Cleared: January 12th, 1972
Clearing Authority: Air Force Materials Laboratory

DYNAMIC BEHAVIOR OF METALS UNDER TENSILE IMPACT

PART I. ELEVATED TEMPERATURE TESTS

ALBERT B. SCHULTZ

FOREWORD

This report was prepared by the Department of Materials Engineering, University of Illinois, Chicago, Illinois, under USAF Contract No. F33615-67-C1283. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735106, "Behavior of Metals". The work was administered by the Metals and Ceramics Division, Air Force Materials Laboratory, Directorate of Laboratories, Air Force Systems Command, with Dr. T. Nicholas, MAMD, project engineer.

This report covers work conducted from 1 March 1967 to 15 January 1969. The manuscript of this report was released by the author 30 January 1969 for publication.

This technical report has been reviewed and is approved.

W. J. Trapp

W. J. TRAPP
Chief, Strength and Dynamics Branch
Metals and Ceramics Division
Air Force Materials Laboratory

ABSTRACT

The mechanical behavior of metals subjected to uniaxial tensile impact at elevated temperatures is reported. Tests were conducted on annealed 1100 aluminum at 200°, 350°, 550°, and 800°F; annealed 2024 aluminum at 200°, 450°, and 600°; and annealed C1010 steel at 430°, 700°, 1050°, and 1400°F. The materials exhibit a wide range of dynamic behavior, including some in which the stress required to produce a given level of strain is significantly lowered by dynamic loading. The ratios of the dynamic ultimate stresses to the static are found to range from 0.71 to 6.0.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS AND TABLES

SECTION I

INTRODUCTION

The mechanical behavior of metals subjected to impact loading has been examined frequently over the past thirty years. Nevertheless, only limited amounts of data have been collected, and the conclusions reached concerning such behavior have often been the subject of controversy. Meaningful investigations of impact behavior are difficult to design and the results are difficult to interpret. Under impact conditions, the external load on the test specimen is often not a measure of the stress within the specimen because the kinetic energy that must be imparted to the specimen may be comparable to or much larger than the energy required for deformation. Moreover, stress-wave propagation effects may prevent the achievement of a homogeneous state of deformation within the specimen. When the complexity of the mechanics of such tests were not considered adequately the validity of conclusions reached in investigations of impact behavior were brought into question [1]. To account for the complexity of impact testing requires test conditions for which analysis of the observations can be made without unreasonable assumptions concerning test mechanics.

In two earlier papers, a technique for the determination of material properties under impact loading was described which lends itself to analysis without unwarranted assumptions. Observation of a succession of constant velocity transverse impacts, each on the center of a separate long thin wire specimen of the material to be studied, is used to infer material behavior. The technique permits study of large strain behavior in uniaxial tension without neglecting wave propagation phenomena. The first paper [2] described the technique and outlined the analysis accompanying data interpretation. The second paper [3] extended the analysis, and described the application of the technique to a study of the room temperature behavior of 1100 aluminum. Twenty-one additional series of tests have been completed using this technique and the results obtained concerning the impact behavior of metals will be described in two parts. Part I will describe the results obtained in eleven series of tests conducted at elevated temperature. Part II [4] will describe the results obtained in ten series of tests conducted at room temperature on materials after different amounts of cold work. In both Part I and Part II, it was found that some materials in some states exhibit a dynamic stress-strain curve which falls below the same curve determined in slow-speed tests. Although this finding is not unique to the present investigation, it is unusual. As a consequence, in both parts, the results are presented in more detail than might otherwise be appropriate.

The present paper presents results on the impact behavior of annealed 1100 aluminum at 200°, 350°, 550°, and 800°F; annealed 2024 aluminum at 200°, 450°, and 600°F; and annealed C1010 steel at 430°, 700°, 1050°, and 1400°F.

Reviewing the analysis accompanying data interpretation, which was presented in the earlier papers cited, three main assumptions concerning test mechanics were made. It was assumed that the wire had negligible bending stiffness, that the state of stress was one-dimensional, and that material behavior could be described by a single stress-strain relation applicable over the range of strain rates encountered in the tests. Let engineering stress and strain be denoted by σ, ε; mass density by ρ; impact velocity by V; maximum longitudinal particle velocity by u; angle of deformation behind the transverse wave front by ψ; and longitudinal and transverse wave speeds by c and $\bar{c}$. The analysis showed that the relations among these variables depend on the ordering of the wave speeds. For example, for the most commonly occurring ordering, all $c > \bar{c}$, the relations are

$$\sigma = \sigma(\varepsilon) \tag{1}$$

$$u = -\int_{\varepsilon_o}^{\varepsilon} c(\varepsilon')d\varepsilon' \tag{2}$$

$$V^2 = -2(1+\varepsilon)\bar{c}u - u^2 \tag{3}$$

$$\tan\psi = -\frac{V}{u + (1+\varepsilon)\bar{c}} \tag{4}$$

$$c(\varepsilon)^2 = \frac{1}{\rho}\frac{d\sigma}{d\varepsilon} \tag{5}$$

$$\bar{c}(\varepsilon)^2 = \frac{1}{\rho}\frac{\sigma}{(1+\varepsilon)} \tag{6}$$

ε_o is the strain in the wire before impact occurs. These six equations involve seven variables, so that if one additional relation is supplied from experimental observation, the relation of all other variables may be determined. Similar sets of equations govern for other orderings of wave speeds, as described in [3]. In the experiments the relation between V and ψ and that between V and ε can usually be determined, providing two ways in which to determine $\sigma(\varepsilon)$.

The critical transverse impact velocity is that which produces a maximum strain level corresponding to a horizontal tangent of the engineering stress-strain curve. Strain levels above this cannot be propagated into the wire, and failure occurs at the point of impact for impact velocities above critical. Local necking occuring at the impact point prevents this failure from being instantaneous, so that the achievement of the critical velocity is indicated by a very rapid fall-off of the maximum strain level with increasing impact velocity. The critical transverse velocity is a parameter of material behavior in tension which is directly observable. The corresponding maximum longitudinal particle velocity would be the critical velocity for longitudinal tensile impact, and may be inferred from experimental observations in the same manner as is stress-strain behavior.

The following section of this paper will describe modifications to the experimental procedures from the earlier work. Subsequent sections will present the experimental observations and the behavior which they infer for each of the three materials. The final section will summarize the behaviors found.

SECTION II

EXPERIMENTAL PROCEDURES

The experimental procedures were described in the two papers cited. Briefly, the transverse impact of a projectile traveling at constant velocity with the central section of a long thin wire is observed by multiple-flash stroboscopy over a period of 1.5 msec after impact. From the photographic records of a series of such tests, each at a different velocity on a separate specimen of the material under test, the relationship between the angle of deformation behind the transverse wavefront and the impact velocity, and that between the maximum strain in the wire and the impact velocity is determined. Strain is measured optically, using bands of a marking agent over the gage section. Minor alterations in the present work are that the wire length has been increased to 32 feet, and the wire diameter varies from series to series in the work described in Part II.

The wires were heated by passing an electric current through them in both static and dynamic elevated temperature tests. Temperatures were determined from resistivity measurements and checked with temperature-sensitive paint. The variation in resistivity over the temperature range encountered was determined by placing coils of wire in an argon atmosphere in an oven, raising the oven temperature slowly enough to ensure thermal equilibrium, and observing temperature and coil resistance. Compensation was made for oven temperature gradients and lead resistance. The resistivities obtained are shown in Figure 1.

Static stress-strain behavior was determined as follows. A twelve foot long, annealed wire was suspended horizontally between a load cell and a winch. The wire was placed within a U-shaped channel so that air currents over the wire would be uniformly distributed. The channel opening was to one side. Current was passed through the wire, and after thermal equilibrium was reached, the winch drum was rotated slowly, taking up the wire. Test time was of the order of minutes. Stress was determined from load cell readings, and strain by observing the distance between gage marks in a 100 in. gage length. Catenary effects were negligible. The current in the static tests was initially adjusted to duplicate that used in the dynamic tests. Voltage, current, and wattage were observed during the test, and varied very little. When necessary, the voltage was manually readjusted to maintain constant wattage. As the largest strain observed in these tests was 0.20, the method gave acceptable reproducibility. Temperature variation was checked using bands of temperature sensitive paint along the wire, and insuring that the transition temperature of the paint was reached simultaneously everywhere. When steel wires were heated to luminescence, visual observation showed the glow to be uniform along the test section. Temperature measurements made with the paint agreed with those calculated from resistivity measurements. In the Figures in which static stress-strain properties are presented, only that portion of the curve in which the stress increases is shown. Portions of the engineering stress-strain relation in which stress decreases with increasing strain before fracture would not be relevant when wave propagation occurs, as they imply imaginary values of wave speeds.

