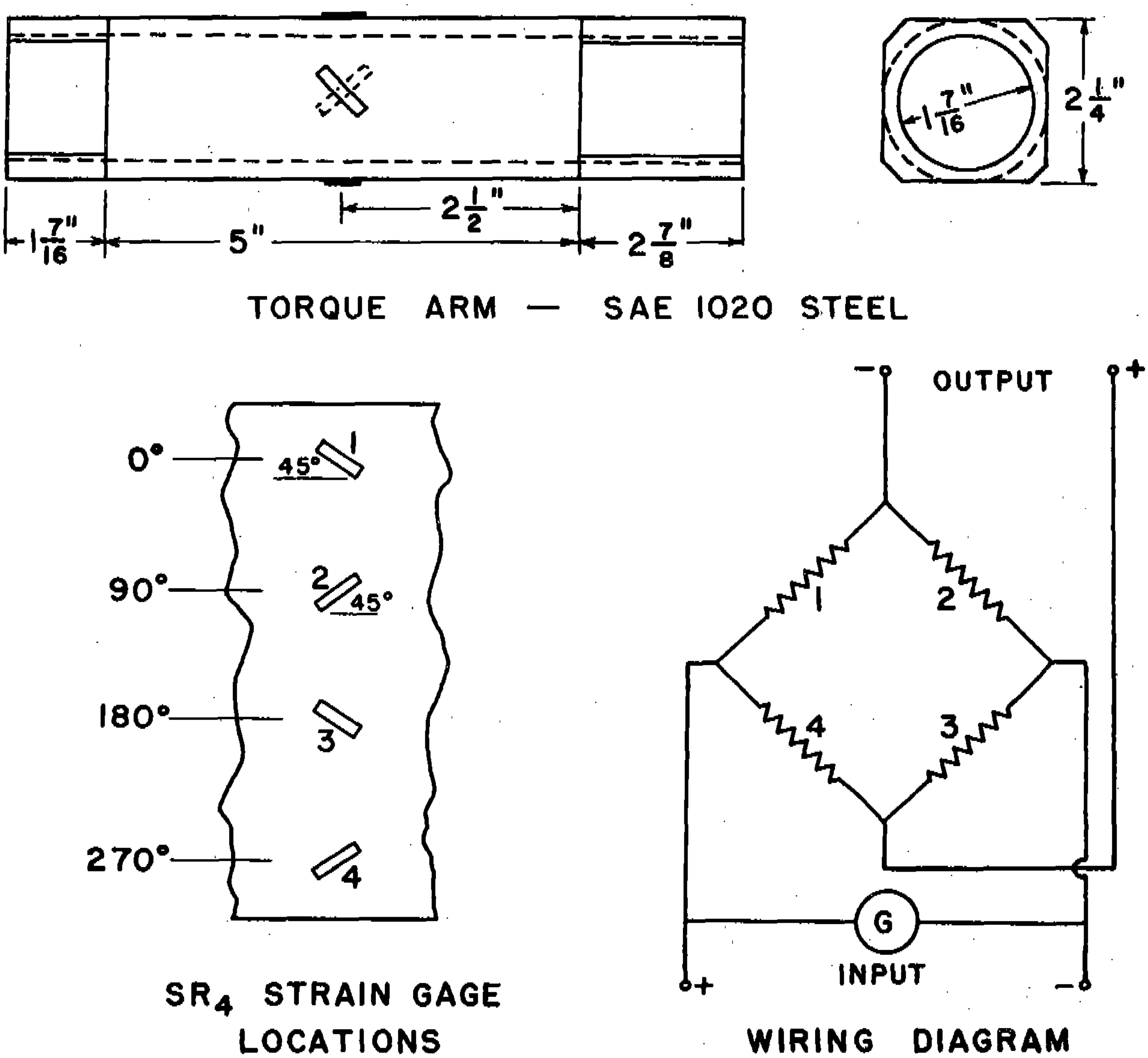
increases with reduction and decreases with increasing specimen thickness and rolling temperature. It is not affected by specimen width or alloy.

4. <u>Lever arm ratio</u> -

decreases with increasing reduction and increases with increasing specimen thickness. Rolling temperature, specimen width and alloy do not affect the lever arm ratio.

5. <u>Spread</u> -

increases with reduction, rolling temperature, and specimen thickness. Spread is comparable for both the alloy and the commercially pure titanium.



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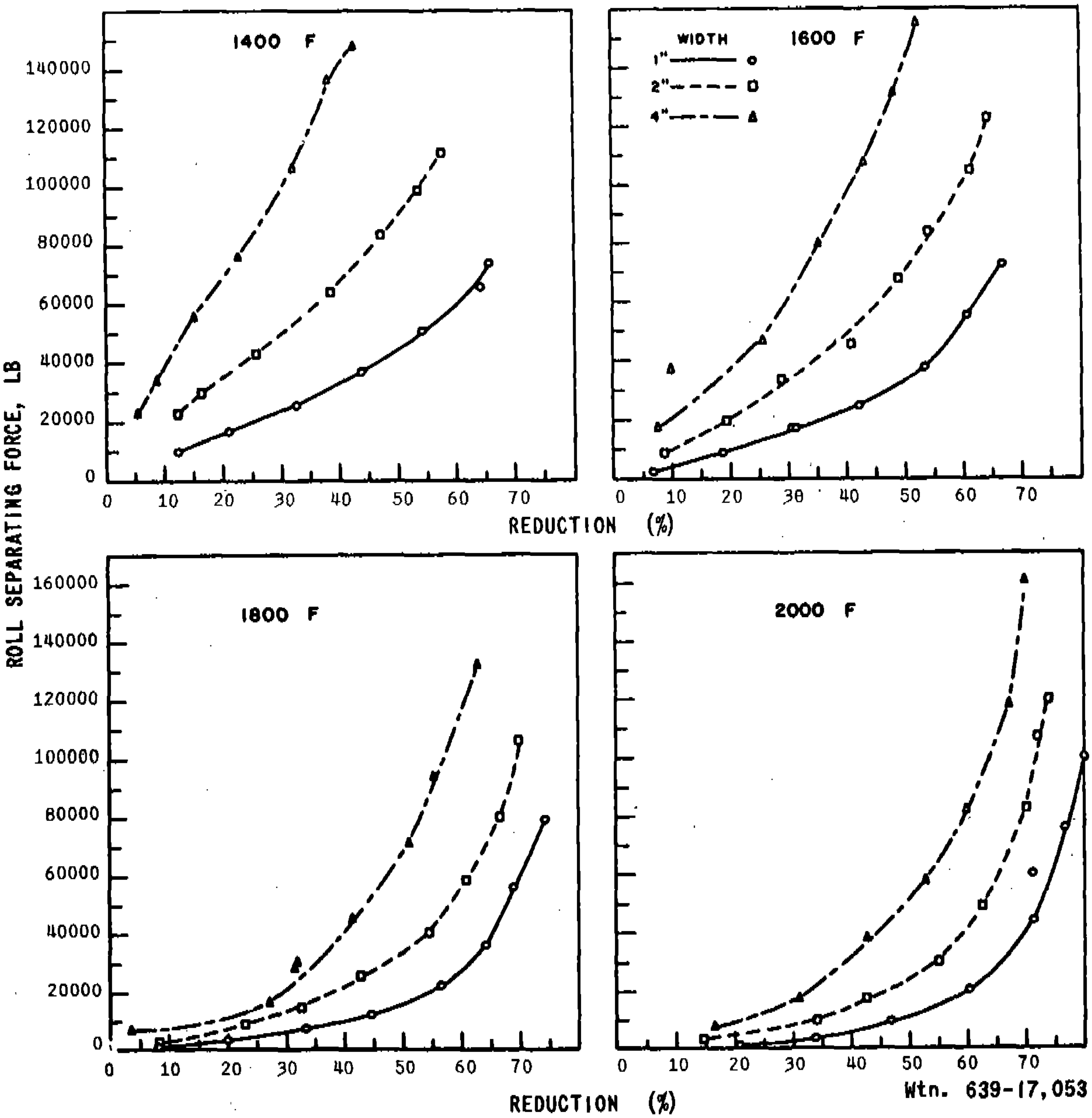
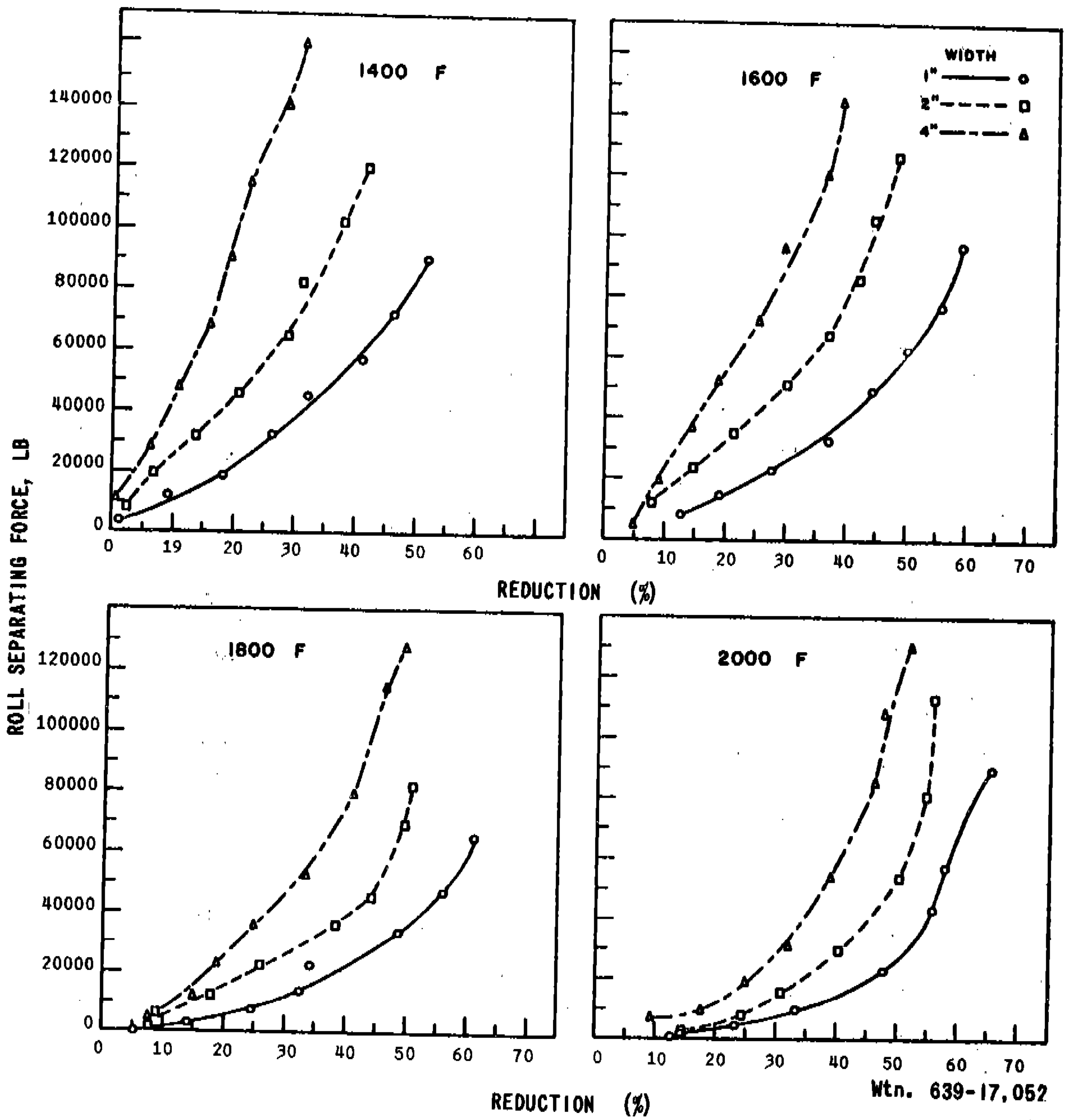
SCHEMATIC OF TORQUE MEASURING ARMS FOR EXPERIMENTAL ROLLING MILL

FIGURE 1



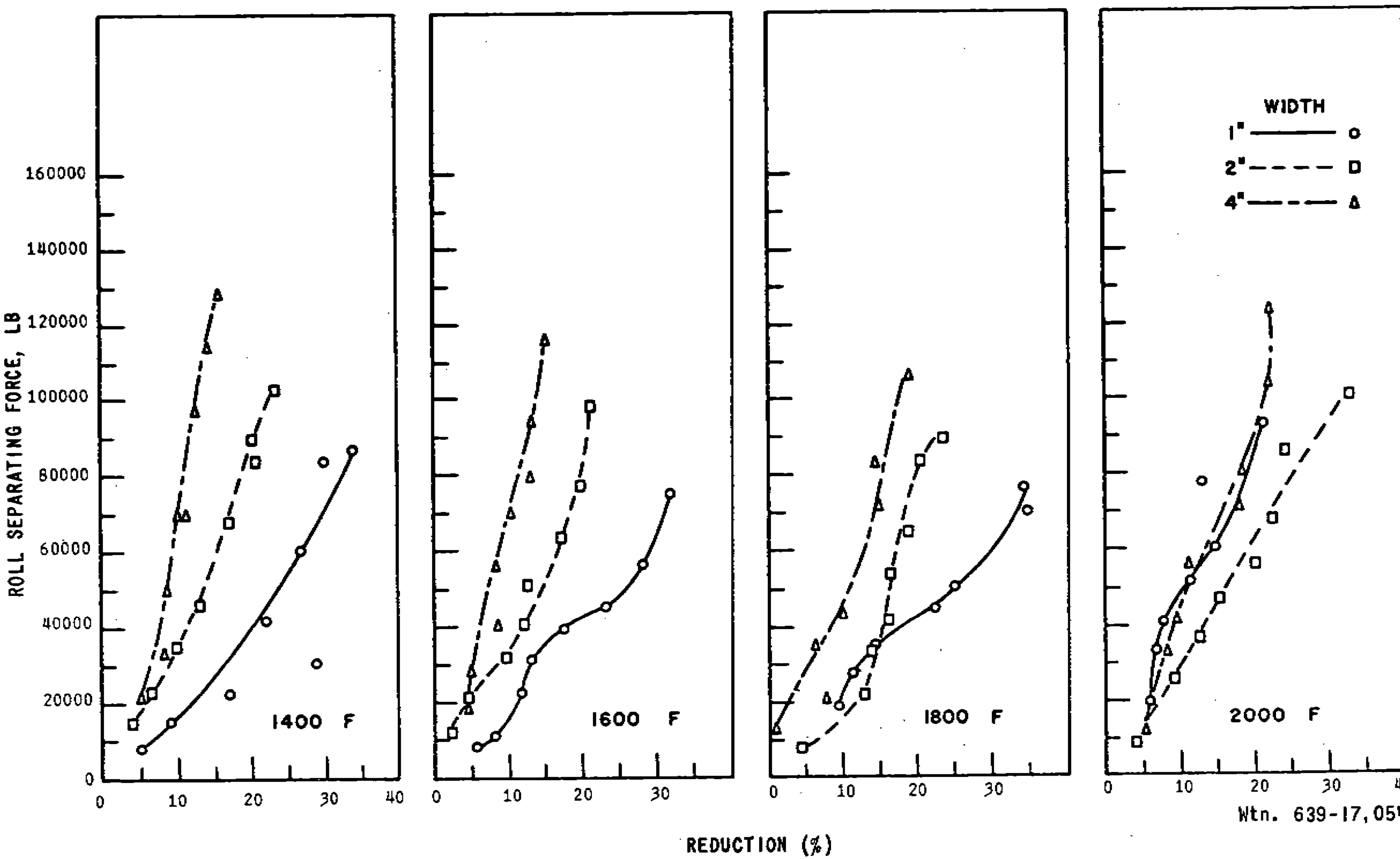
EFFECT OF ROLLING TEMPERATURE, REDUCTION AND WIDTH ON ROLL SEPARATING FORCE FOR COMMERCIALLY PURE TITANIUM 1/8" THICK

FIGURE 2



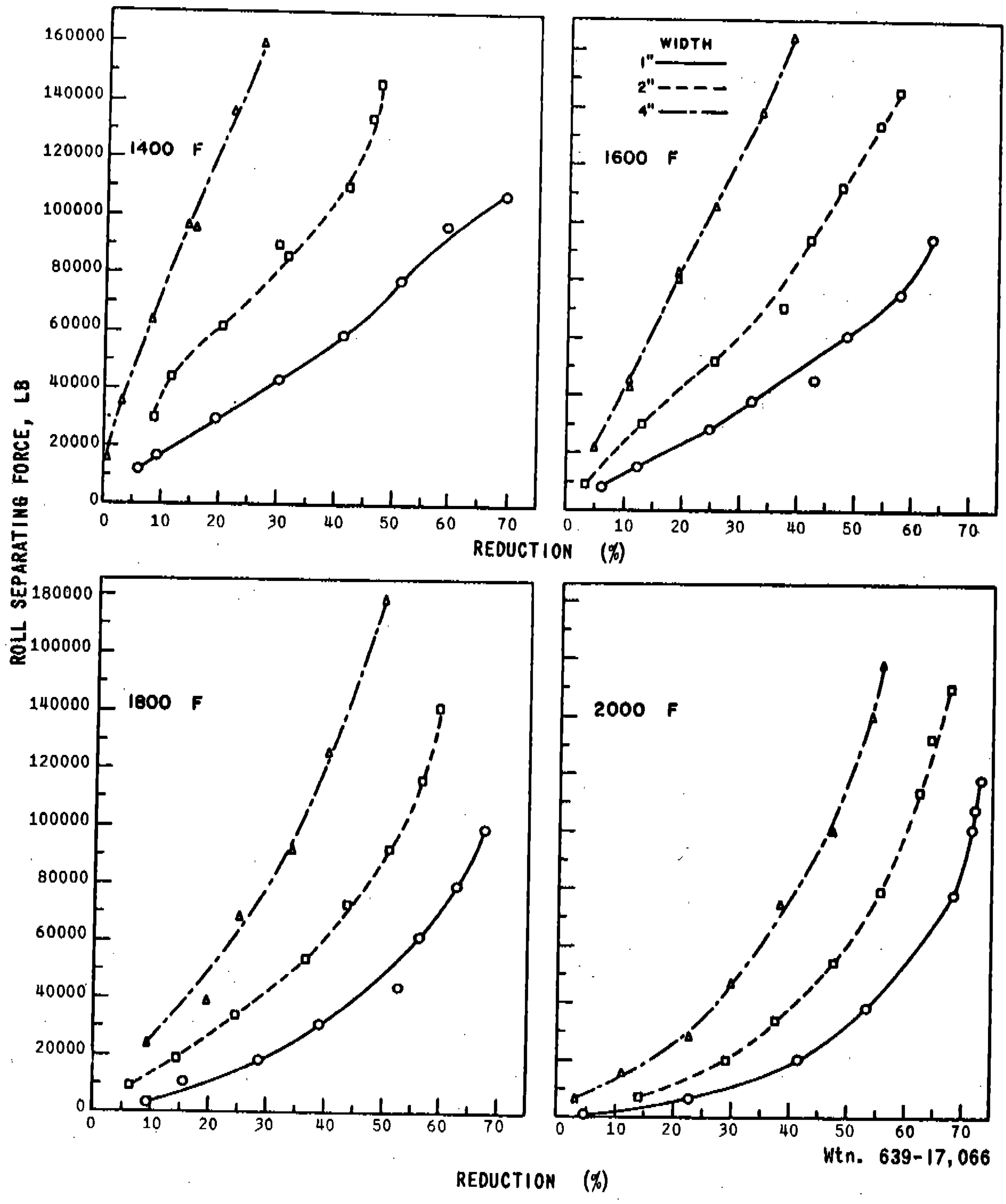
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON ROLL SEPARATING FORCE FOR COMMERCIALLY PURE TITANIUM 1/16" THICK

FIGURE 3



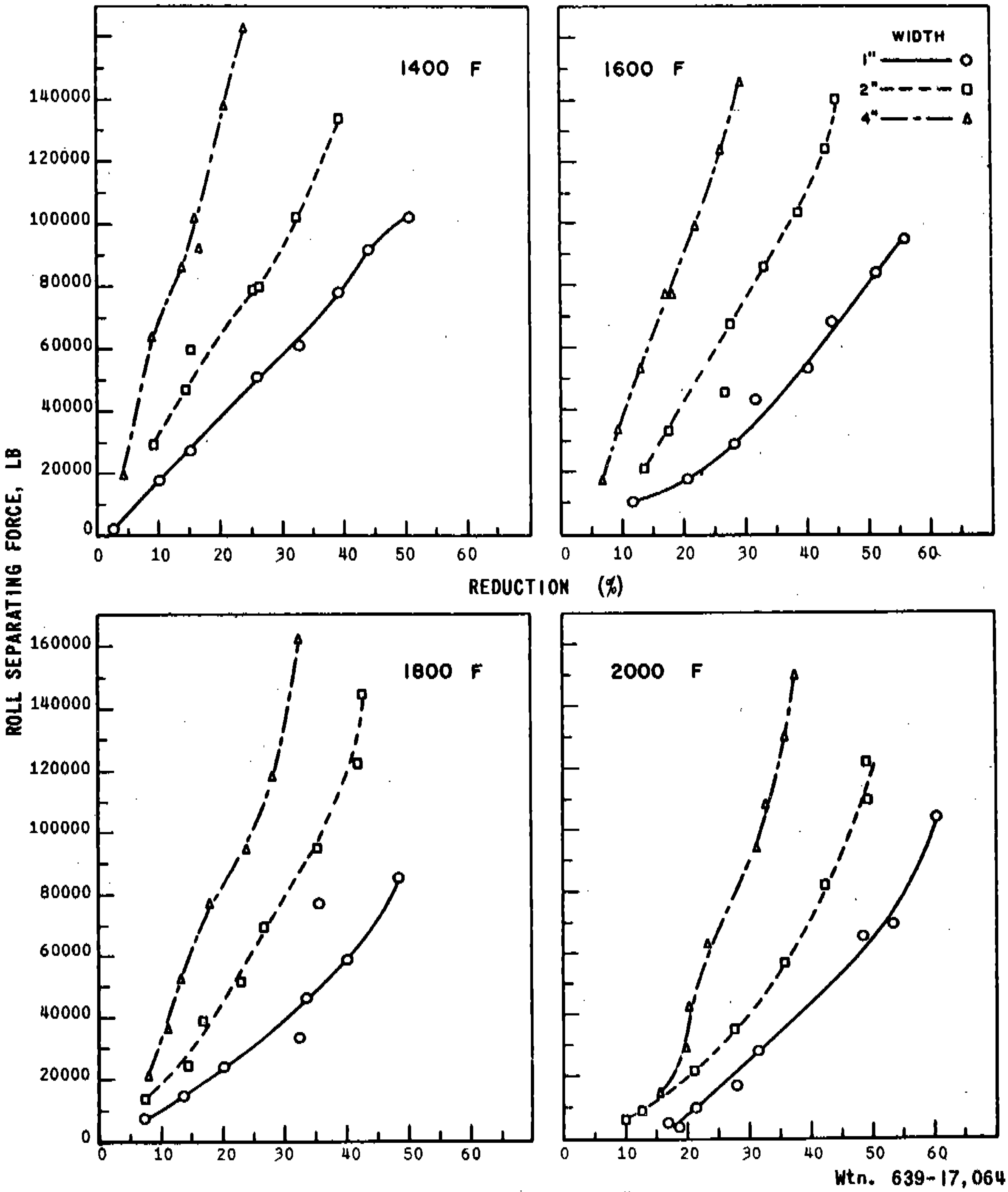
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON ROLL SEPARATING FORCE FOR COMMERCIALLY PURE TITANIUM 1/32" THICK

FIGURE 4



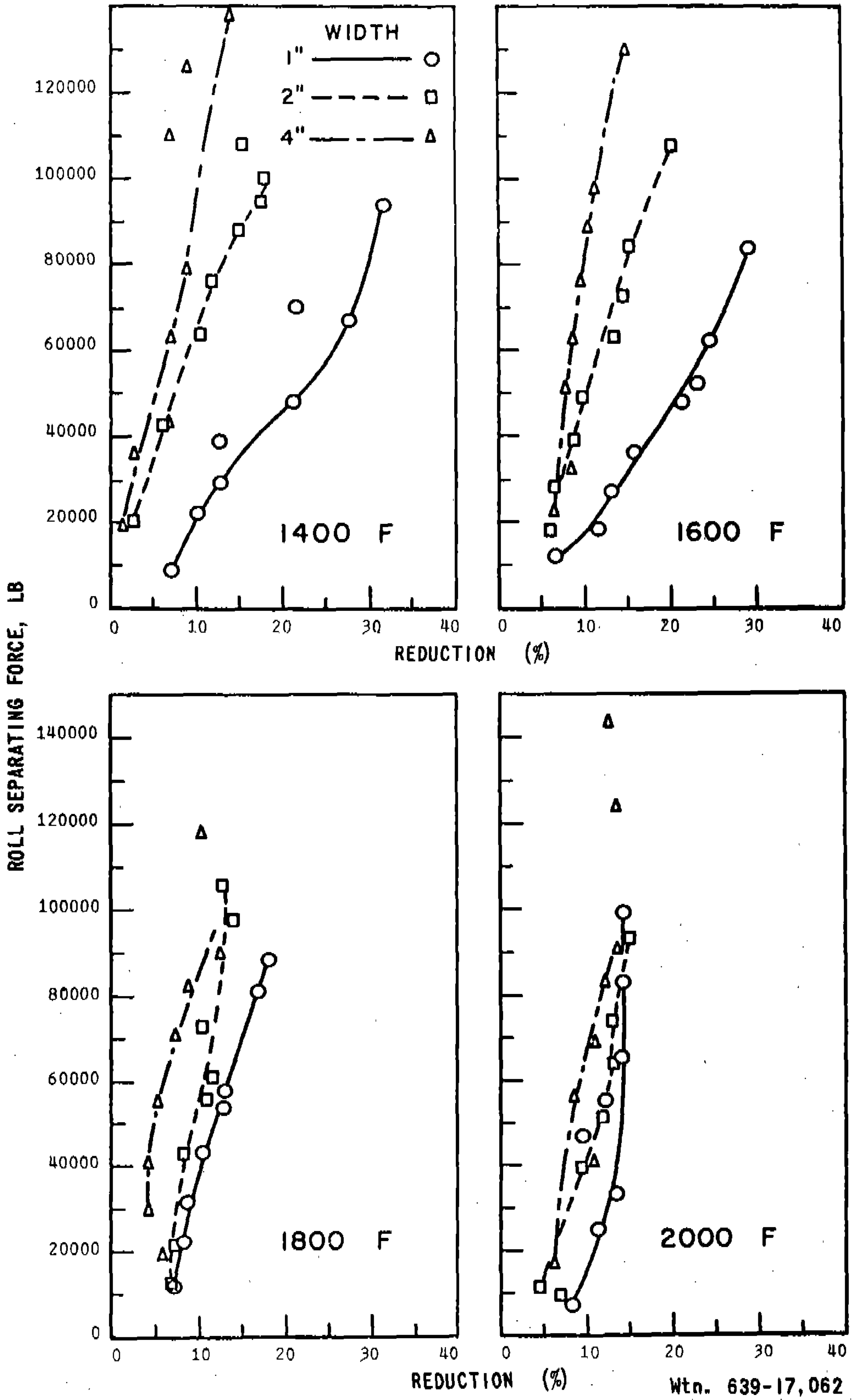
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN WIDTH ON ROLL SEPARATING FORCE FOR Ti-6Al-4V ALLOY 1/8" THICK

FIGURE 5



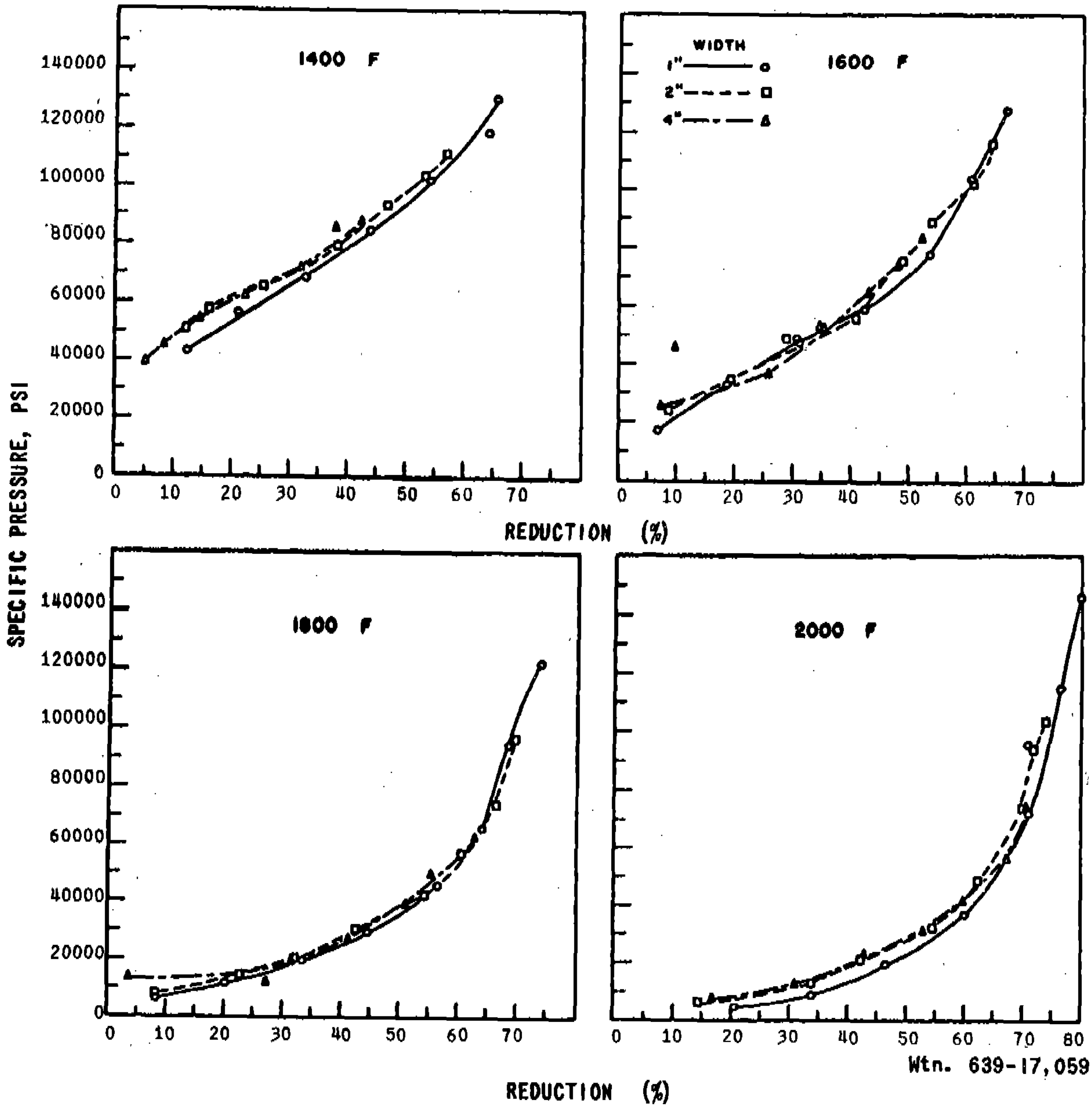
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON ROLL SEPARATING FORCE FOR Ti-6Al-4V ALLOY 1/16" THICK

FIGURE 6



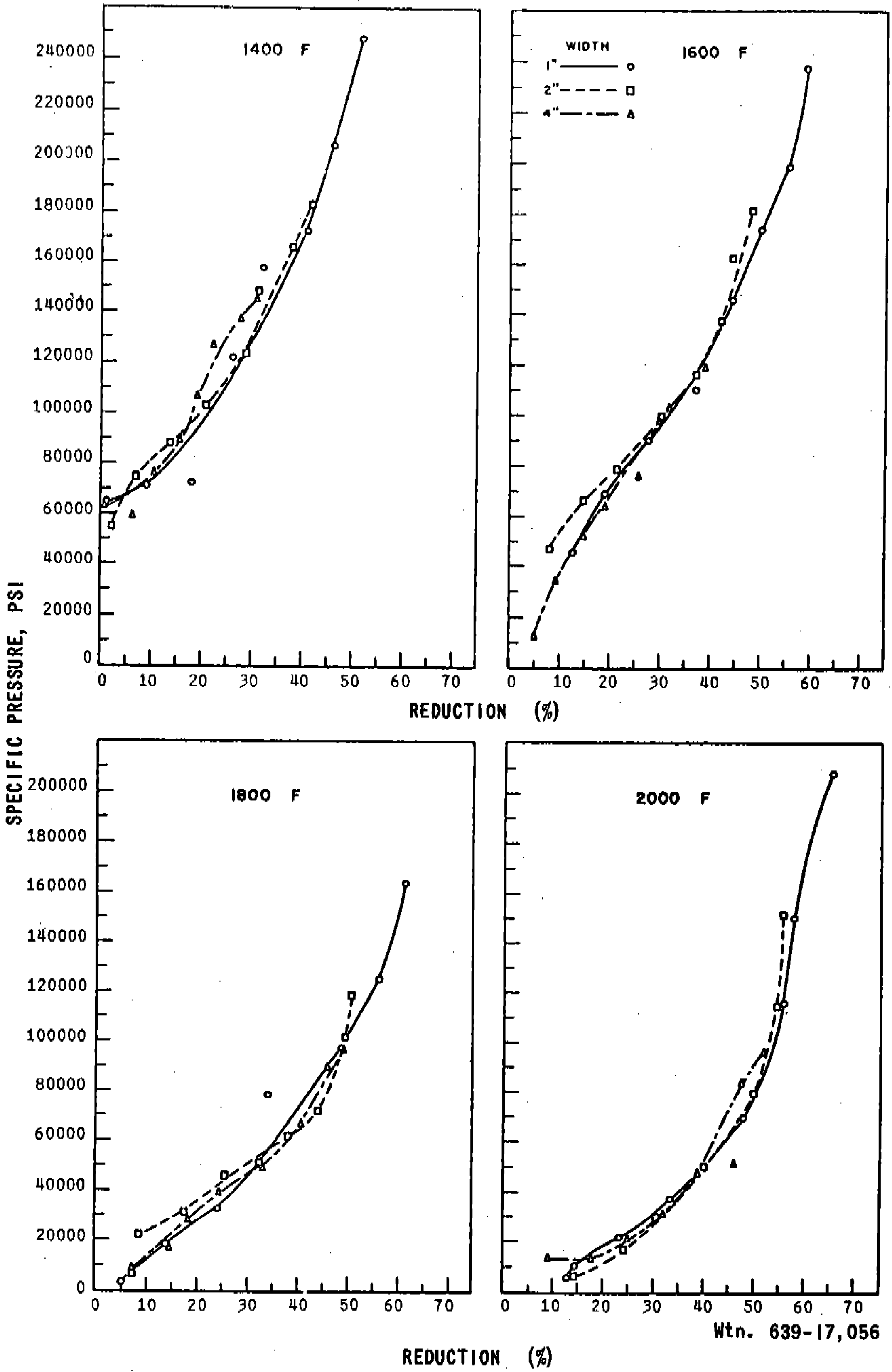
EFFECT OF ROLLING TEMPERATURE, REDUCTION AND WIDTH ON ROLL SEPARATING FORCE FOR Ti-6Al-4V ALLOY 1/32" THICK