Dynamic tests at elevated temperature were made using the same heating scheme, but with the longer test section. In the central section of the wire, a flat surface under the wire substituted for the channel, permitting observation of the impact from above. Uniformity of temperature distribution was checked in the same manner as for the static tests. Prior to impact, the wires were annealed and then brought to thermal equilibrium at the test temperature. The photographic image of the undeformed wire was made seconds before impact in order for any creep or thermal expansion strain in the wire prior to impact to be excluded from strain measurements. The opening in the channel permitted the wire to deform freely upon impact. Heating current was supplied until after the impact observations were made.

It is assumed that the error in impact velocity determination is negligibly small, that angular measurements are accurate to within 0.5°, and that strain measurements are usually accurate to within 0.01. In certain series of tests, depending on temperature, marking agent properties, and photographic contrast between banded and unbanded sections, strain can be measured only to within 0.02. In the two highest temperature test series on steel, strain could not be measured with acceptable accuracy at all. These situations and those in which pronounced data scatter occurs will be noted in discussing individual series results.

SECTION III

RESULTS: 1100 ALUMINUM

The material used in these tests is from the same lot as that used earlier [3]. Wire diameter was 0.02 in., and prior to any testing, wires were heated to 800°F and held for 3.5 minutes to anneal. Room temperature stress-strain behaviors for the material in the as-received condition and after annealing are given in [4].

200°F (Figures 2 and 3) - Figure 2 shows velocity-strain and velocity-angle observation for this series. Predictions of these relationships from static stress-strain behavior are also shown. The smoothed curve of velocity-strain observations shown in the figure was used to infer dynamic behavior, implying the modified velocity-angle relation also shown. Despite some scatter in observations, the two independent observations are self consistent. Figure 3 shows static and dynamic stress-strain behavior. Static properties showed little variability from specimen to specimen.

450°F (Figures 4 and 5) - Figure 4 shows observations and static predictions, and Figure 5 static and dynamic stress-strain behavior. Static tests were reproducible. Observations depart markedly from static predictions, but the two sets are only partially self-consistent. The velocity-strain data infers a dynamic stress-strain curve higher (12,000 psi ultimate stress) than that of the velocity-angle data. Velocity-angle data are considered the more reliable for this series.

550°F (Figures 6 and 7) - Static tests were reproducible. Observations depart substantially from static predictions. The observed velocity-angle relation is used to infer dynamic behavior, leading to results consistent with velocity-strain data.

800°F (Figures 8 and 9) - Static properties show some variability, the range indicated in Figure 9. The observations exhibit a large amount of scatter. To illustrate how potential ambiguity of the results can sometimes be resolved the procedure by which dynamic behavior was inferred will be described. Three possible smoothed representations of the velocity-strain relation, labelled A, B, and C, are assumed. Dynamic stress behavior is inferred from all of them, as well as the corresponding velocity-angle relationship. (In cases A and B, the computations must take account of the existence of longitudinal shock waves in the response. The details of this are described in Part II [4].) The three resulting velocity-angle relations are shown in Figure 8, and the stress-strain behavior in Figure 9. Curve C produces velocity-angle predicitions most consistent with observations. Independently, a smoothed representation of the velocity-angle relation was used to infer dynamic stress-strain behavior as well as velocity-strain behavior, and yielded consistent results. Finally, the dynamic stress-strain relation is used to predict again the velocity-angle and velocity-strain relationships, which serves to check computations.

Table I summarizes the behavior of 1100 aluminum in these tests, illustrating how the observed dynamic behavior differs from static. At the three lower temperatures, ductility is reduced by dynamic loading, but it is substantially increased at the highest temperature. The ultimate stress in every case is raised by dynamic loading, up to a factor of 2.7.

Investigations of the elevated temperature dynamic behavior of 1100 aluminum using several different experimental techniques are described, for example, by Nadai and Manjoine [5], Alder and Phillips [6], Bailey and Singer [7], Chiddester and Malvern [8], Lindholm, et al [9], and Suzuki, et al [10]. Nadai and Manjoine found the ultimate stress raised by factors of 2.1 and 4.8 at temperatures of 392°F (200°C) and 752°F (400°C) over a strain rate range 10^6 per sec. Alder and Phillips obtained factors up to 1.45 over a range of approximately 30 per sec. at similar temperatures. Bailey and Singer obtained 2.4 over a range of 10^3 per sec. at 752°F for high purity aluminum in agreement with Suzuki, et al. Lindholm, et al, whose results agreed with the more limited data of Chiddester and Malvern found the ultimate stress raised by a factor of 3.2 over a strain rate range of 10^6 per sec. at 750°F. The present results are in agreement with these other findings. It should be noted that only references [5] and [9] report behavior in tension.

SECTION IV

2024 ALUMINUM

The material used was commercially drawn to 0.02 in. diameter from heavier stock wire. Prior to any testing the wires were heated to 600°F and held for 3.5 minutes to anneal. Room temperature stress-strain behaviors in the as-received and annealed conditions are given in [4].

200°F (Figures 10 and 11) - The velocity-strain relation shown was used to infer dynamic behavior, with similar results obtainable from the velocity-angle relation. The variability in static properties cannot account for the departure of the observations from those predicted from static behavior.

450°F (Figures 12 and 13) - The velocity-strain relation was used to infer behavior, and is consistent with the angle observations.

600°F (Figures 14 and 15) - The velocity-angle relation was used to infer behavior, and produced satisfactory agreement with strain observations. A closer fit to the velocity-strain observations indicates less rate sensitivity (ultimate stress 17,400 psi).

Table I summarizes the behavior of 2024 aluminum in these tests. This alloy, which in most circumstances is rate insensitive at room temperature, exhibits considerable rate sensitivity at elevated temperature. In every case, ductility is reduced by dynamic loading. The most striking feature of its behavior, however, is that at 200°F it exhibits a negative rate sensitivity, the tensile stress at ultimate strain in the dynamic tests being 0.71 times that in the static tests. At 600°F, the ultimate stress is raised by a factor of 3.5 over the static ultimate stress.

Bailey and Singer [7] report a raising of ultimate stress by a factor of 1.8 at 662°F over a strain rate range of 5 x 10^2 per sec. for a similar alloy. Both Lindholm, et al [9] and Green and Babcock [11] report comparable results for 6061 and 7075 aluminum, both of which are believed rate insensitive at room temperature. Suzuki, et al [10] report negative rate sensitivity in an aluminum -3.5 percent copper alloy at 392°F for large compressive strains. They show flow stress decreasing with strain rates in the range 0.2-3.5 per sec. and then increasing with rates up to 30 per sec. for strains larger than 0.35. This behavior may be associated with precipitation rates.

SECTION V

C1010 STEEL

The wires used were commercially drawn to 0.02 in diameter from heavier stock. Prior to any testing, the wires were heated to 1400°F and held for 15 sec. to anneal. Holding for longer times did not change the properties of the wire. Room temperature stress-strain behaviors in the as-received and annealed conditions are given in [4]. Tests were made to see that scale formation in any of the heating processes had negligible effect on static behavior or the weight per unit length.

430°F (Figures 16 and 17) - The behaviors inferred from velocity-strain and from velocity-angle observations are not completely consistent, although the differences are not large. Both inferences are shown in Figure 17. Static test data predict linear elastic behavior up to an impact velocity of 2100 in. per sec. The velocity-angle observations in this region indicate yielding occurs below this velocity. A dynamic yield stress of approximately 30,000 psi is indicated, compared to the 45,000 psi static yield stress. The unusual shapes of the static predictions in Figure 16 arise because shock waves would occur if static stress-strain behavior governed.

700°F (Figures 18 and 19) - The behaviors inferred from the two sets of observations are not consistent, and a dynamic stress-strain curve in reasonable agreement with both could not be found. Therefore, two possible inferences are shown, neither completely satisfactory. Both indicate the dynamic yield stress to be above the static, and both indicate dynamic stresses at larger strains fall below the static. The curve inferred from strain data is assumed the more reasonable, despite the scatter in the observations.