FIGURE 7



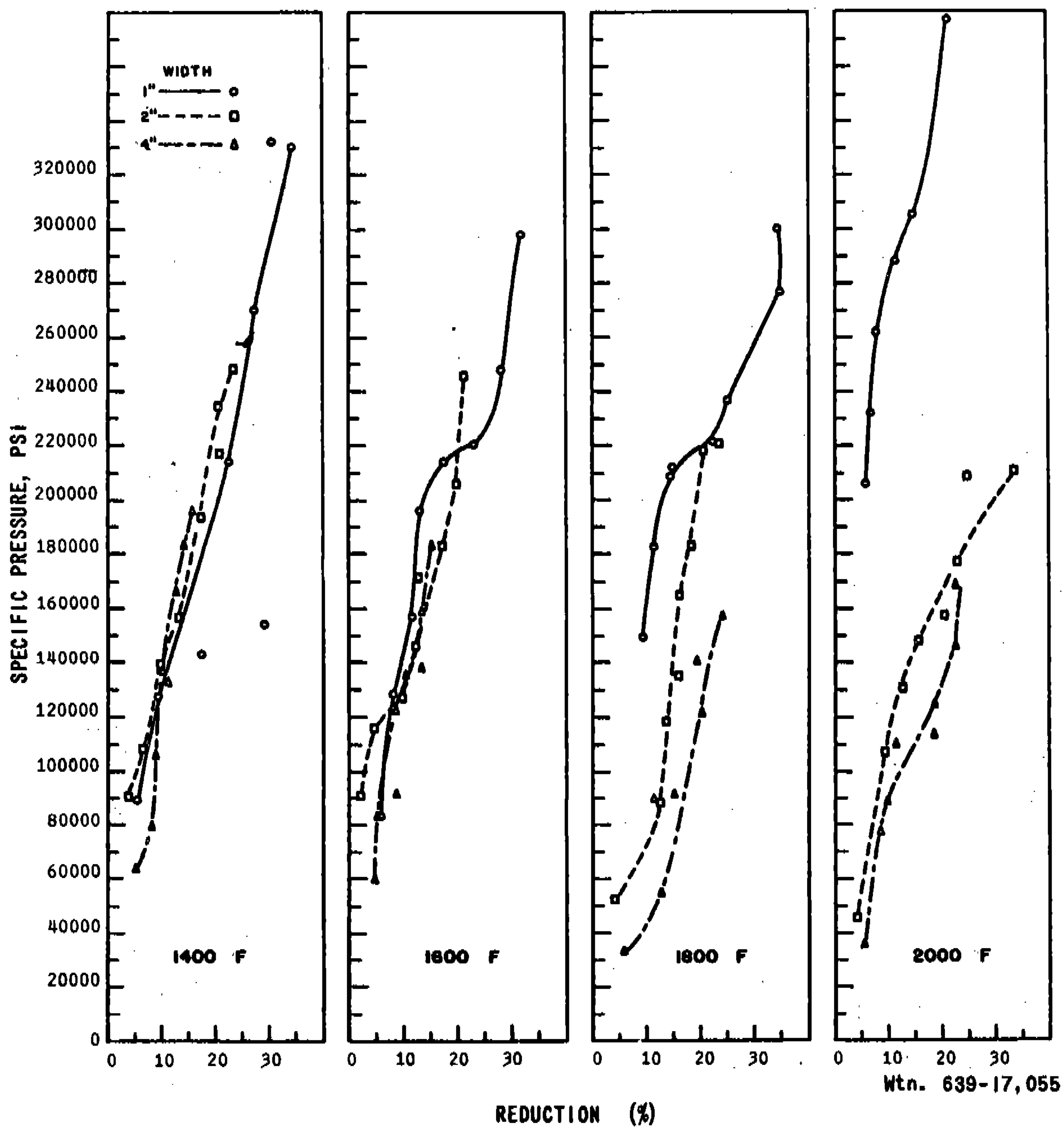
EFFECT OF ROLLING TEMPERATURE, REDUCTION AND WIDTH ON SPECIFIC PRESSURE FOR COMMERCIALLY PURE TITANIUM 1/8" THICK

FIGURE 8



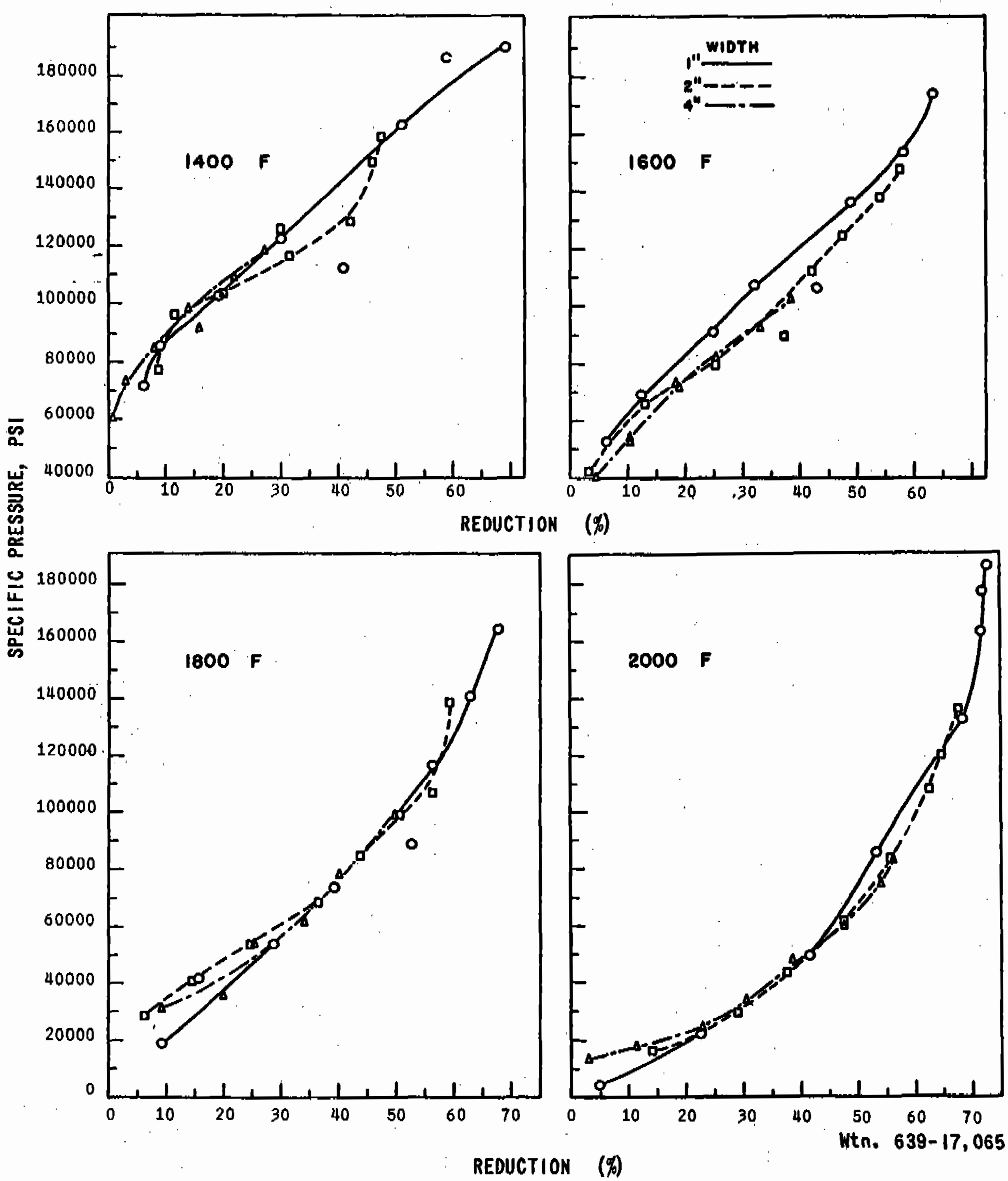
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON SPECIFIC PRESSURE FOR COMMERCIALLY PURE TITANIUM 1/16" THICK

FIGURE 9



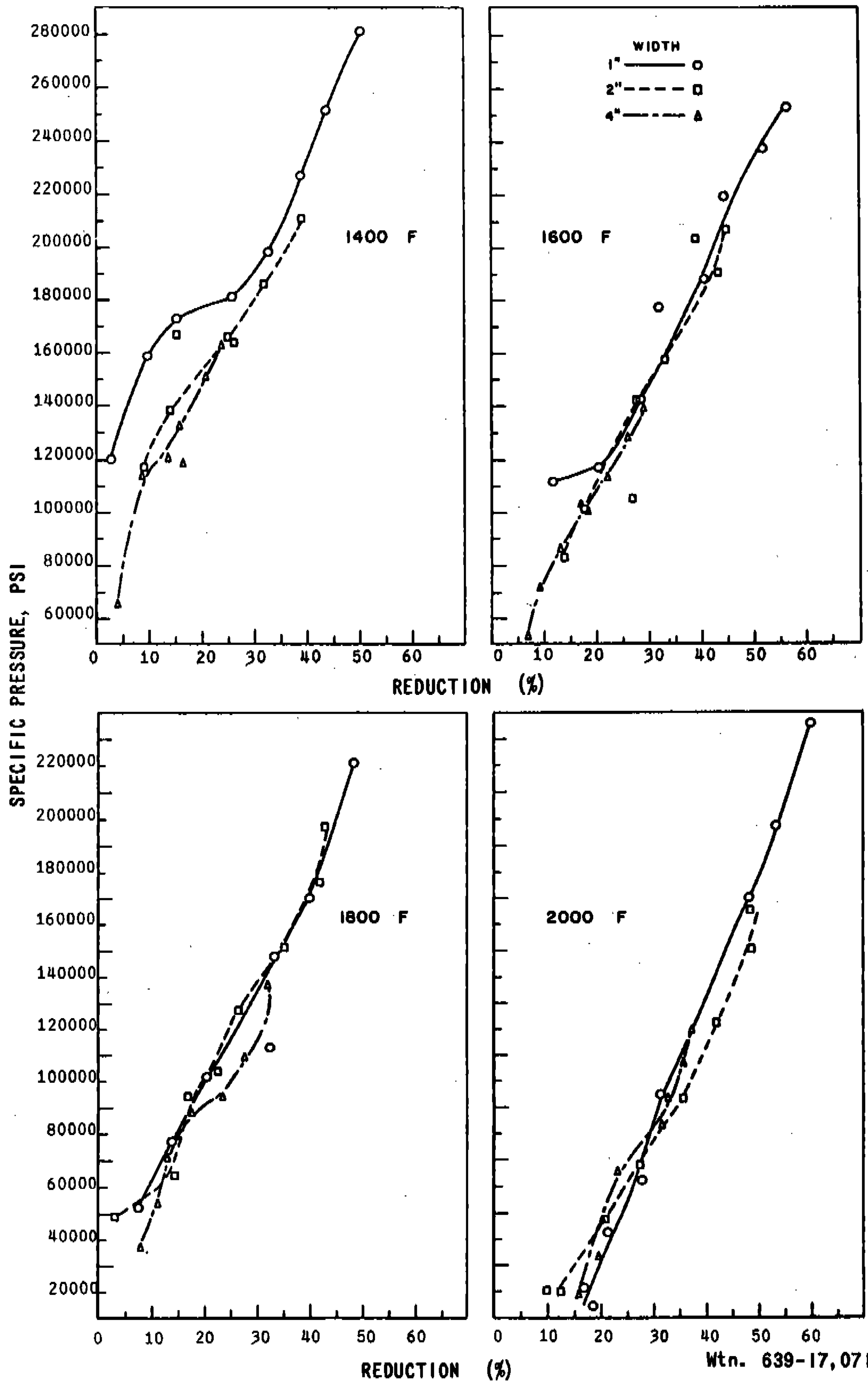
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON SPECIFIC PRESSURE FOR COMMERCIALLY PURE TITANIUM 1/32" THICK

FIGURE 10



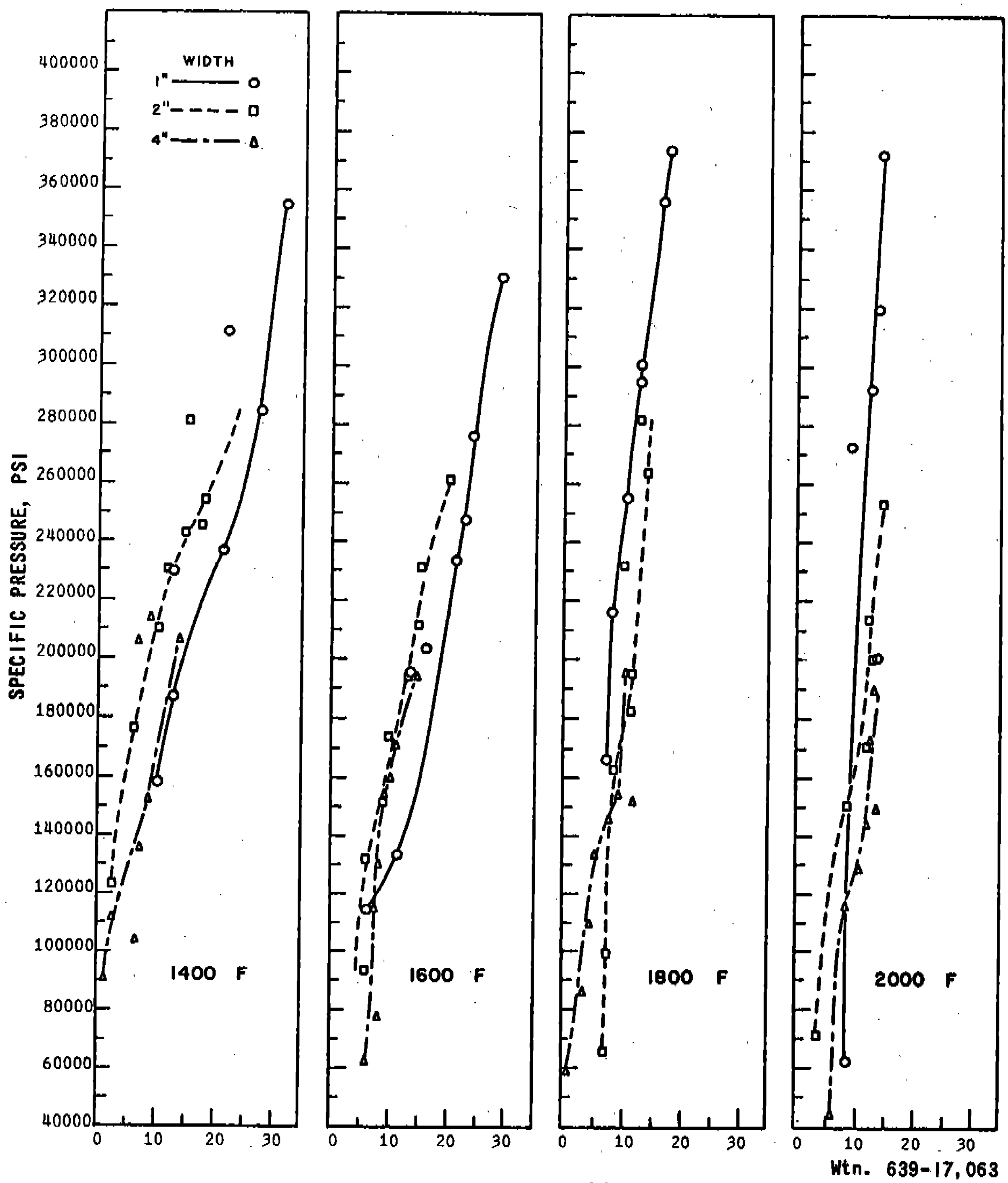
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON SPECIFIC PRESSURE FOR Ti-6Al-4V ALLOY 1/8" THICK

FIGURE 11



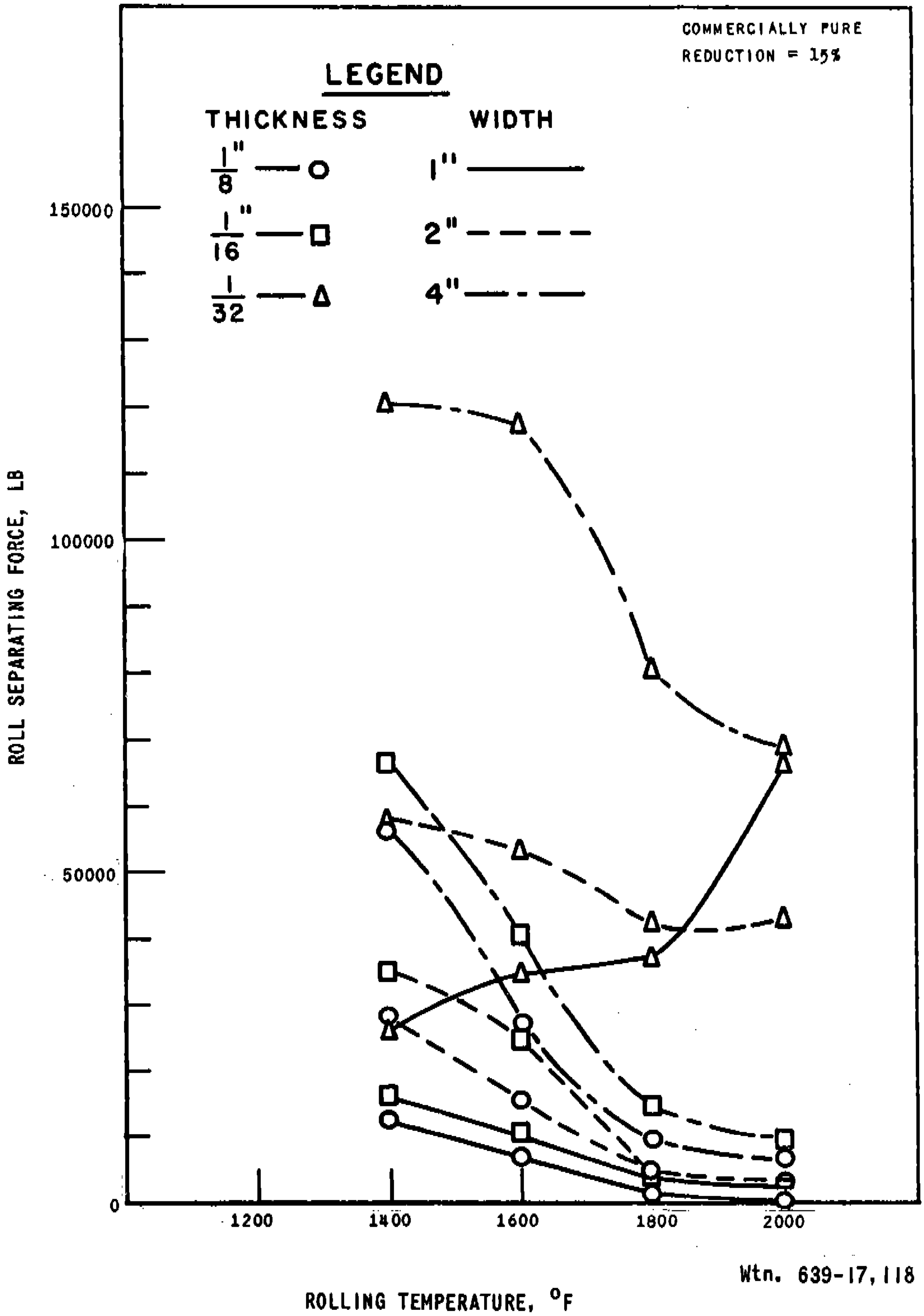
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON SPECIFIC PRESSURE FOR Ti-6Al-4V ALLOY 1/16" THICK

FIGURE 12



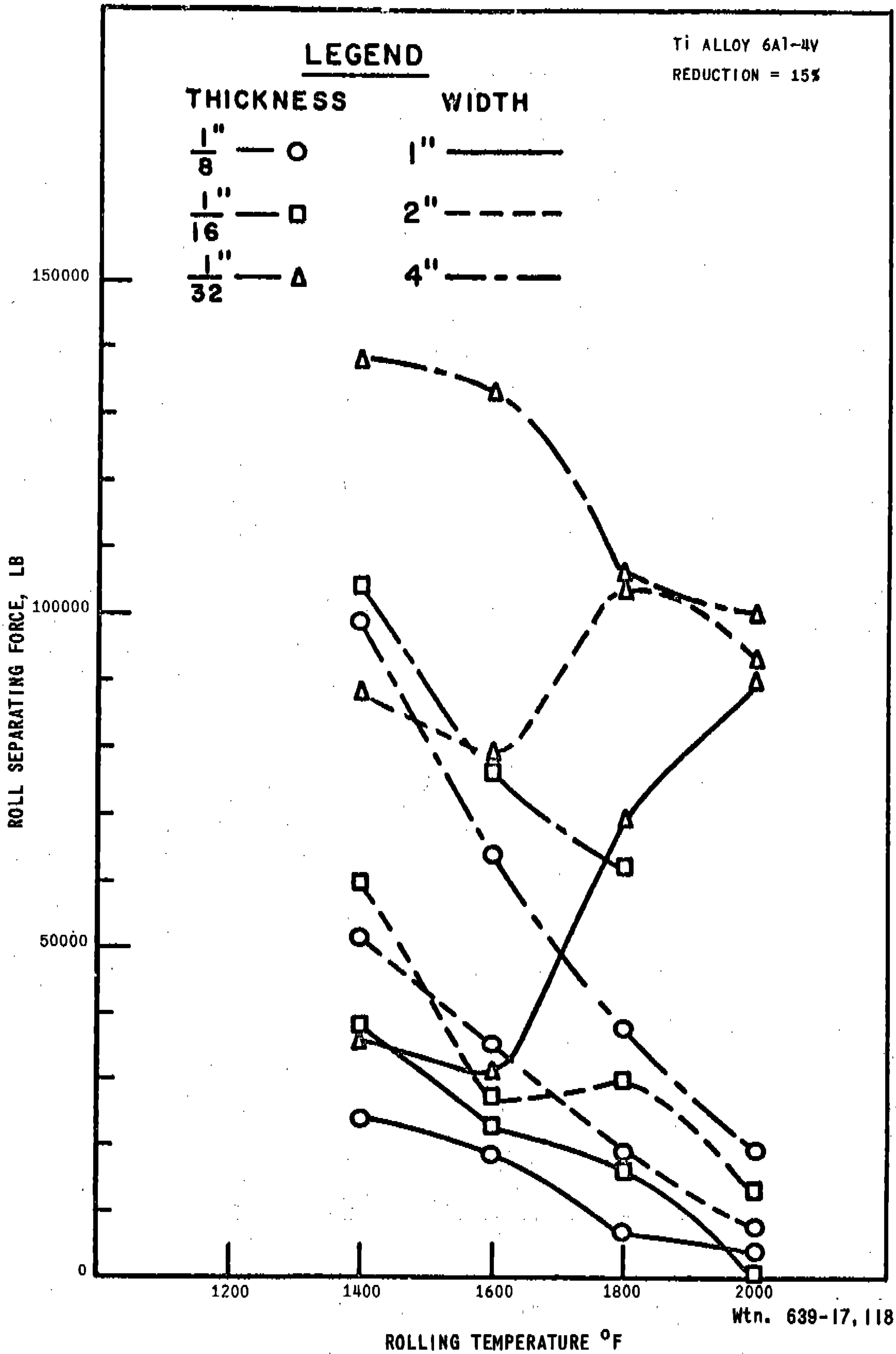
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND WIDTH ON SPECIFIC PRESSURE FOR Ti-6Al-4V ALLOY 1/32" THICK