1050°F (Figures 20 and 21) - Static tests exhibit the variability shown. No marking agent was found, either for this or the next series, which had properties suitable for use in strain measurement. Behavior is therefore inferred entirely from V-ψ observations.

1400°F (Figures 22 and 23) - Strain measurements could not be made, but the velocity-angle observations clearly indicate pronounced rate sensitivity. There was a small increase in ψ with time in many of the experiments, the amounts shown in Figure 22. This cannot be explained if behavior is governed by a single dynamic stress strain curve. (In contrast, increases in ε with time are sometimes explainable on the basis of rate independent behavior. Such increases appear when wave propagation speeds are very low. See p. 345 of [3].) The increase in ψ with time seems to indicate that the material is sufficiently rate sensitive to begin to require a more complex behavioral model to describe test mechanics. The two interpretations of the observations shown in Figure 22 do not infer (under the assumption that the behavior is rate independent) much difference in the dynamic behavior.

A summary of the behavior of C1010 steel is given in Table I. This material's dynamic behavior varies in a complex way with temperature. At 430°F the dynamic yield stress is lower than the static, while at the other three temperatures it is raised. The dynamic ultimate stress, on the other hand, is lower than the static at 700°F, but higher at the other three temperatures. There is often a considerable difference between the shape of the static and the dynamic stress-strain curve. Dynamic ductility is from one quarter to three times that determined statically. The strain rate sensitivity at the highest temperature is pronounced, the dynamic ultimate stress being six times the static.

Nadai and Manjoine [5] reported the ultimate tensile stress of mild steel at 1472°F (800°C) to be raised by a factor of 5.5 over a strain rate range of 10^6 per sec. They found negative strain rate sensitivity over various strain rate ranges at 392°F, 752°F, and 932°F. The maximum lowering of the dynamic stress was by a factor of 0.6. Alder and Phillips [6] reported the compressive stress in a 0.17 percent carbon steel to be raised by a factor of 1.16 by only a five-fold increase in strain rate. Suzuki, et al [10], in their comprehensive report on compressive behavior of metals when deformed in a cam plastometer, found that raising strain rate two orders of magnitude caused a 30-50 percent increase in stress at 1472°F over a range of carbon content from .08-.15 percent. For a .15 percent carbon steel, they found negative rate sensitivity for large strains at 392°F, and ranges of both positive and negative rate sensitivity at 752°F.

SECTION VI

DISCUSSION

The tests described here are not constant strain rate tests. Because of the wave propagation in the specimens, strain rates vary with both distance along the wires and time. Average strain rates probably most often fall into the range 10^2-10^3 per second, but when shock waves propagate, for example, strain rates may be considerably above these figures. Under certain conditions, they may be much smaller. In the analysis of the data it is assumed that a single dynamic stress strain curve can describe material behavior over the range of strain rates encountered. The behavior determined under this assumption is in good agreement with the results of other investigations in which behavior was determined under more nearly constant strain rate conditions. Only in the highest temperature tests on steel, in which the dynamic ultimate stress appeared to be raised by a factor of 6 over the static, were there definite indications that a single dynamic stress-strain curve might not suffice to describe material behavior. It is possible this was also the case in steel at 700°F.

The test results indicate a wide range of behavior in metals subject to tensile impact loading at elevated temperatures. It has sometimes been stated that at high strain rates, metals either behave the same as at low strain rates or else the stress at a given strain is raised by dynamic loading. However, the present results, and those described in Part II, confirm that the stress at a given strain is sometimes substantially lowered by dynamic loading. By comparing the results of the present tensile tests with the results of other investigations of dynamic behavior in compression, it can be seen that the two behaviors appear to be similar. Metals which exhibit little or no rate sensitivity at room temperature may exhibit considerably rate sensitivity at elevated temperatures.

In these tests, the critical velocity for transverse tensile impact differs from the value predicted from static behavior by factors ranging from 0.67 to 3.9. For critical longitudinal velocity, the factors range from 0.41 to 5.5. Ultimate strains under dynamic loading differ from those found statically by factors ranging from 0.28 to 3.2. Ultimate stresses differ by factors ranging from 0.71 to 6.0. The energy that can be absorbed by a material can be determined from the area enclosed by its stress-strain curve. Again, large differences between static and dynamic behavior in this respect were found to exist, with the ability to absorb energy under dynamic loading sometimes considerably larger and sometimes considerably smaller than under static loading.

REFERENCES

[1] W. Goldsmith, Impact, Edward Arnold, London 1960, Chapter VII.

[2] A. B. Schultz, P. A. Tuschak, and A. A. Vicario, Jr., "Experimental Evaluation of Material Behavior in a Wire Under Transverse Impact," Journal of Applied Mechanics, Vol. 34, No. 2, Trans. ASME, Vol. 89, Series E, June 1967, pp. 392-396.

[3] A. B. Schultz, "Material Behavior in Wires of 1100 Aluminum Subjected to Transverse Impact," Journal of Applied Mechanics, Vol. 35, No. 2, Trans. ASME, Vol. 90, Series E, June 1968, pp. 342-348.

[4] A. B. Schultz, "Dynamic Behavior of Metals Under Tensile Impact. Part II: The Effect of Cold Work," manuscript in preparation.

[5] A. Nadai and M. J. Manjoine, "High-Speed Tension Tests at Elevated Temperatures - Part II and III," Journal of Applied Mechanics, Trans. ASME, Vol. 63, 1941, pp. A-77-A-91.

[6] J. F. Alder and V. A. Phillips, "The Effect of Strain Rate and Temperature on the Resistance of Aluminum, Copper, and Steel to Compression," Journal of the Institute of Metals, Vol. 83, 1954-1955, pp. 80-86.

[7] J. A. Bailey and A. R. E. Singer, "Effect of Strain Rate and Temperature on the Resistance to Deformation of Aluminum, Two Aluminum Alloys, and Lead," Journal of the Institute of Metals, Vol. 92, 1963-64, pp. 404-408.

[8] J. L. Chiddester and L. E. Malvern, "Compression-Impact Testing of Aluminum at Elevated Temperatures," Experimental Mechanics, Vol. 3, 1963, pp. 81-90.

[9] U. S. Lindholm, L. M. Yeakley, and R. L. Bessey, "An Investigation of the Behavior of Materials Under High Rates of Deformation," Southwest Research Institute Report, May 1967, 38 pp.

[10] H. Suzuki, S. Hashizume, Y. Yabuki, Y. Ichihara, S. Nakajima, and K. Kenmochi, "Studies on the Flow Stress of Metals and Alloys," Report of the Institute of Industrial Science, The University of Tokyo, Vol. 18, No. 3, March 1968, pp. 139-240.

[11] S. J. Green and S. G. Babcock, "Response of Materials to Suddenly Applied Stress Loads, Part I: High Strain-Rate Properties of Eleven Reentry-Vehicle Materials at Elevated Temperatures," GM Defense Research Laboratories TR 66-83, November 1966, 110 pp.