FIGURE 13



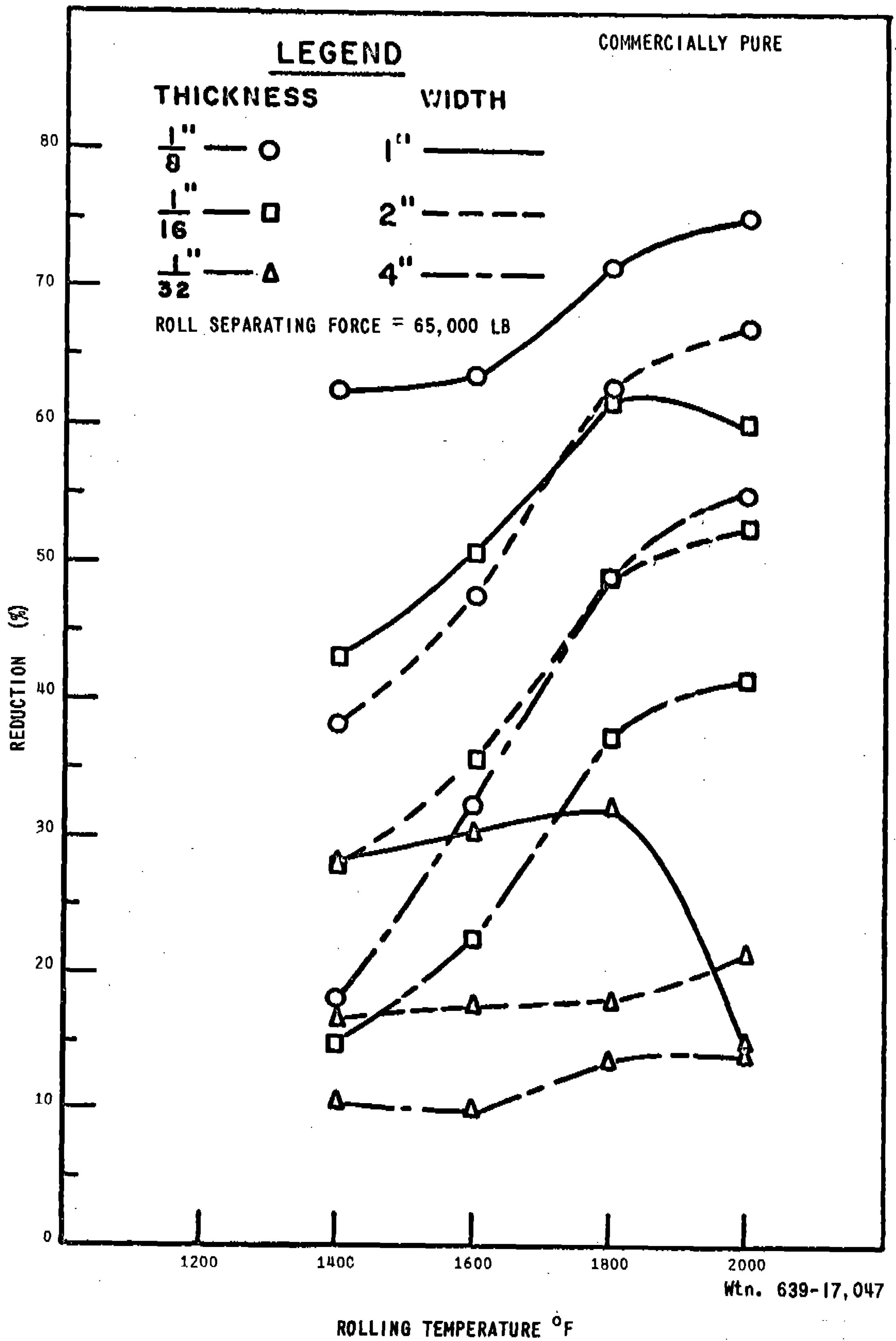
EFFECT OF ROLLING TEMPERATURE AND SPECIMEN SIZE ON ROLL SEPARATING FORCE

FIGURE 14



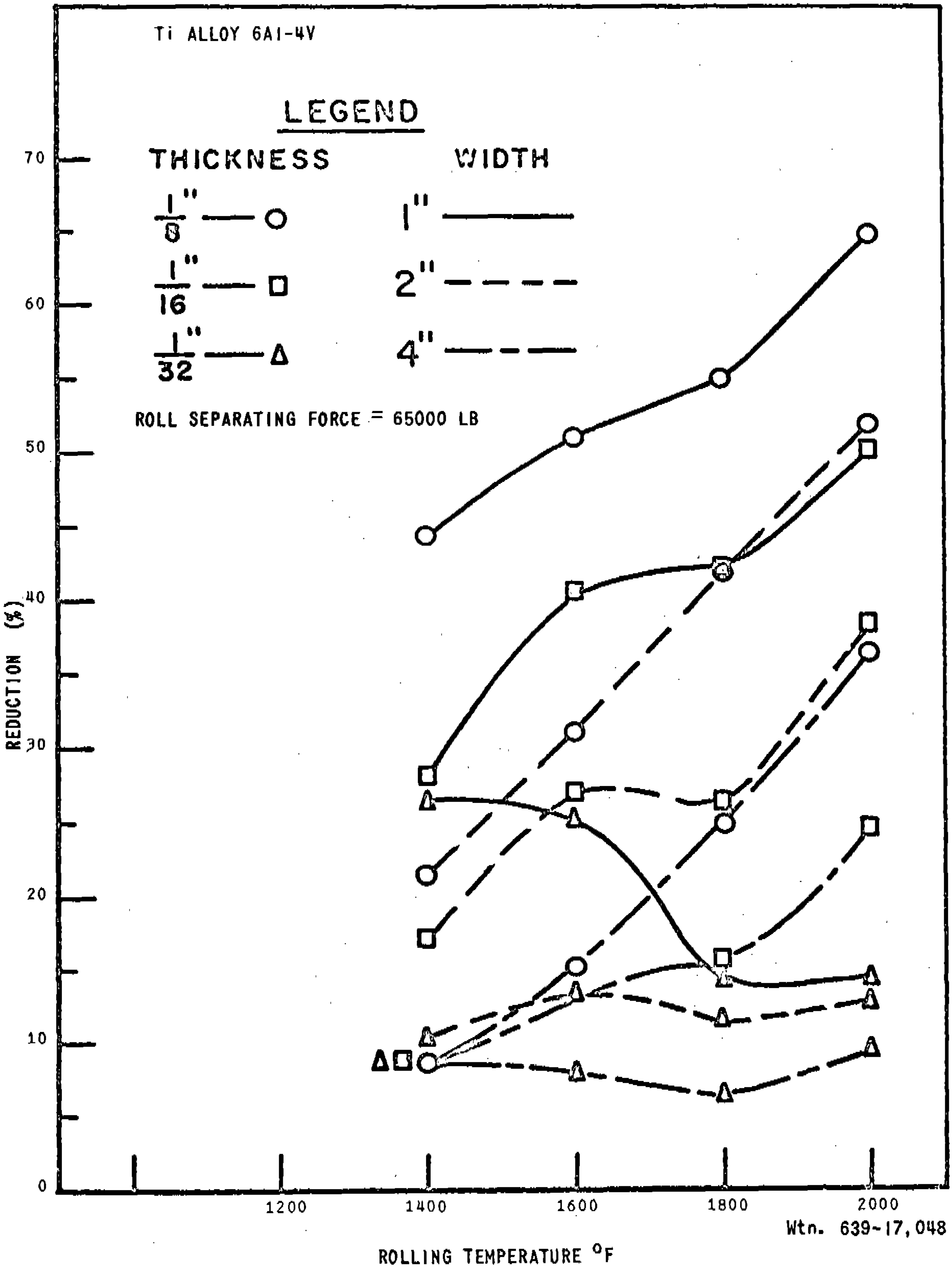
EFFECT OF ROLLING TEMPERATURE AND SPECIMEN SIZE
ON ROLL SEPARATING FORCE

FIGURE 15



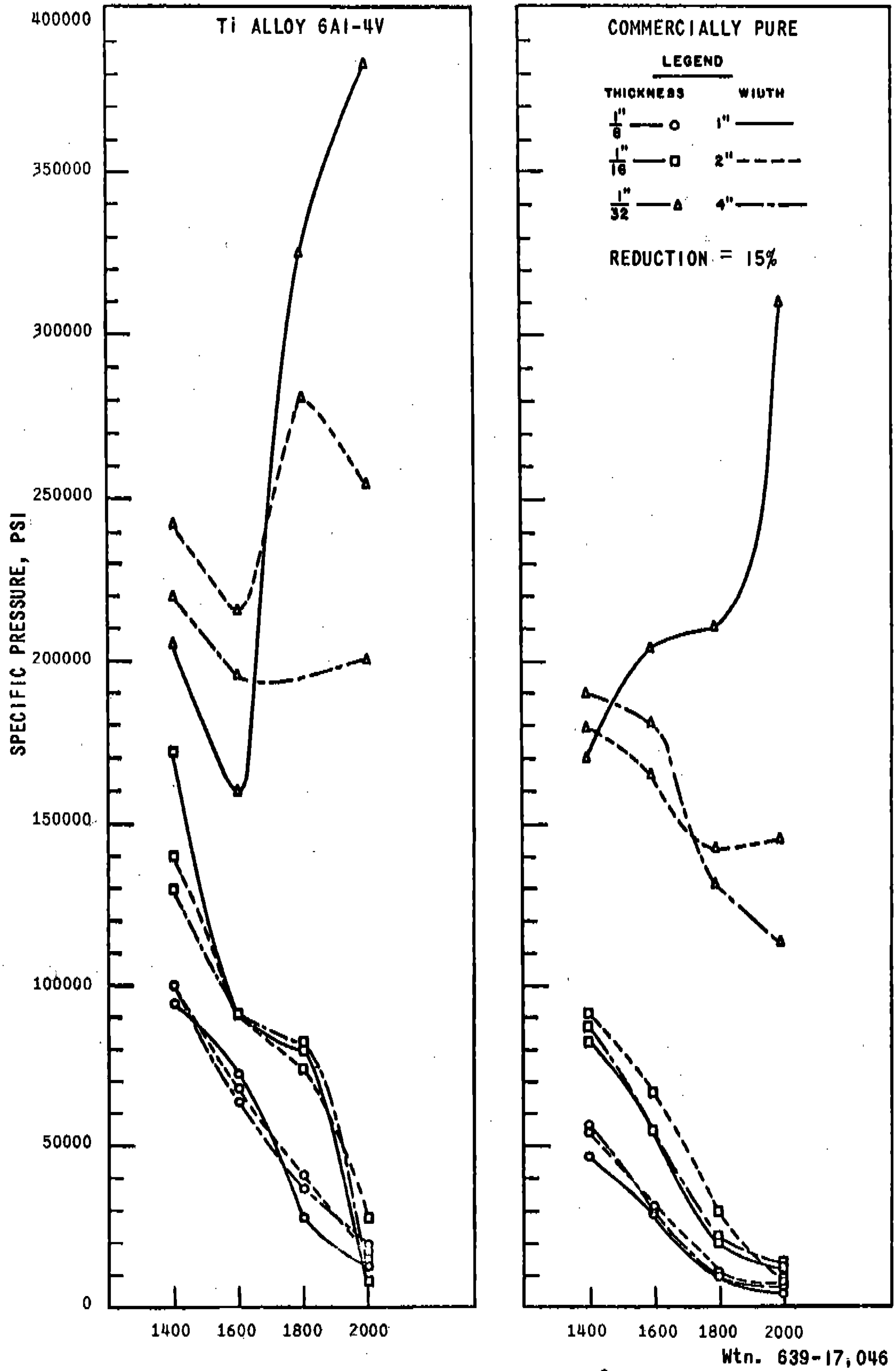
EFFECT OF ROLLING TEMPERATURE AND SPECIMEN SIZE ON PERCENT REDUCTION

FIGURE 16



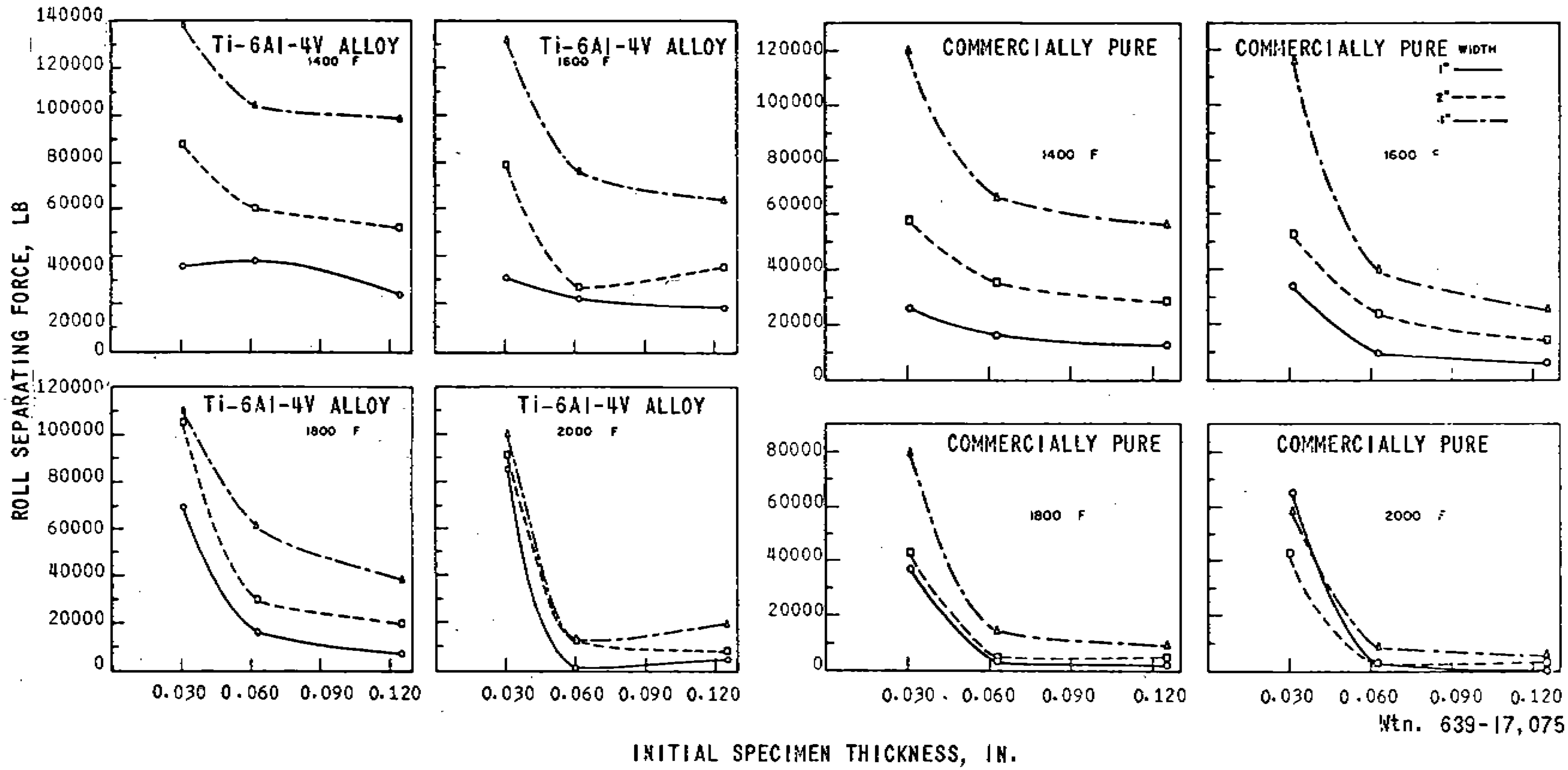
EFFECT OF ROLLING TEMPERATURE AND SPECIMEN SIZE ON PERCENT REDUCTION

FIGURE 17



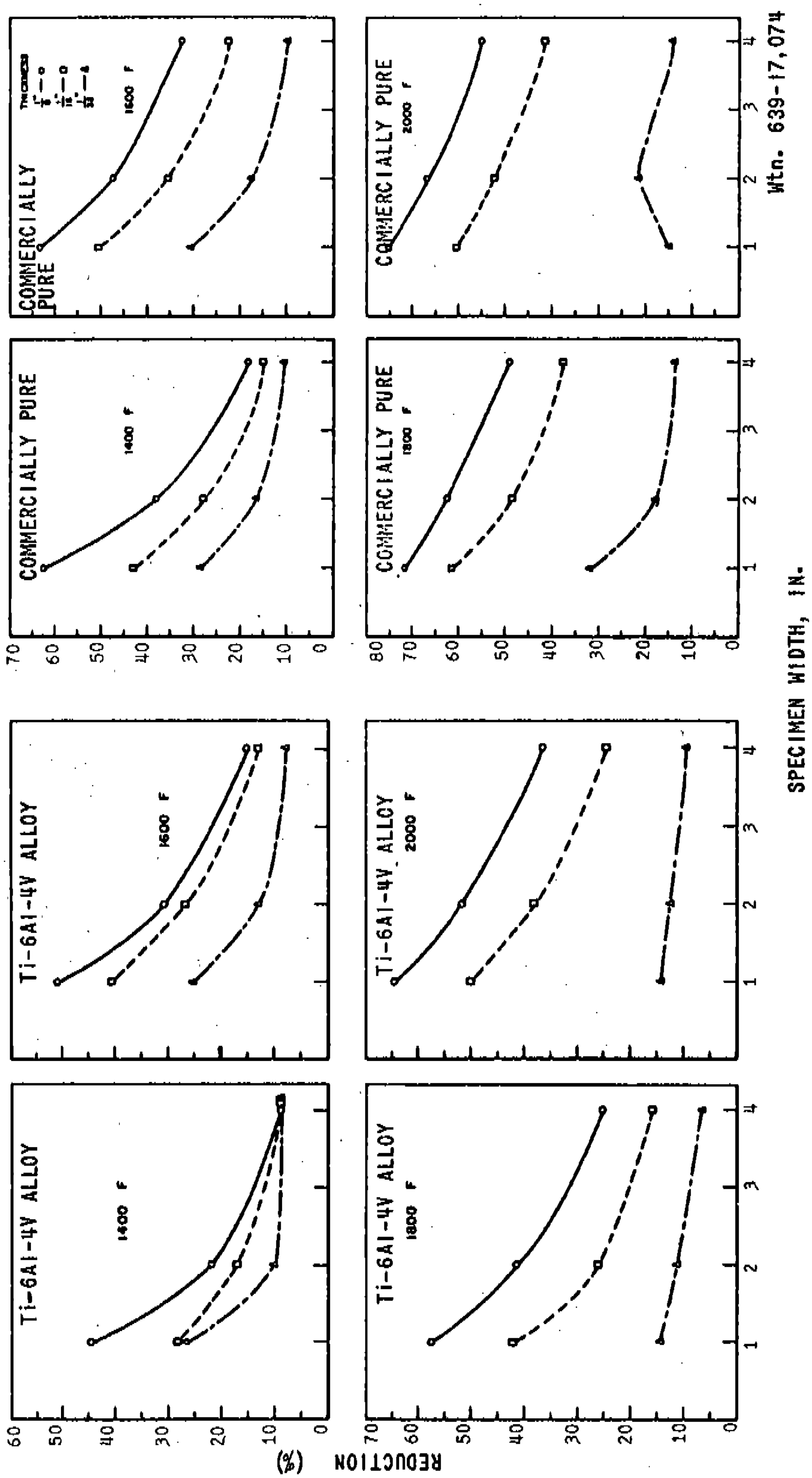
EFFECT OF ROLLING TEMPERATURE AND SPECIMEN SIZE ON SPECIFIC ROLLING PRESSURE

FIGURE 18



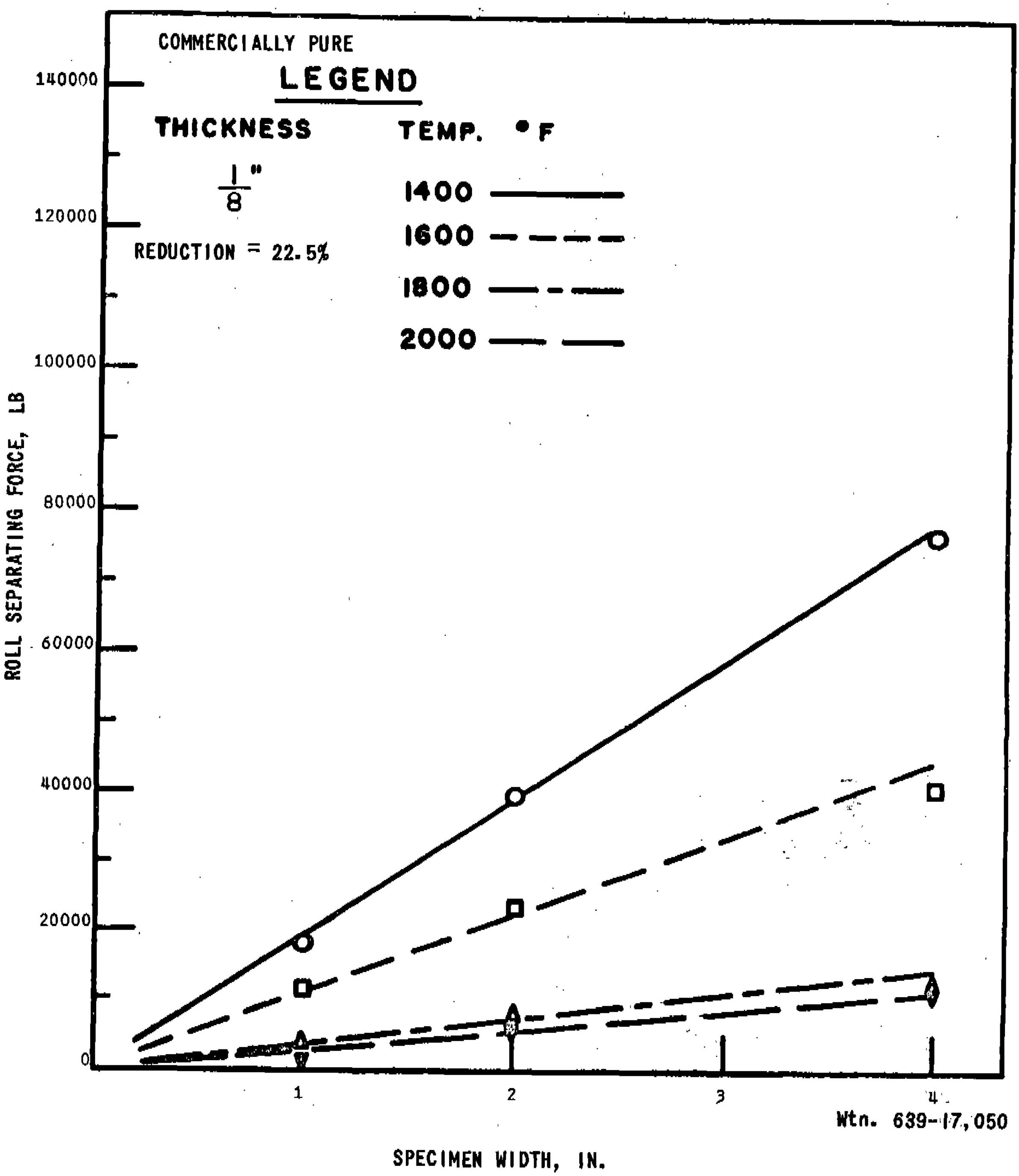
EFFECT OF INITIAL SPECIMENS THICKNESS, WIDTH, AND ROLLING TEMPERATURE ON ROLL SEPARATING FORCE FOR A 15% REDUCTION

FIGURE 19



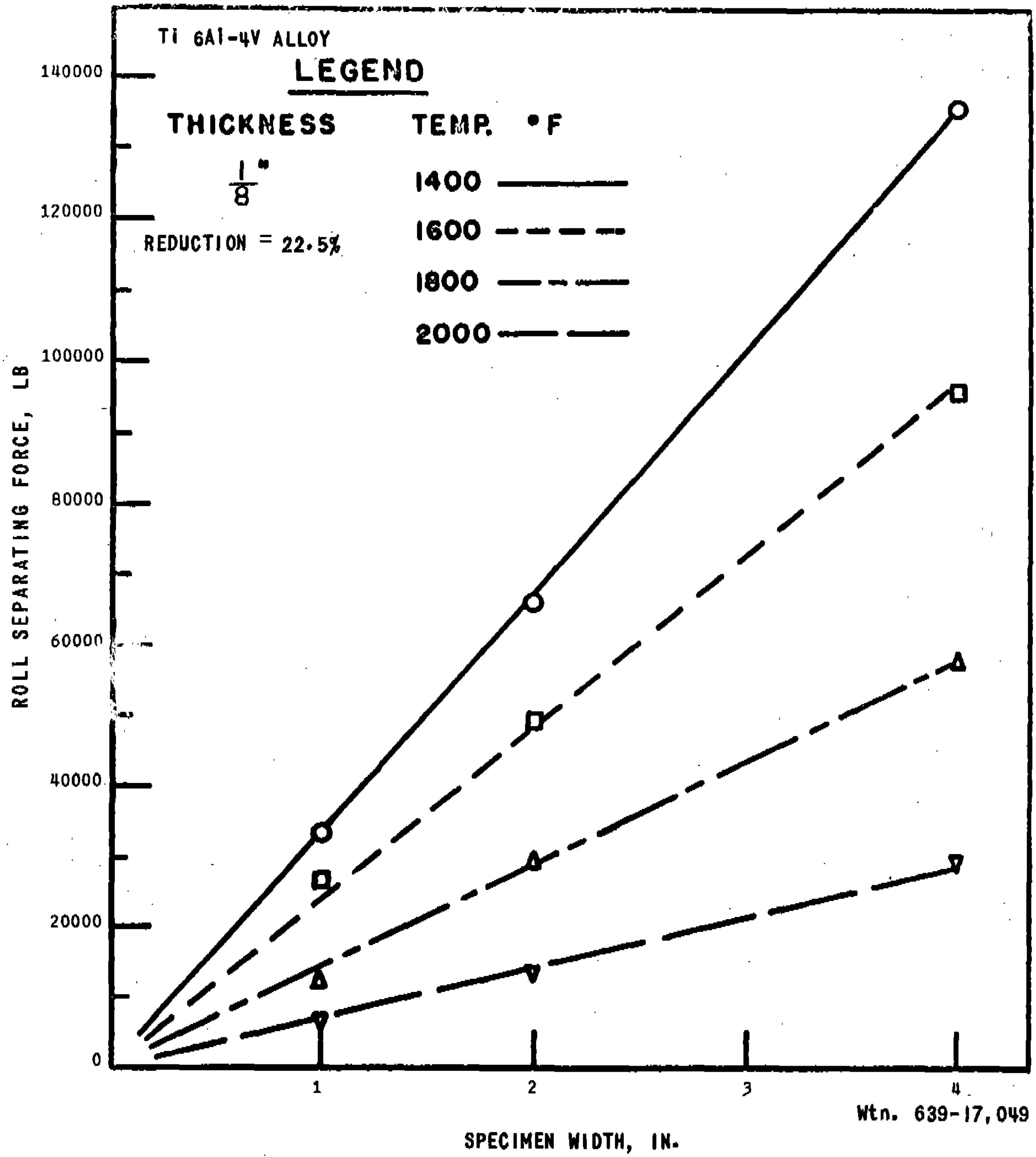
EFFECT OF SPECIMEN WIDTH, INITIAL THICKNESS AND ROLLING TEMPERATURE ON REDUCTION FOR A CONSTANT ROLL SEPARATING FORCE OF 65,000 LB

FIGURE 20



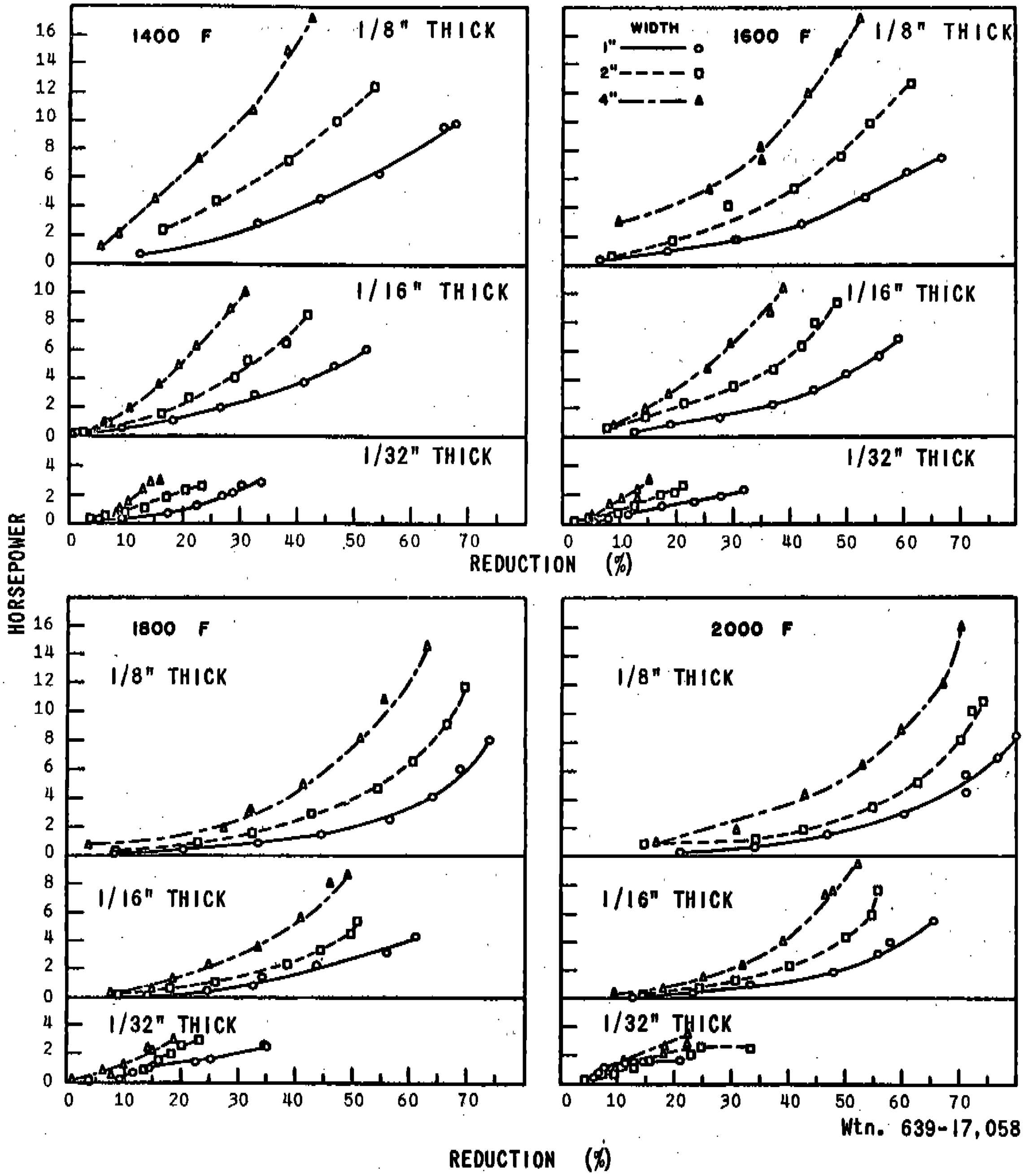
EFFECT OF ROLLING TEMPERATURE AND SPECIMEN WIDTH ON ROLL SEPARATING FORCE

FIGURE 21

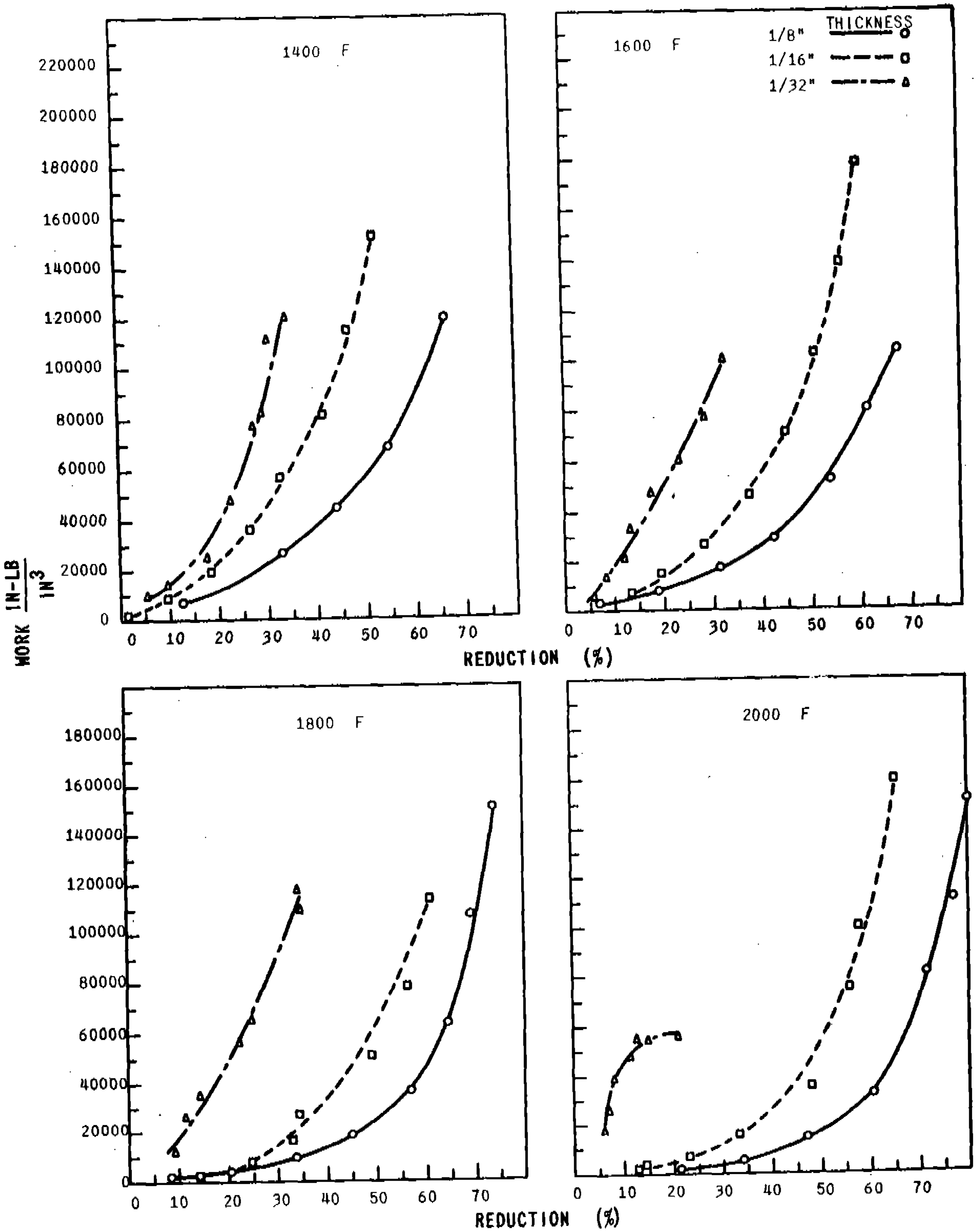


EFFECT OF ROLLING TEMPERATURE AND SPECIMEN WIDTH ON ROLL SEPARATING FORCE

FIGURE 22

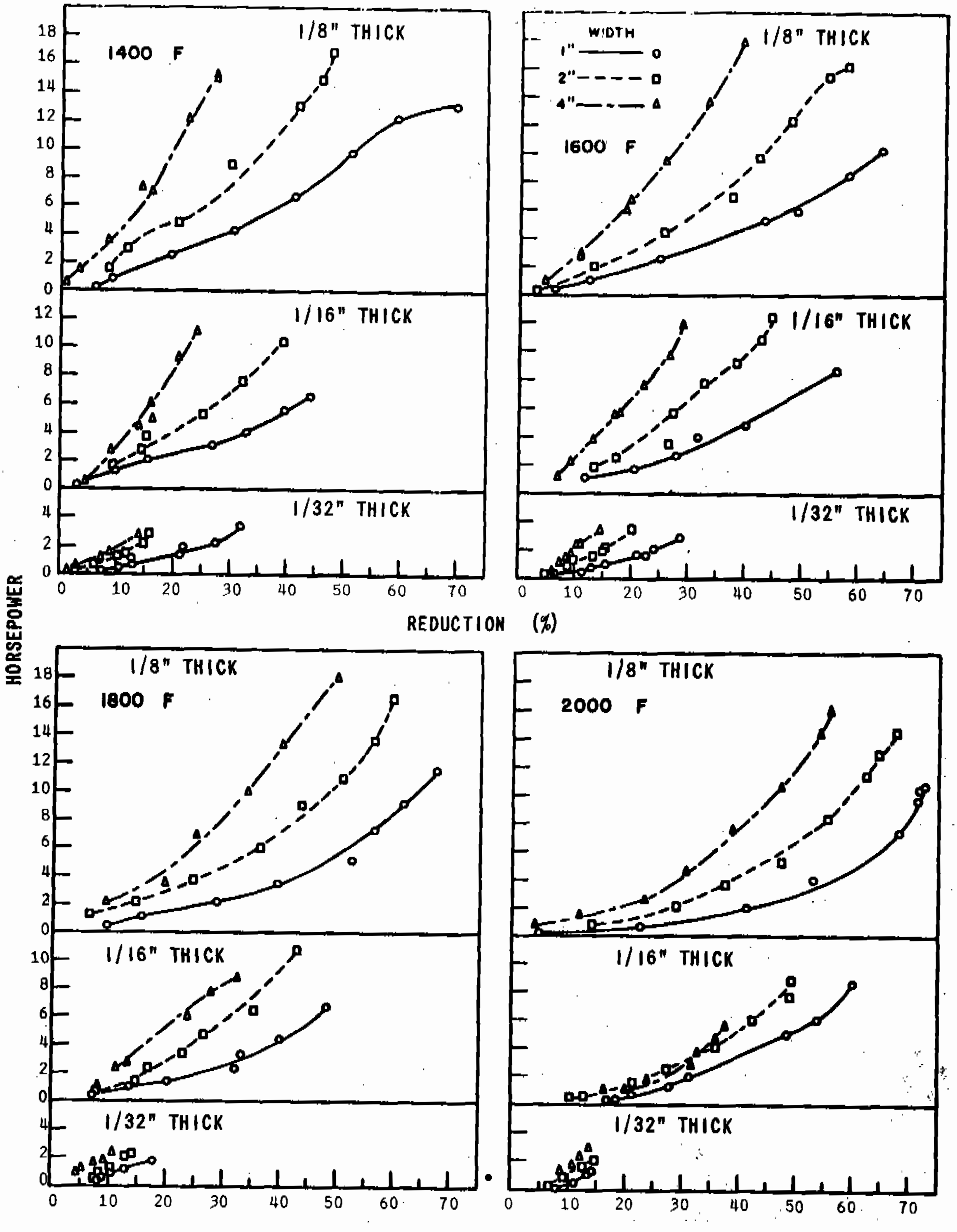


EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON HORSEPOWER CONSUMPTION FOR COMMERCIALLY PURE TITANIUM



EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND INITIAL THICKNESS ON WORK PER UNIT VOLUME FOR COMMERCIALLY PURE TITANIUM 1" WIDE

FIGURE 24



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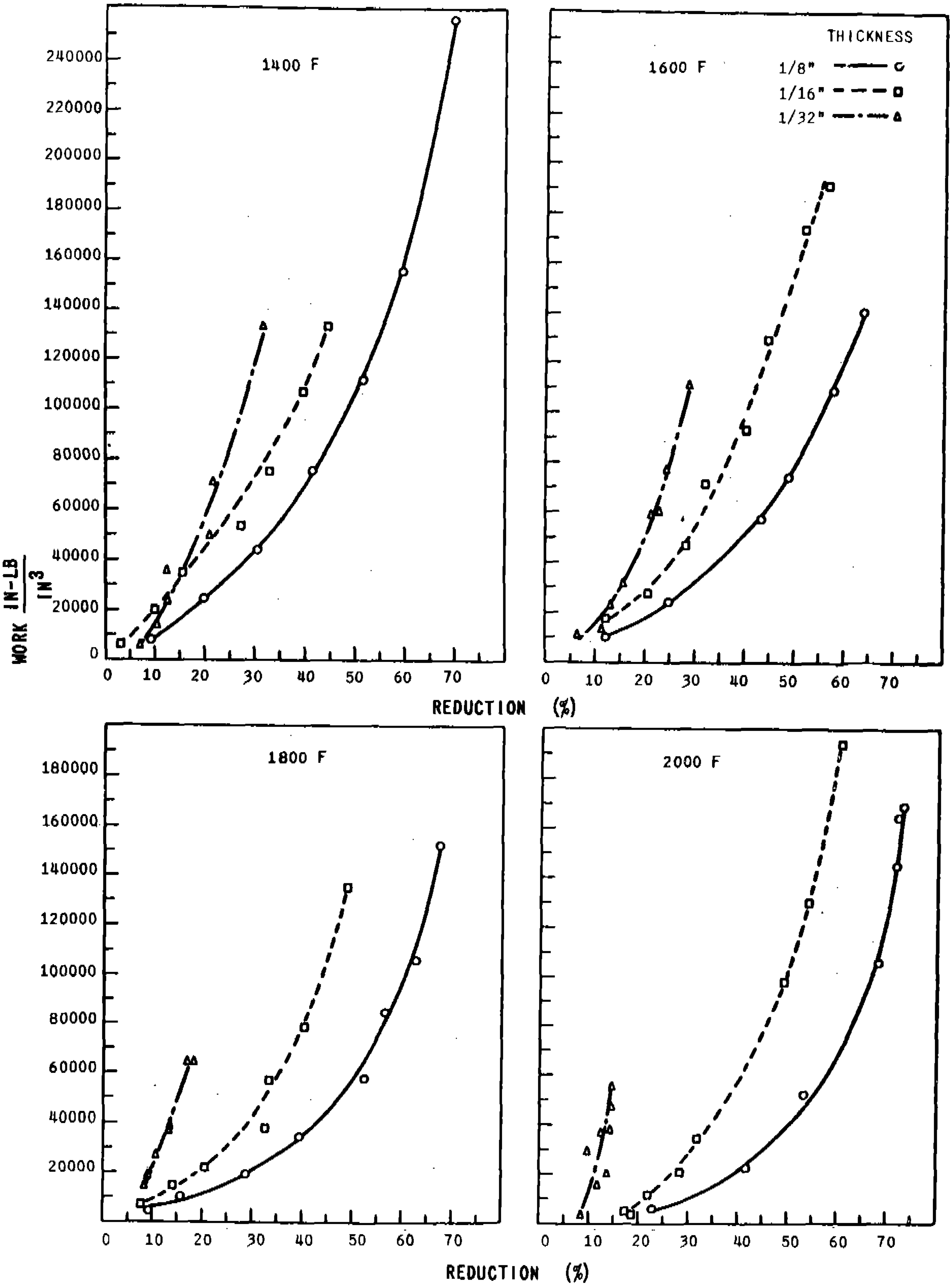
REDUCTION (%)

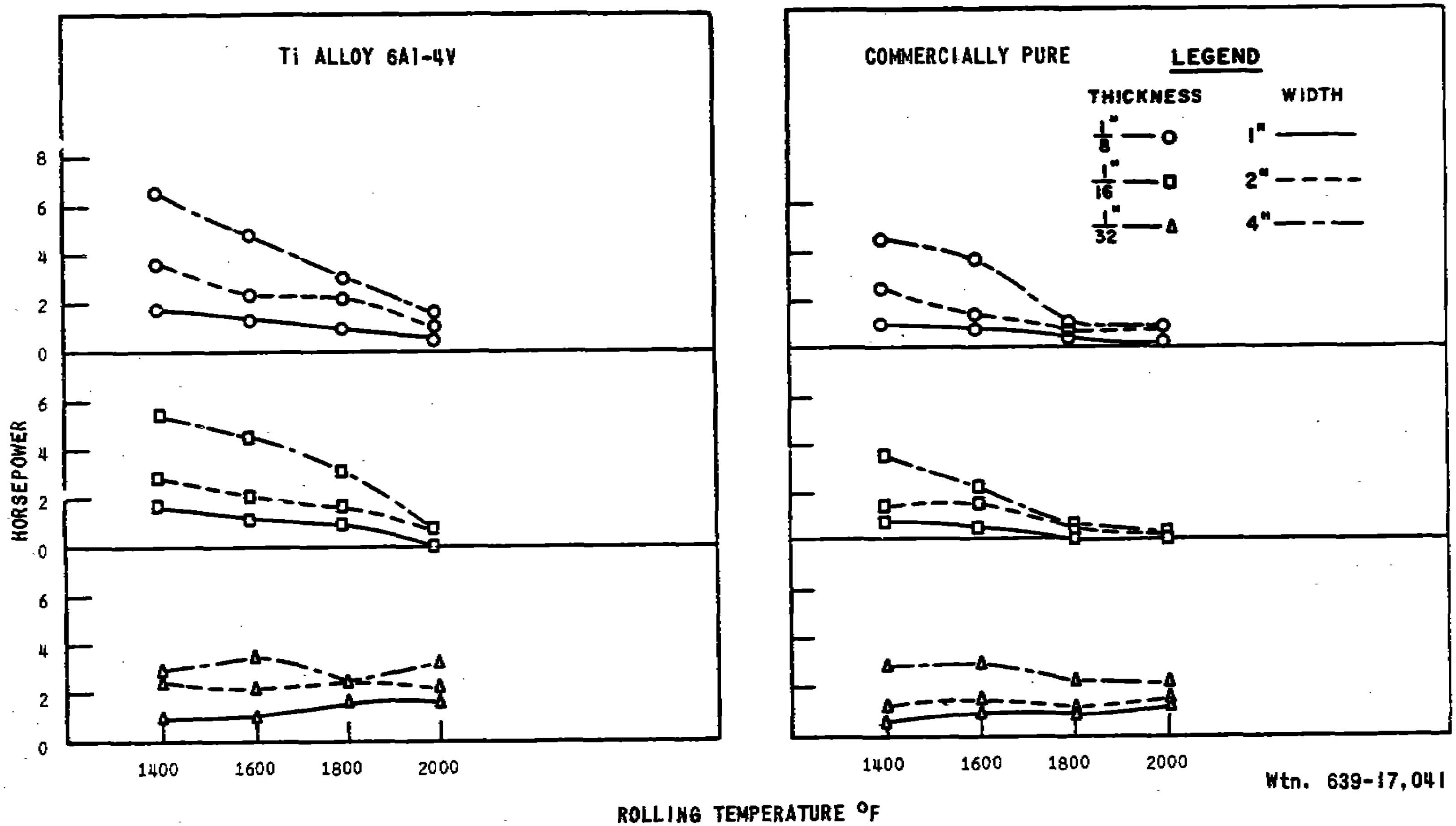
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON HORSEPOWER CONSUMPTION FOR Ti-6Al-4V ALLOY