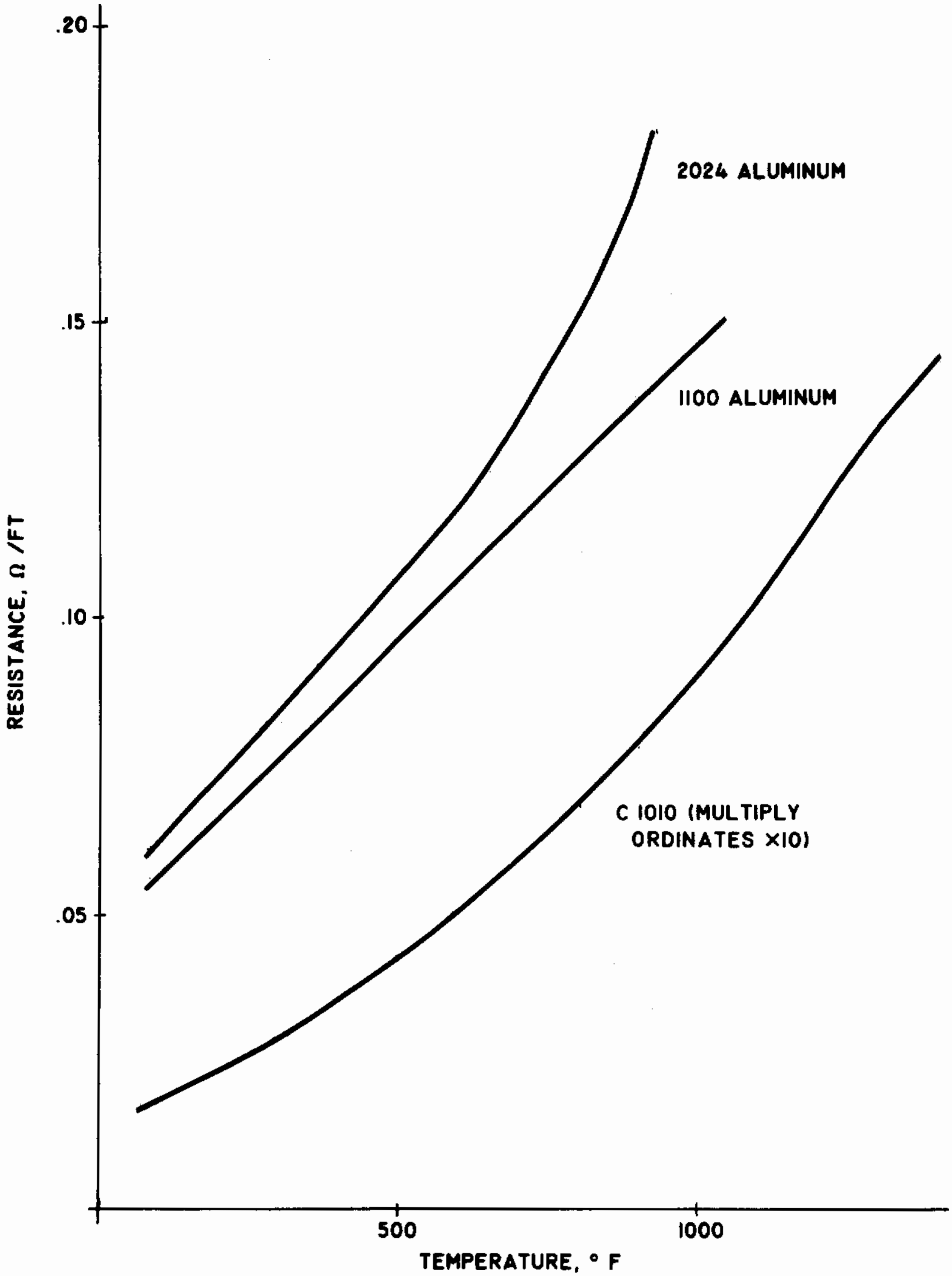

FIG. 1 RESISTANCE VERSUS TEMPERATURE FOR 0.02 INCH WIRES

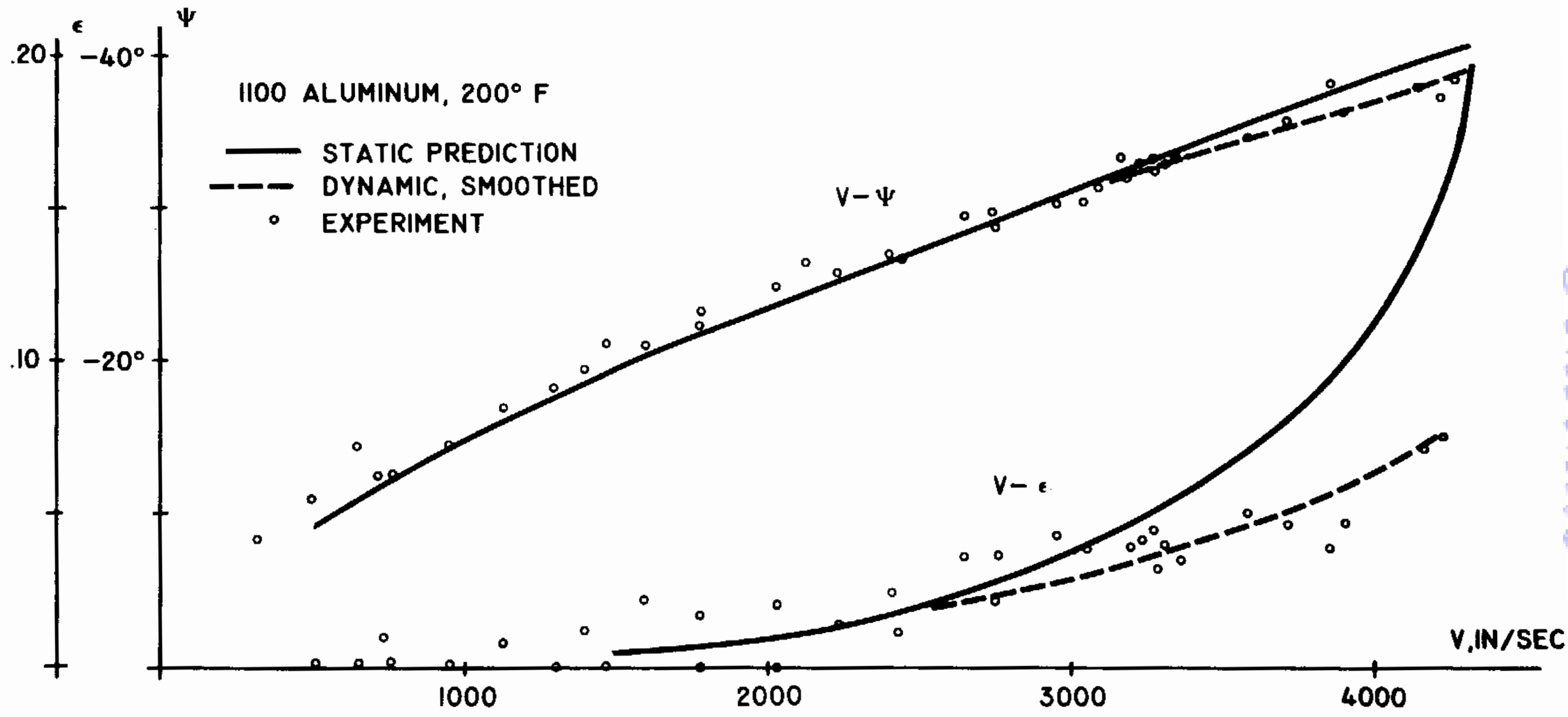

FIG. 2 EXPERIMENTAL OBSERVATIONS, 1100 ALUMINUM, 200°F