FIGURE 25



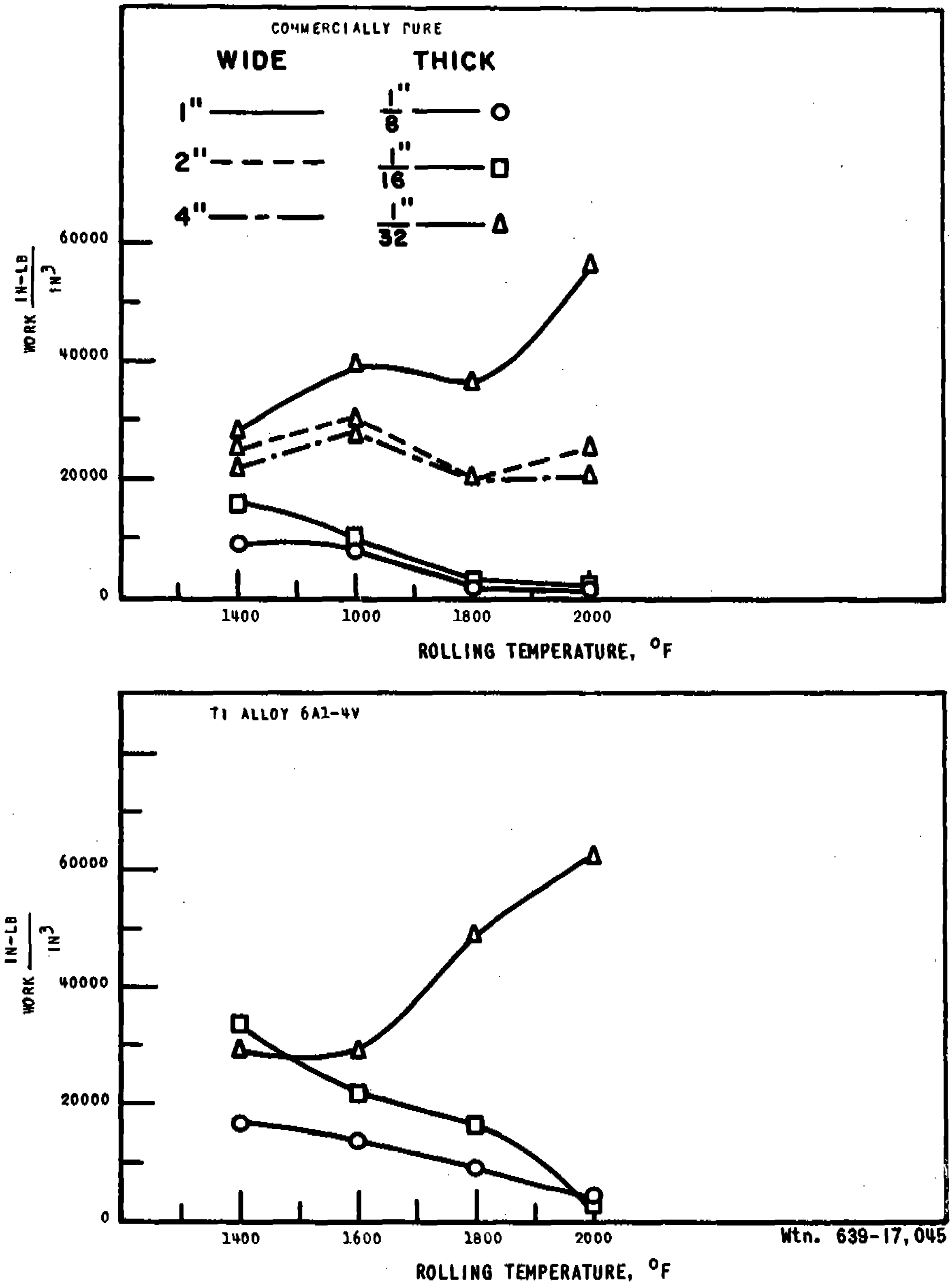
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN THICKNESS ON WORK PER UNIT VOLUME FOR Ti-6Al-4V ALLOY 1" WIDE