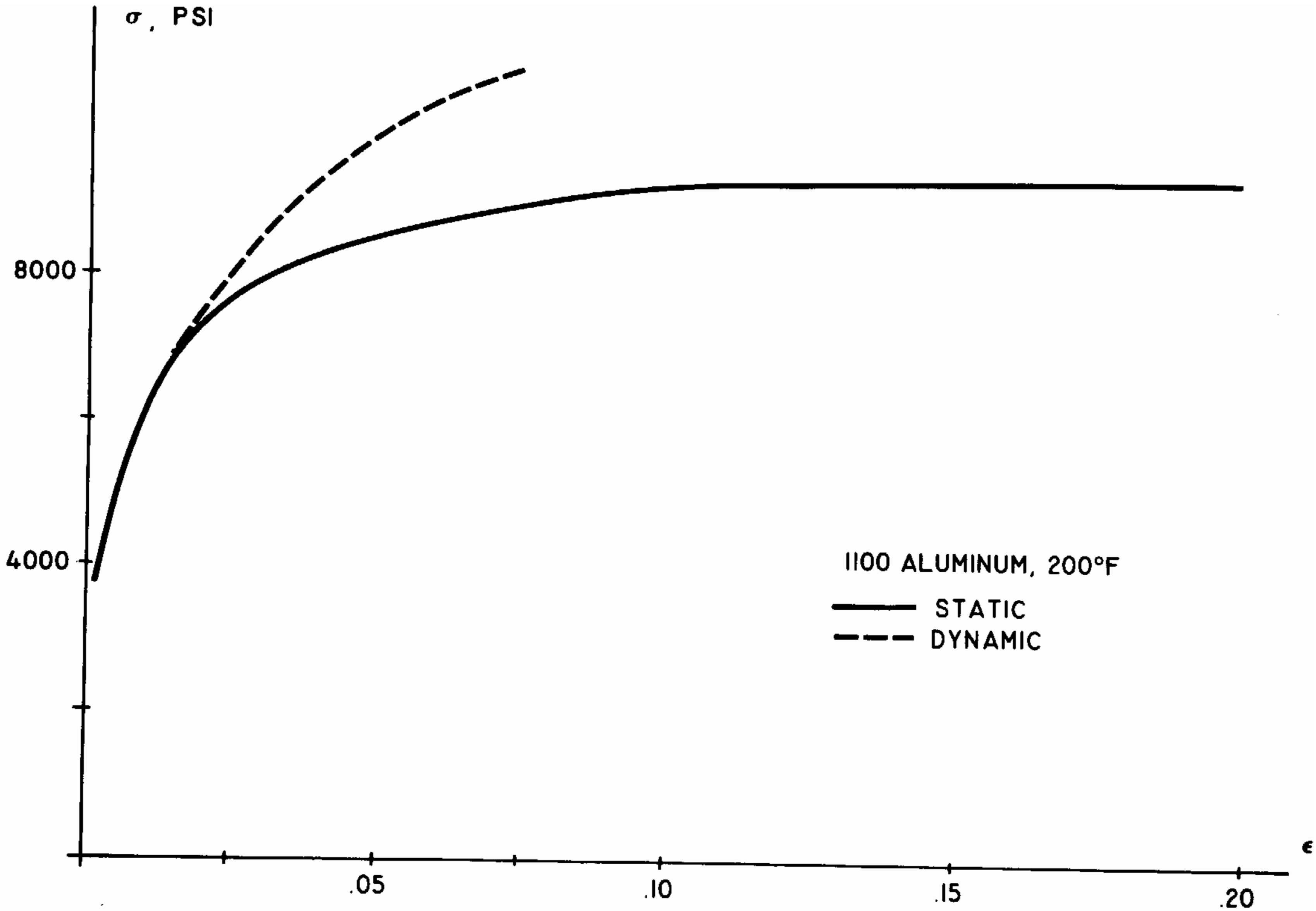

FIG. 3 STRESS-STRAIN DATA, 1100 ALUMINUM, 200°F

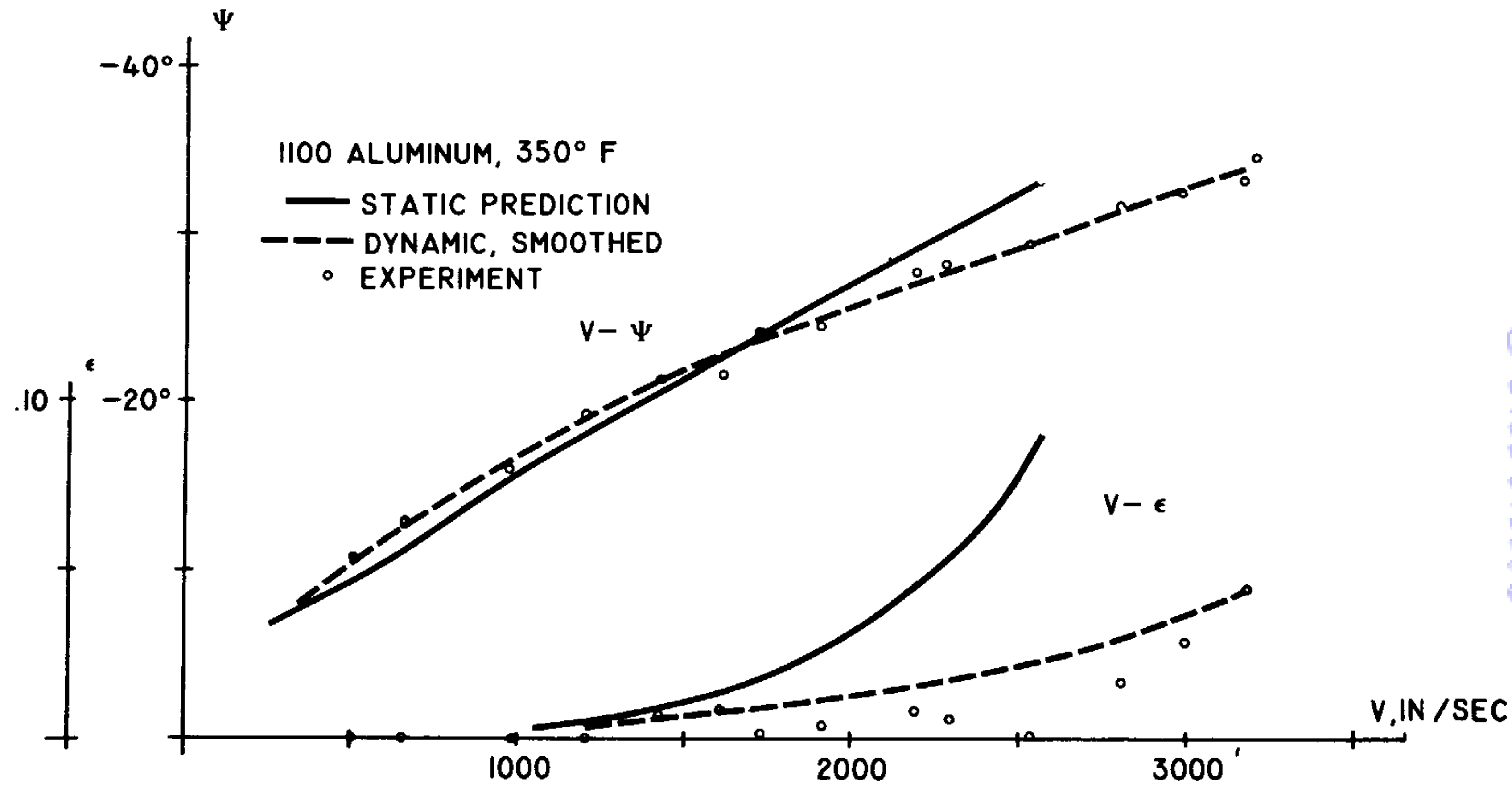

FIG. 4 EXPERIMENTAL OBSERVATIONS, 1100 ALUMINUM, 350°F

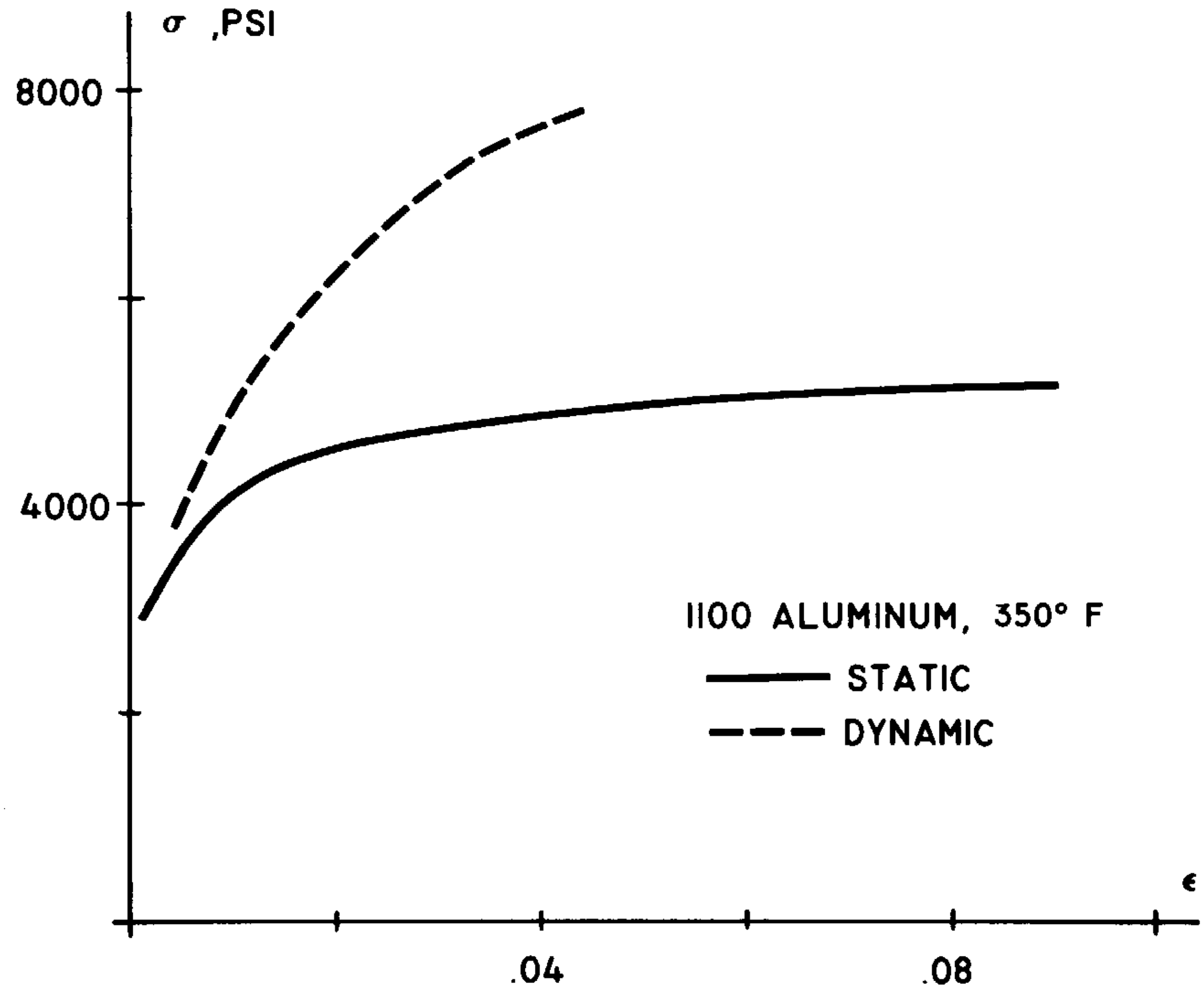

FIG. 5 STRESS-STRAIN DATA, 1100 ALUMINUM, 350°F

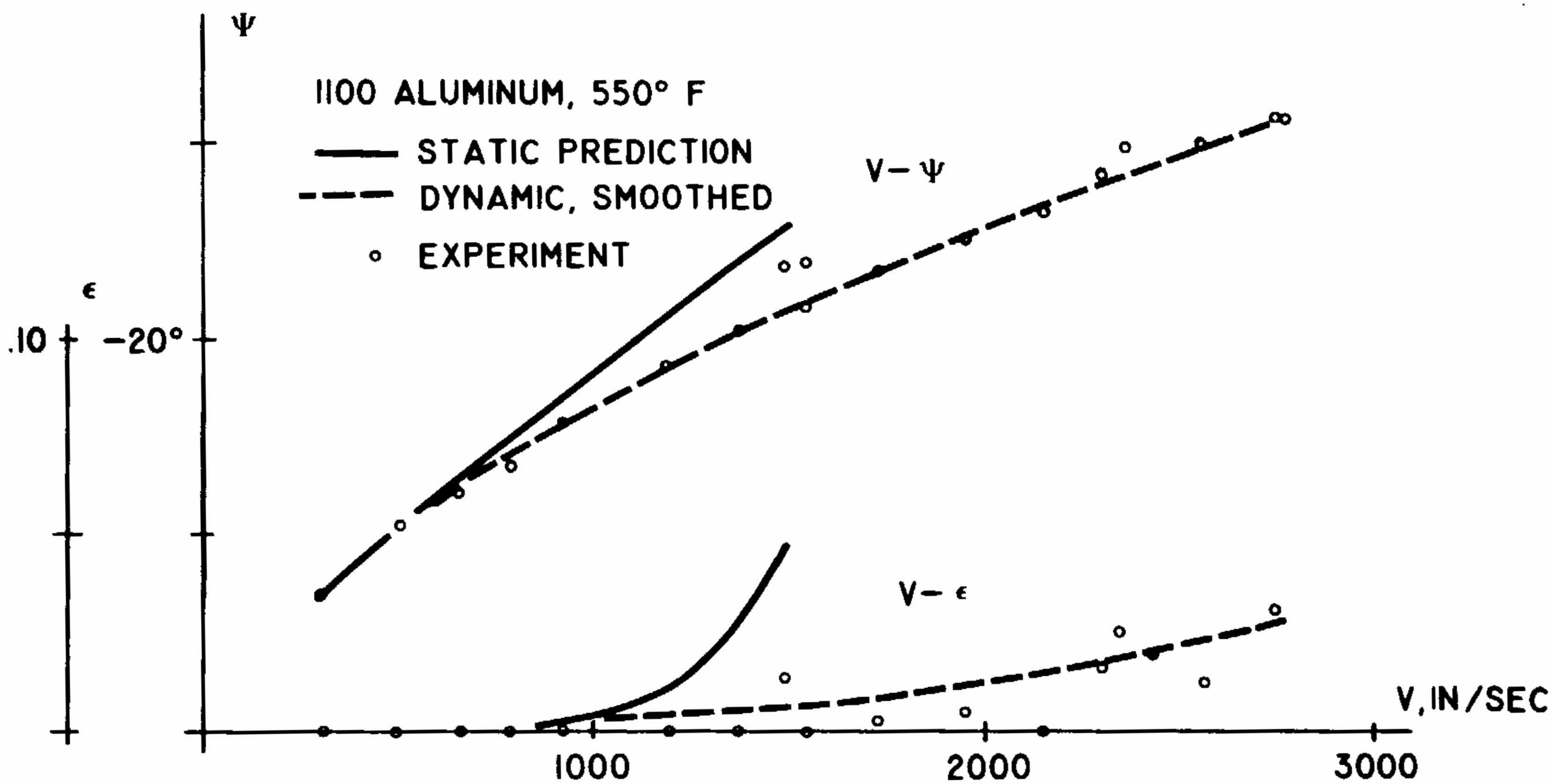

FIG. 6 EXPERIMENTAL OBSERVATIONS, 1100 ALUMINUM, 550°F

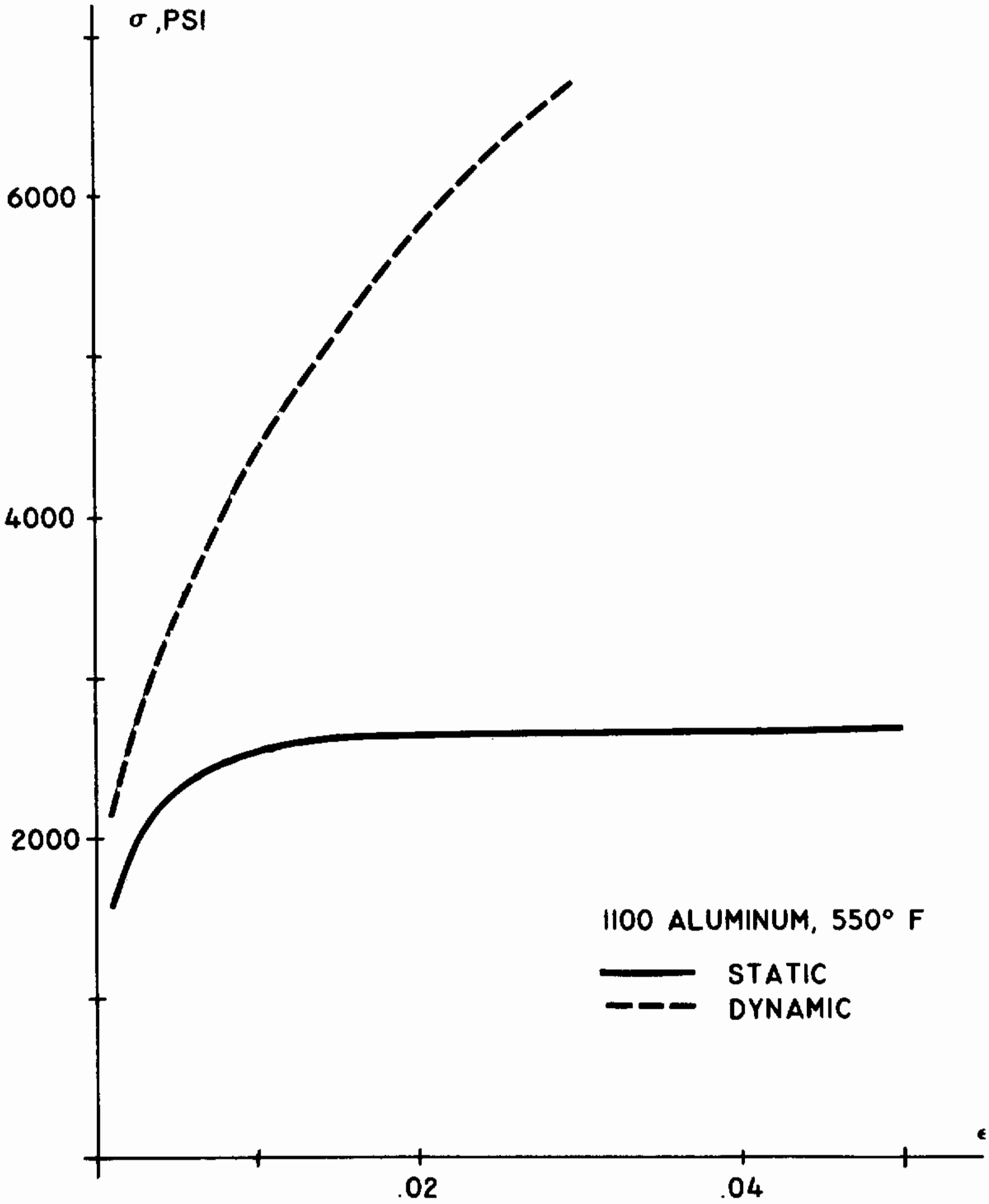