FIGURE 26

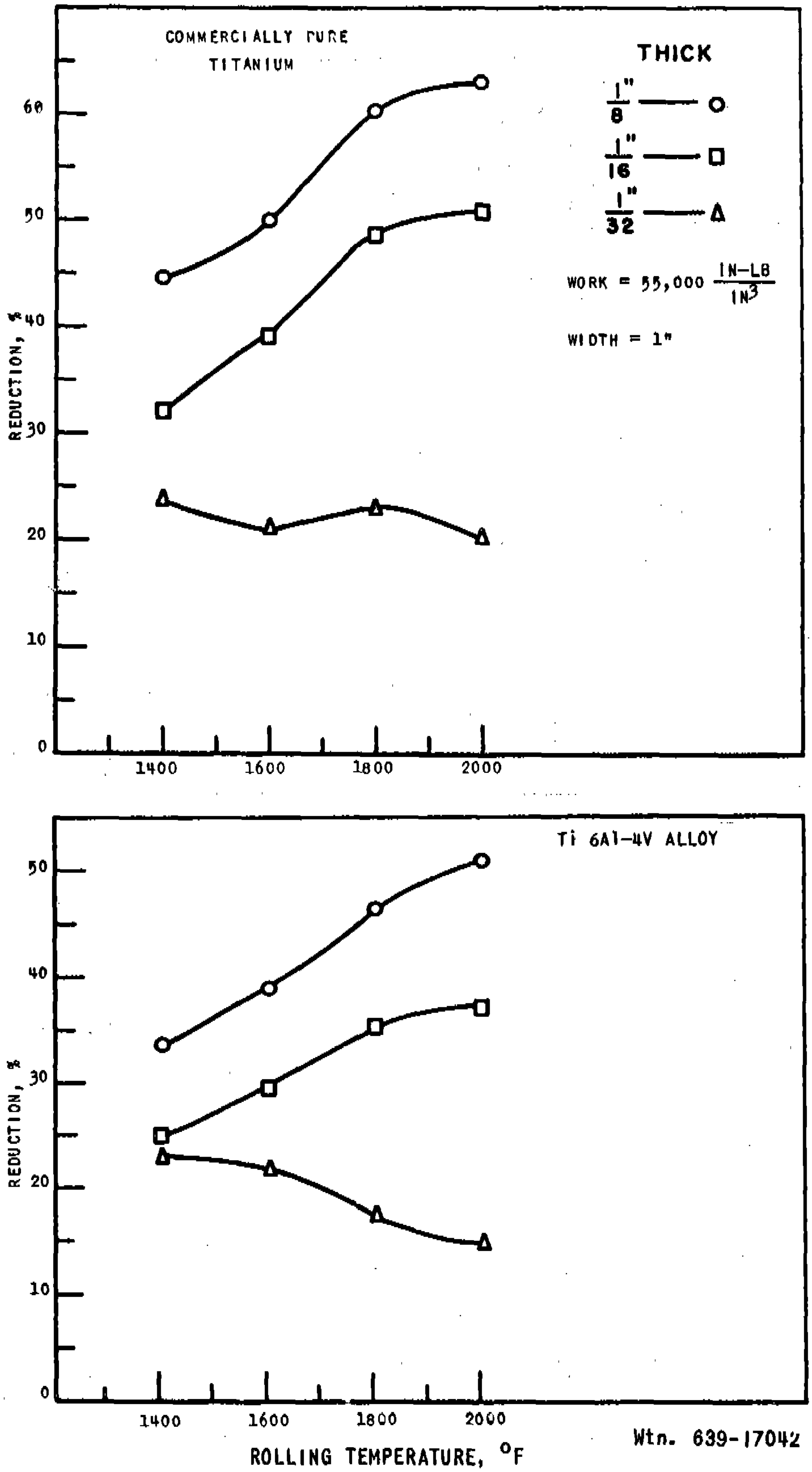


EFFECT OF ROLLING TEMPERATURE AND SPECIMEN SIZE ON HORSEPOWER CONSUMPTION FOR A 15% REDUCTION

FIGURE 27

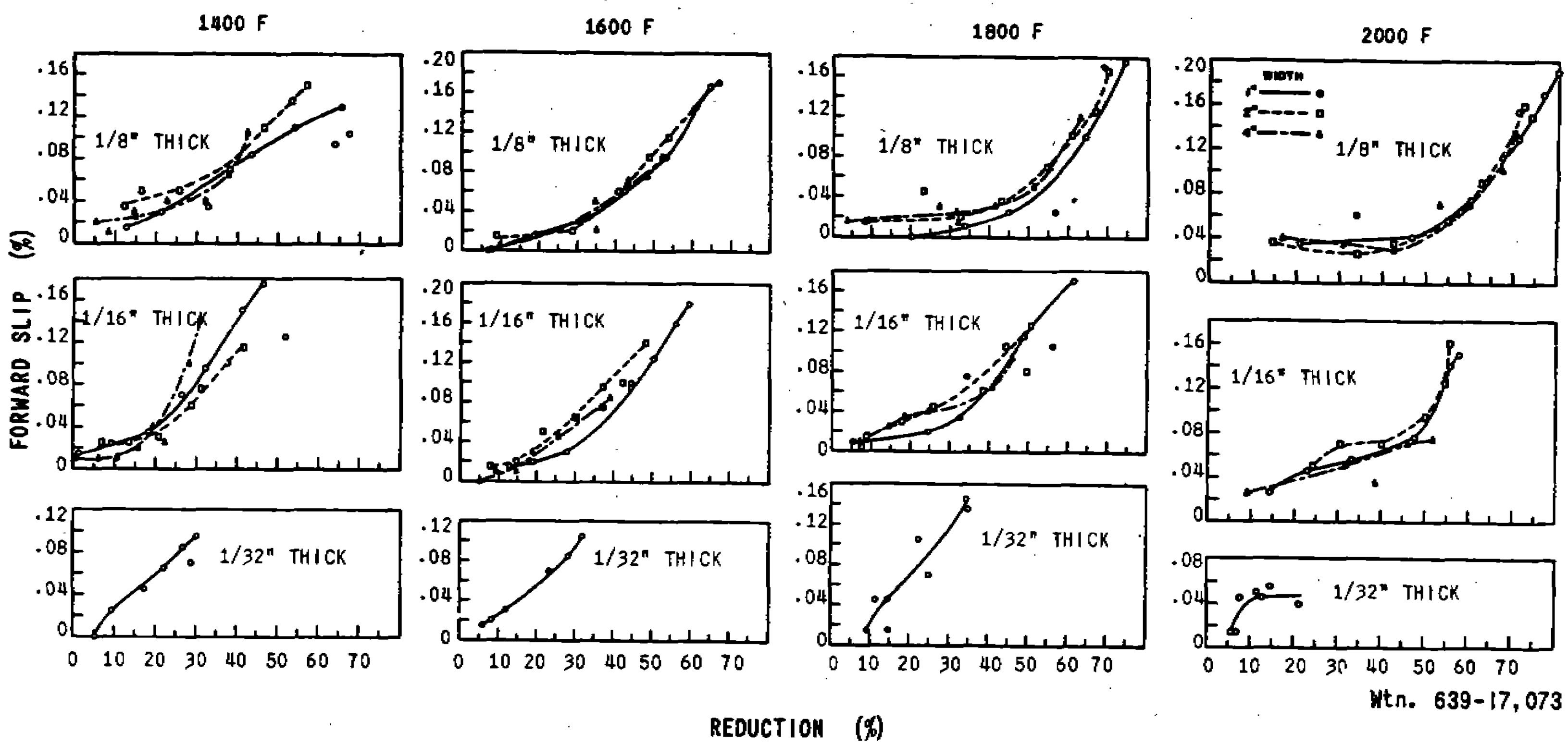


EFFECT OF ROLLING TEMPERATURE AND SIZE ON
WORK PER UNIT VOLUME FOR A 15% REDUCTION



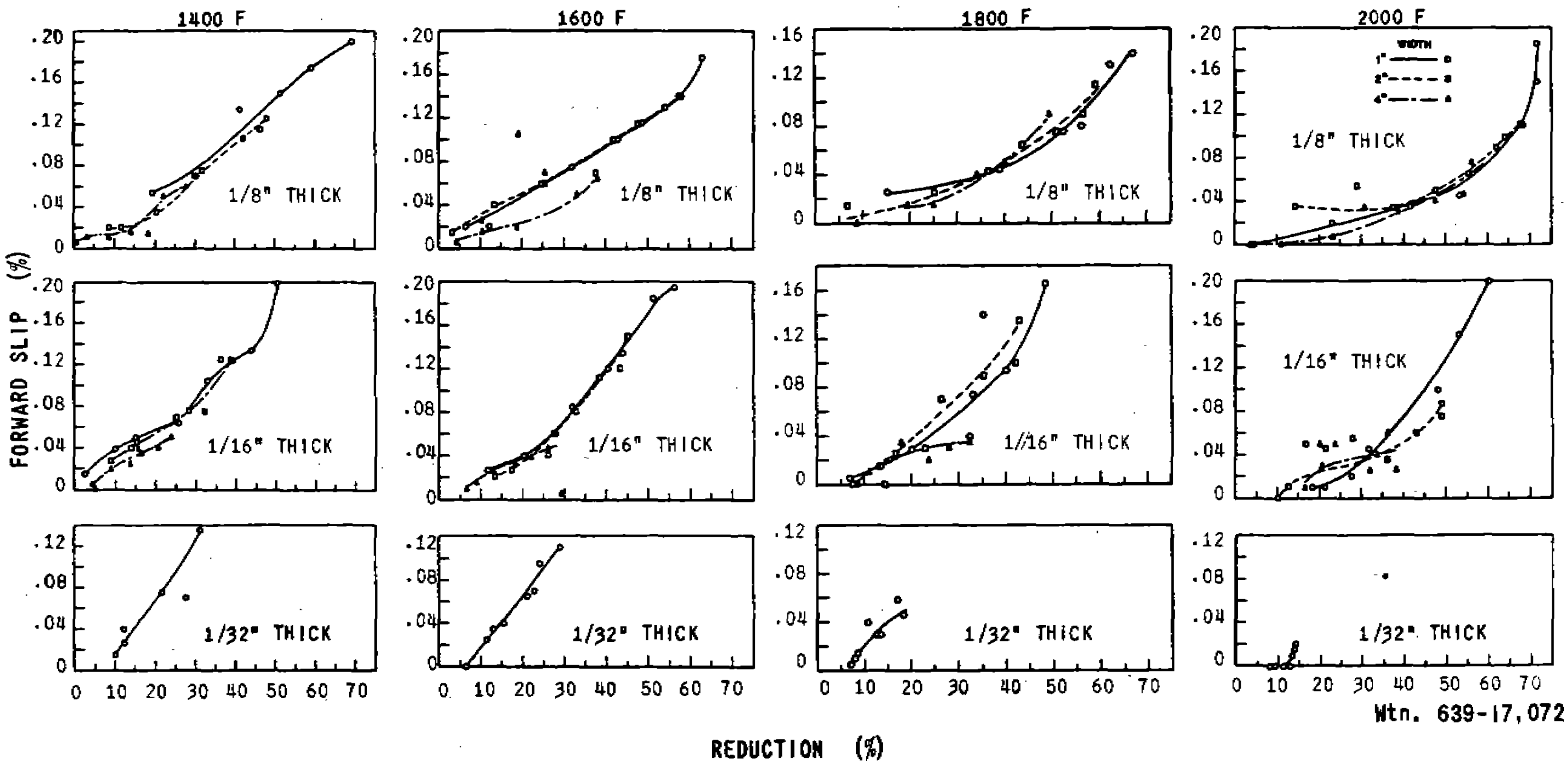
EFFECT OF ROLLING TEMPERATURE
AND SPECIMEN THICKNESS ON REDUCTION

FIGURE 29



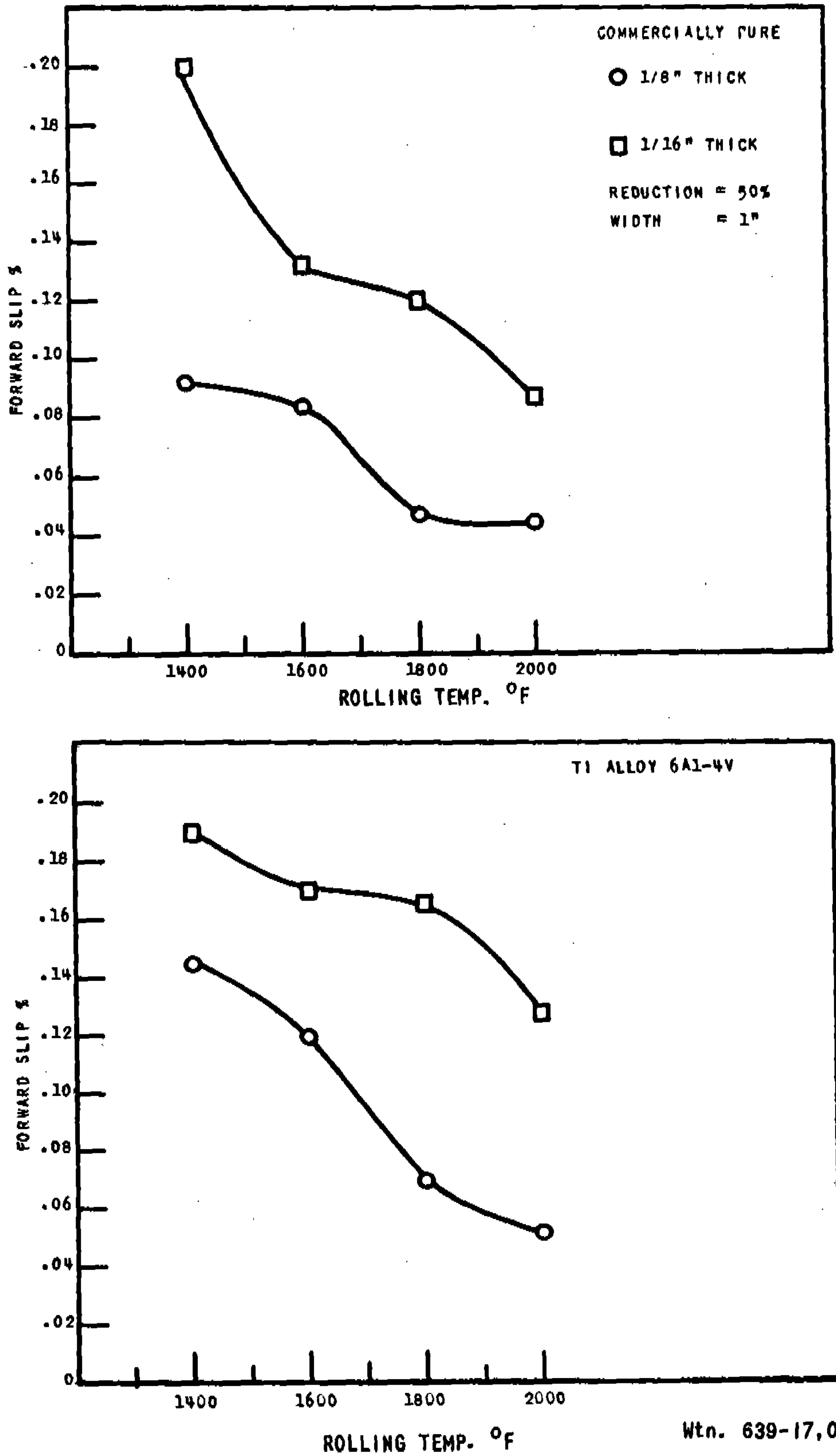
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON FORWARD SLIP FOR COMMERCIALLY PURE TITANIUM

FIGURE 30



EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON FORWARD SLIP FOR Ti 6Al-4V ALLOY

FIGURE 31



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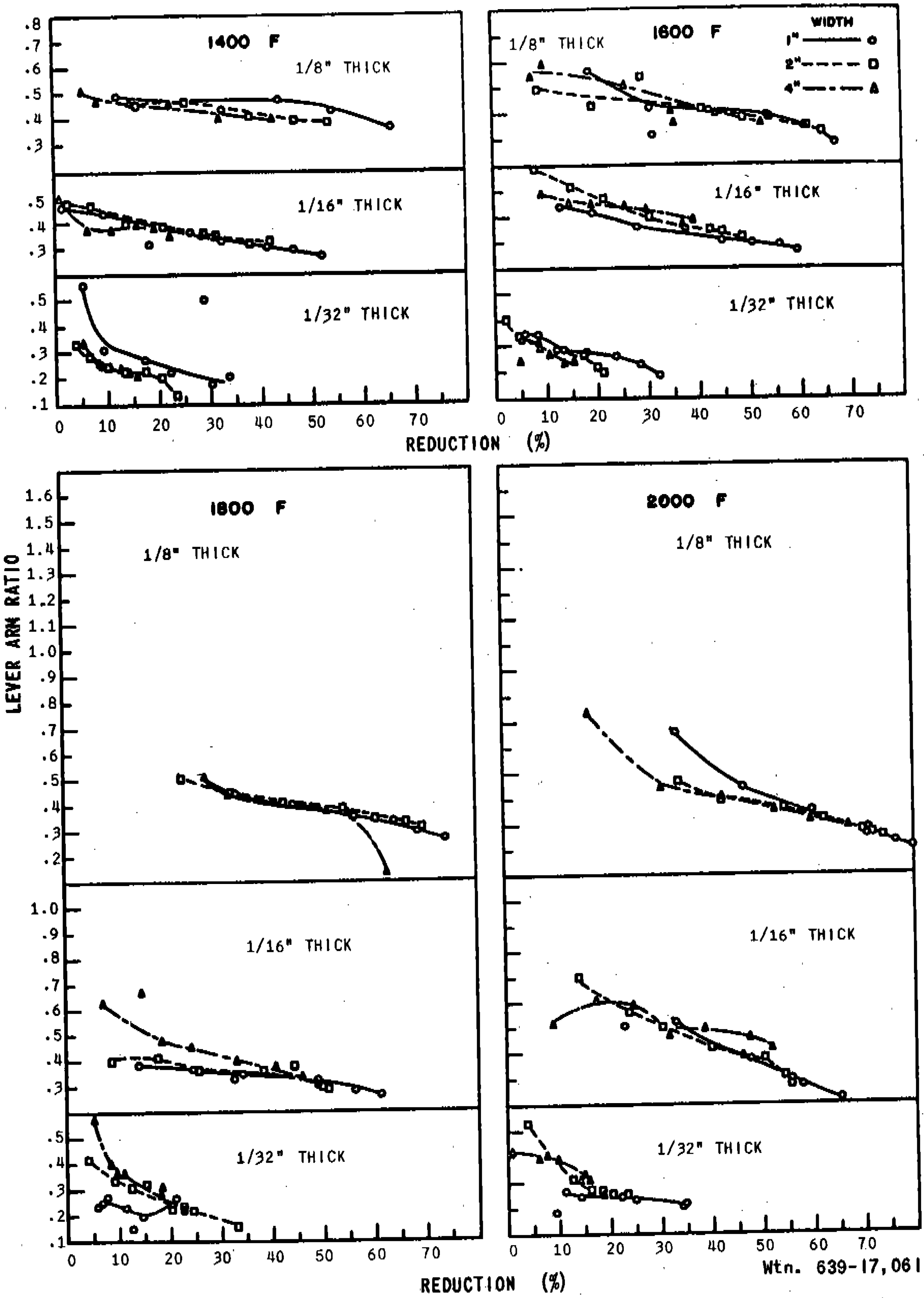
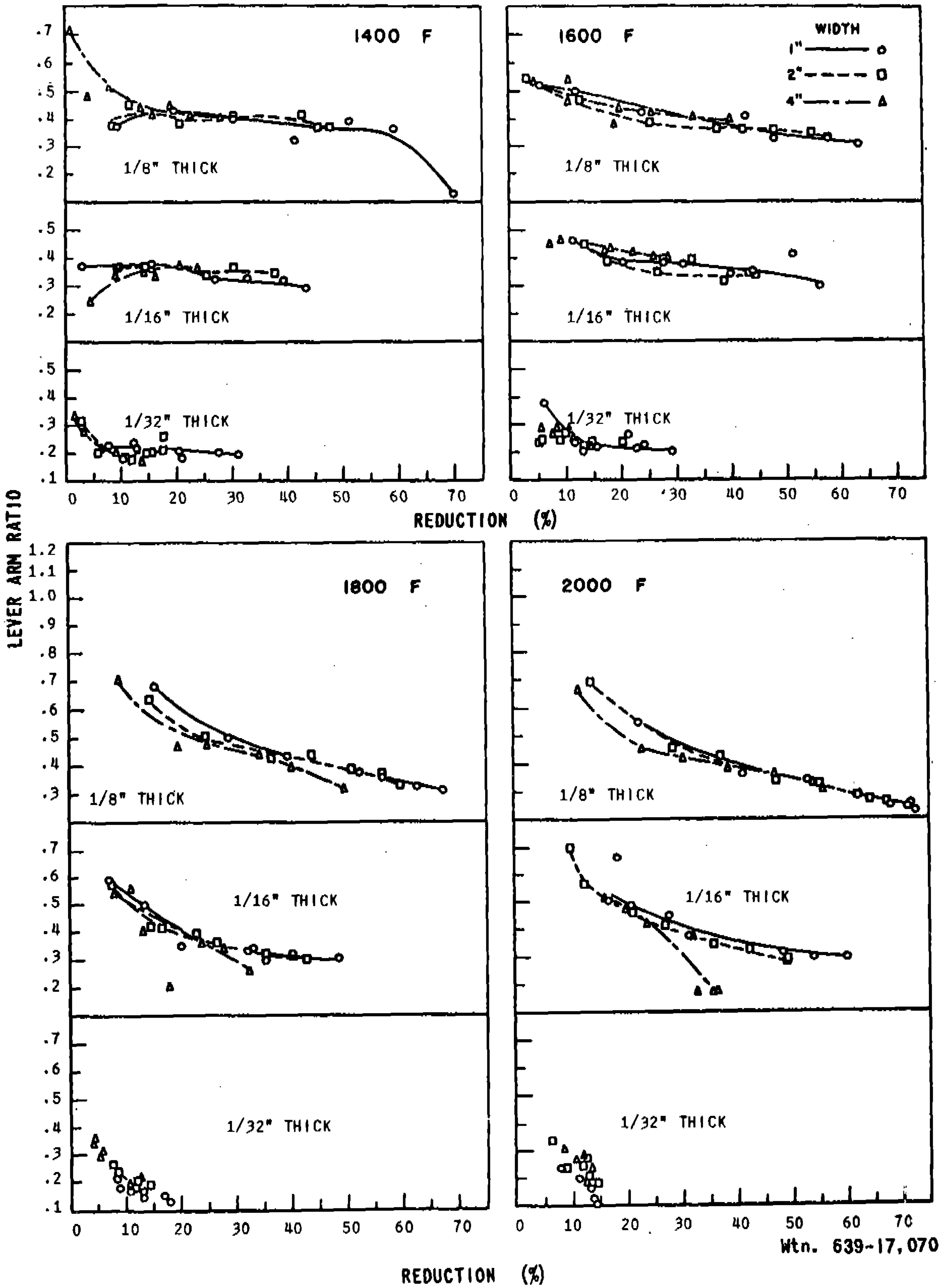
EFFECT OF ROLLING TEMPERATURE AND
SPECIMEN THICKNESS ON FORWARD SLIP

FIGURE 32



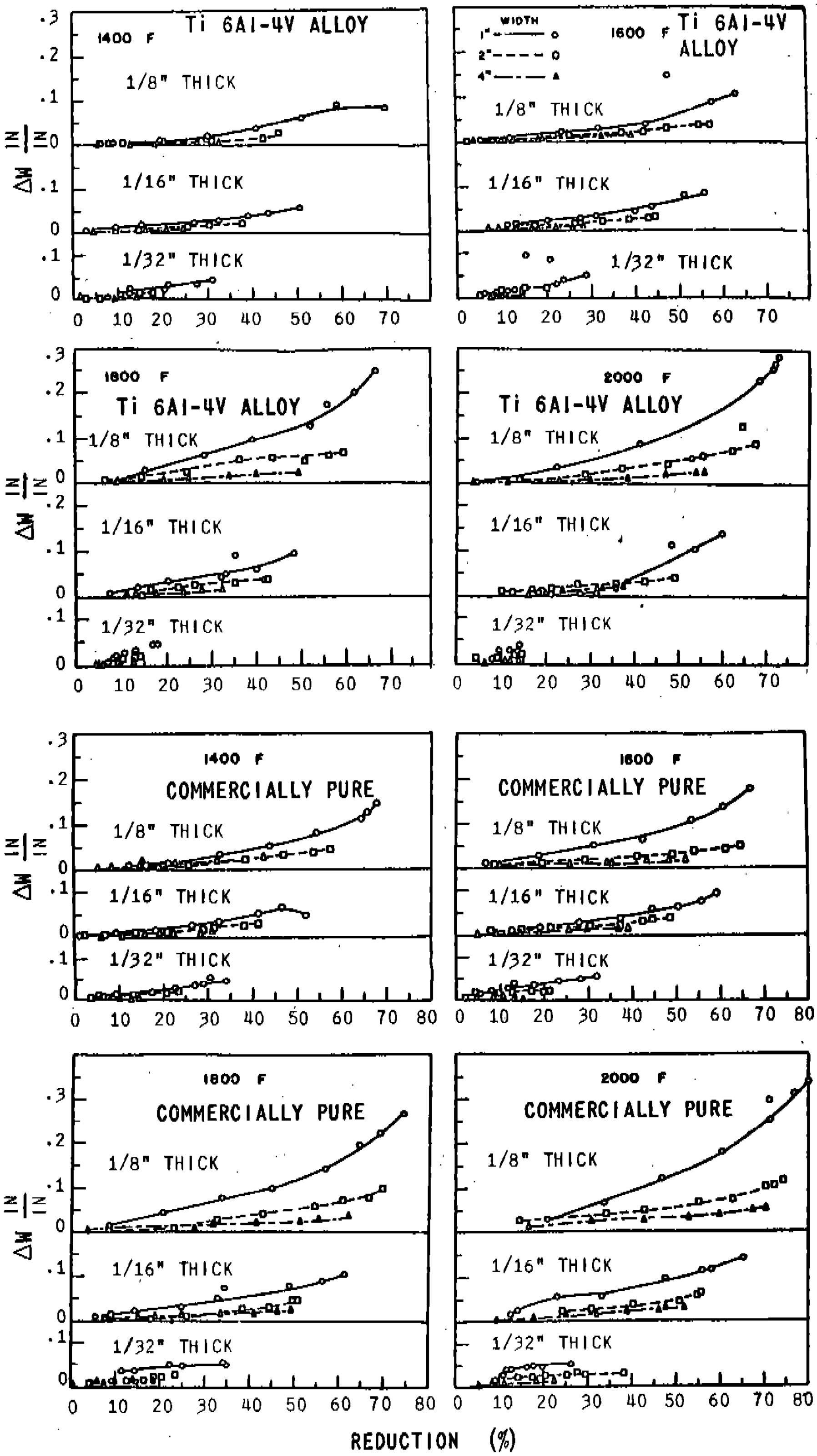
EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON LEVER ARM RATIO FOR COMMERCIALLY PURE TITANIUM

FIGURE 33



EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON LEVER ARM RATIO FOR Ti-6Al-4V TITANIUM

FIGURE 34



EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND SPECIMEN SIZE ON SPREAD

FIGURE 35

APPENDIX A

CALCULATIONS

1. Specific Pressure

$$P_s = \frac{P}{Lb_m}$$

Correct for roll deformation as follows:

a. Determine P_s

b. Determine % change in L from Figure A-1, Appendix A for P_s and $h_o - h_f$.

c. Calculate $P_s' = \dfrac{P_s}{1 + \dfrac{L' - L}{L}}$

d. Determine % change in L for P_s' (Figure 1)

e. Calculate new $L' = \left(1 + \dfrac{L' - L}{L}\right) L$

f. Calculate $P = P_s' \, b_m L'$

g. Determine new P_s' and L' by trial-and-error until P equals the measured roll separating force. P_s' is then specific pressure corrected for roll deformation.

2. Forward Slip

$$F_s = \frac{S_f - S_o}{S_o}$$

3. Lever Arm Ratio $= \dfrac{L_f}{L'}$

where $L_f = \dfrac{T_{ave}}{P}$

4. Percent Reduction $= \dfrac{h_o - h_f}{h_o} \times 100$

5. Horsepower

$$\text{Mill } H_p = \frac{T_t \, v_m}{33000 \, R} = \frac{T_t \, (30)}{33000 \, (2.623)} = .000347 \, T_t$$

6. Work per Unit Volume of Metal Rolled

Work calculations were based on conditions at the no-slip point or the center of a no-slip zone during rolling and were made as follows:

$$\text{Work per unit volume} = \frac{33000 \, H_p}{v_m b_m h_m}$$

It was assumed that the specimen width at the no-slip point (b_m) was the average of the initial and final widths. As the change in width was small, the error was negligible.

The velocity of the specimen at the no-slip point was the same as that of the rolls, $v_m = 30$ fpm.

Calculation of specimen thickness at the no-slip point was based on the lever arm ratio and the initial and final thicknesses according to the following ratio:

$$\frac{L_f}{L'} = \frac{h_x}{\Delta h}$$

Specimen thickness at the no-slip point, $h_m = h_x + h_f$; therefore

$$h_m = \Delta h\left(\frac{L_f}{L'}\right) + h_f$$

Horsepower was calculated from the experimental torque data.

DEFINITION OF SYMBOLS

L	Contact length for rigid roll, in. = $\sqrt{R\Delta h}$
L'	Contact length corrected for roll deformation, in.
L_f	Lever arm, in.
R	Roll radius, 2.623 in.
h_o	Entering thickness, in.
h_f	Exit thickness, in.
Δh	Reduction in thickness, in.
h_m	Thickness at no-slip point, in.
h_x	Difference between specimen thickness at the no-slip point and the exit
b_m	Average width, in.
P_s	Specific roll pressure, psi
P_s'	Specific roll pressure corrected for roll deformation, psi
P	Roll separating force, lb
S_o	Distance between punch marks on roll, in.
S_f	Distance between marks on surface of rolled specimens, in.
T_{ave}	Average torque, in-lb
T_t	Total torque, in-lb
v_m	Linear velocity of specimen at the no-slip point = roll surface speed, = 30 fpm

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