FIG. 7 STRESS-STRAIN DATA, 1100 ALUMINUM, 550°F

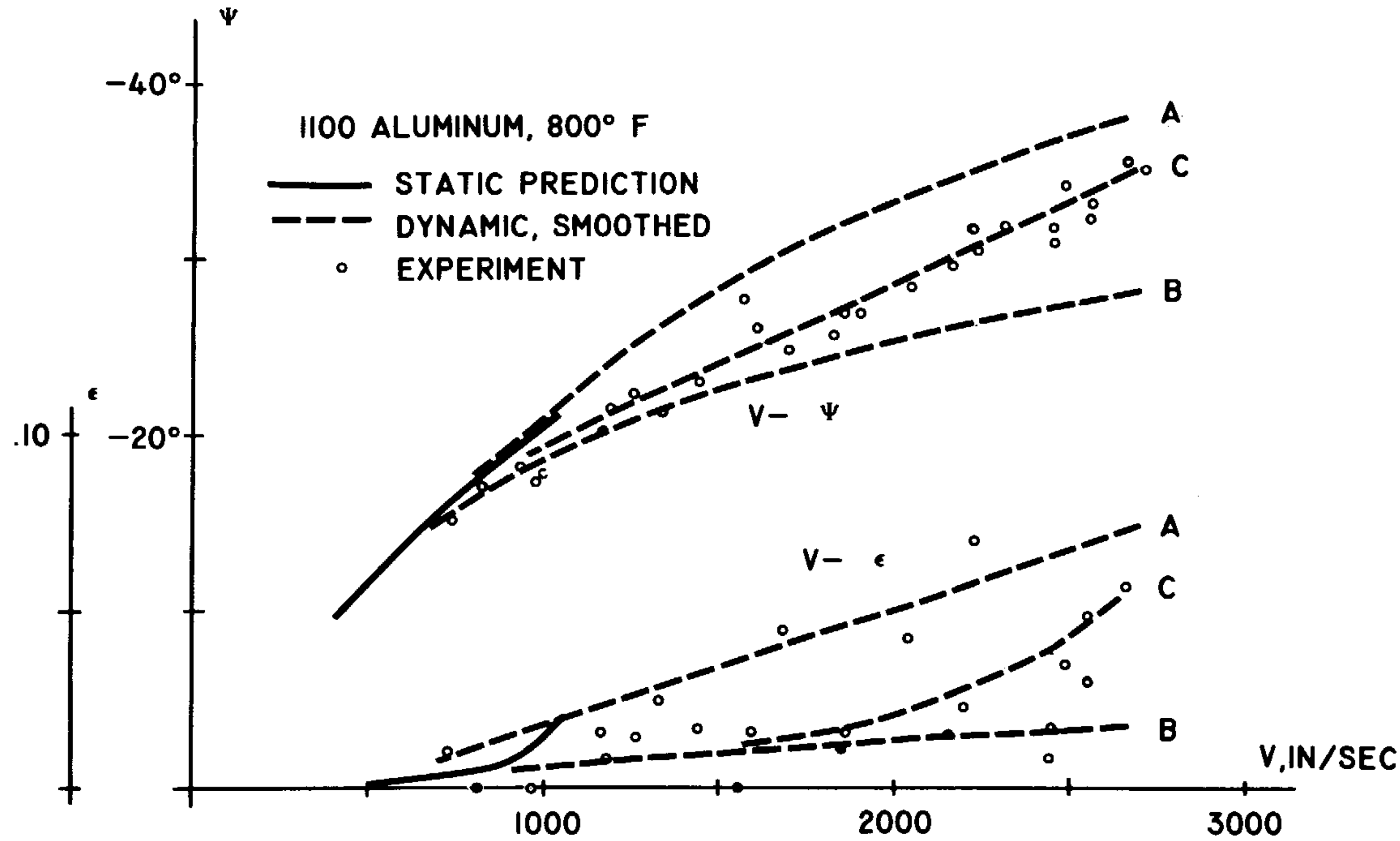

FIG. 8 EXPERIMENTAL OBSERVATIONS, 1100 ALUMINUM, 800°F

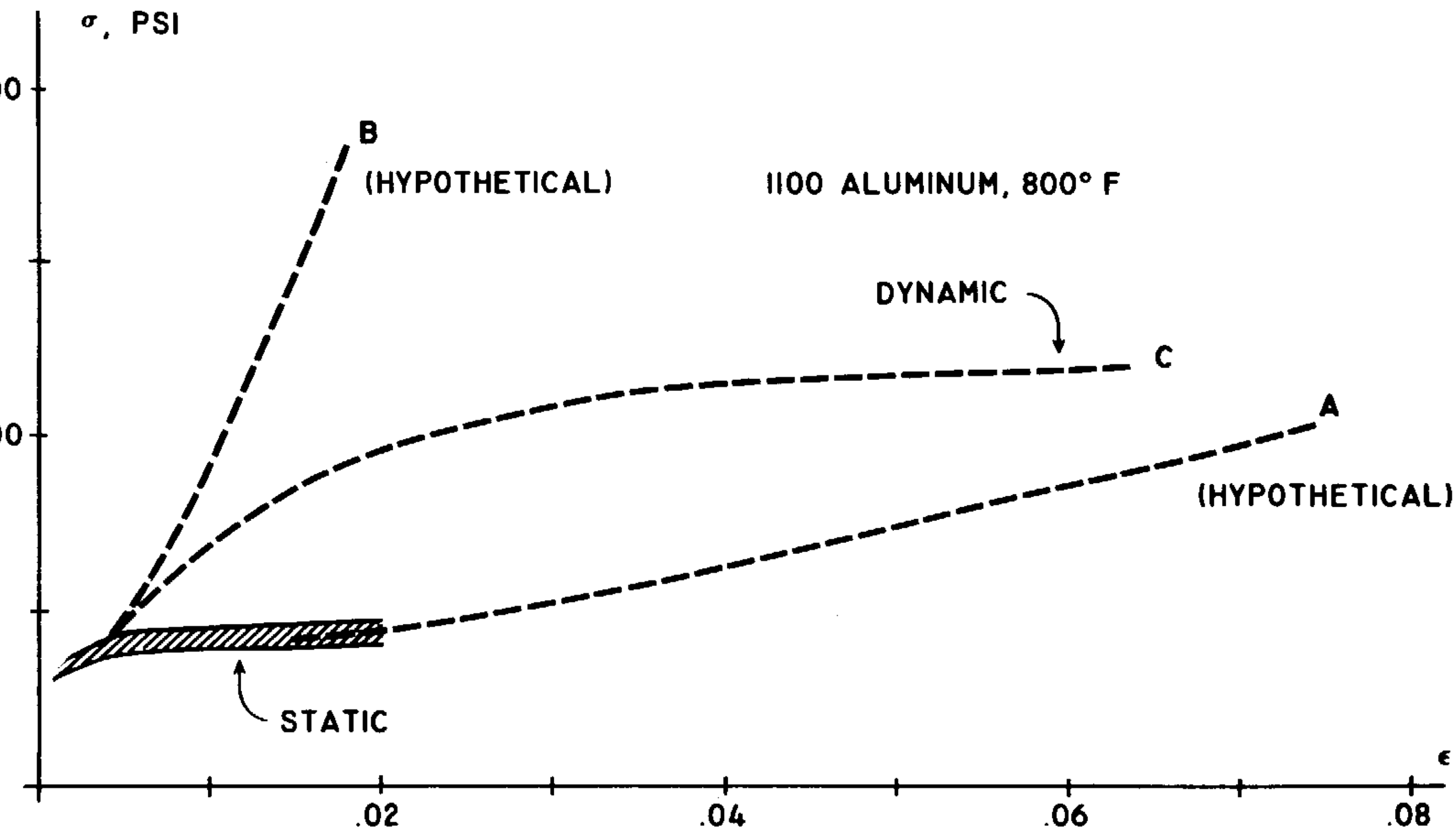

FIG. 9 STRESS-STRAIN DATA, 1100 ALUMINUM, 800°F

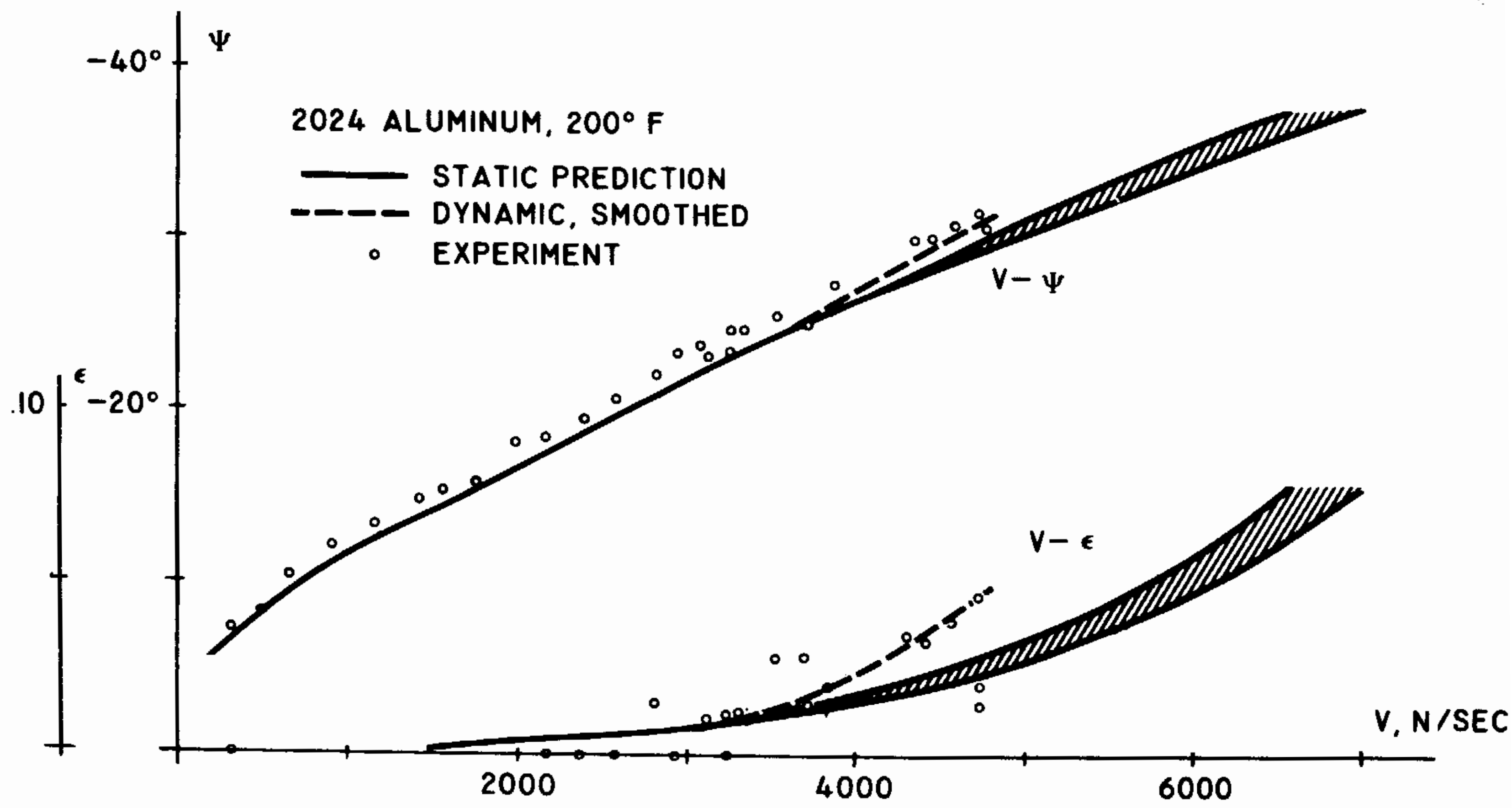

FIG. 10 EXPERIMENTAL OBSERVATION, 2024 ALUMINUM, 200°F

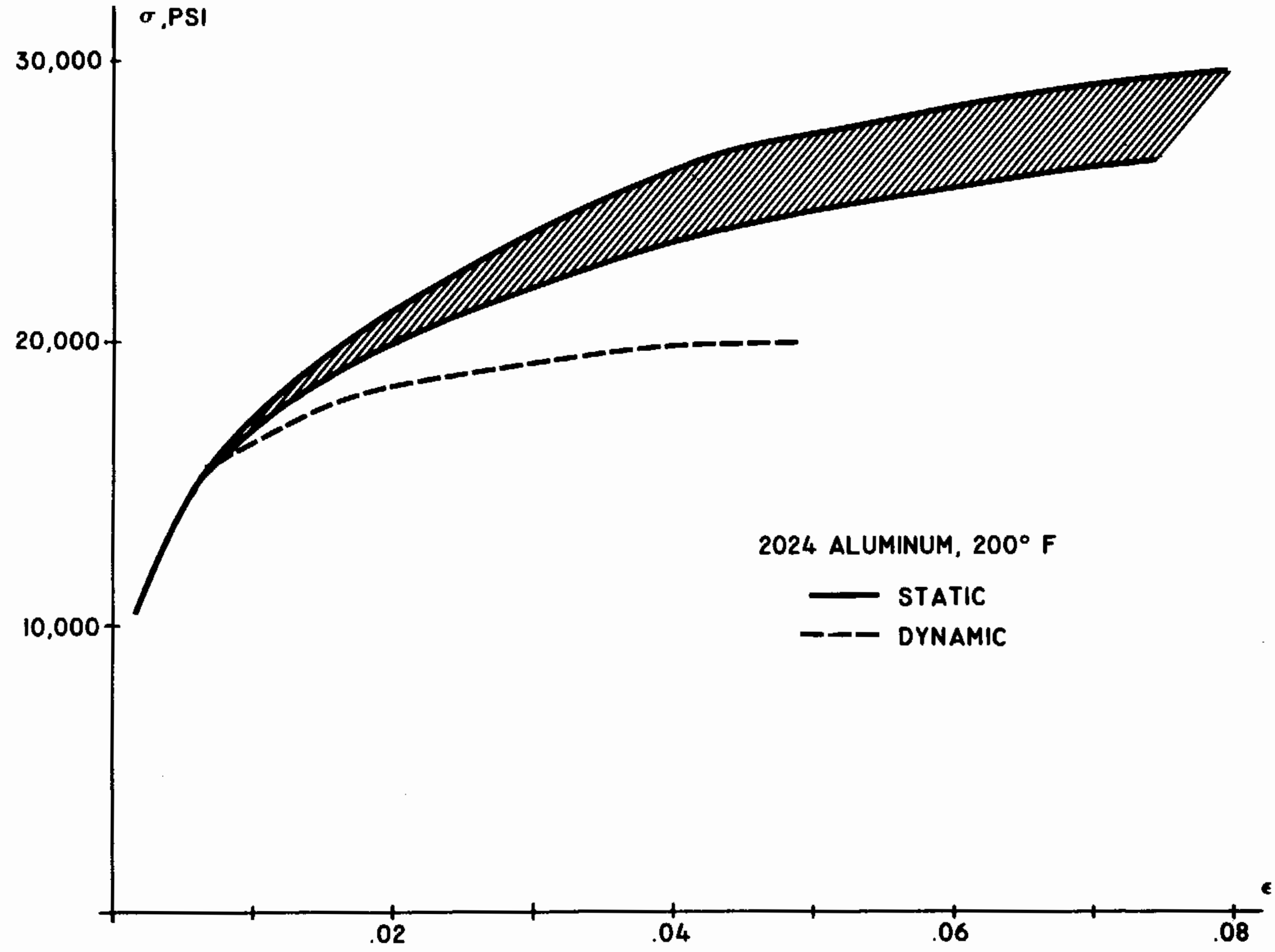

FIG. 11 STRESS-STRAIN DATA, 2024 ALUMINUM, 200°F

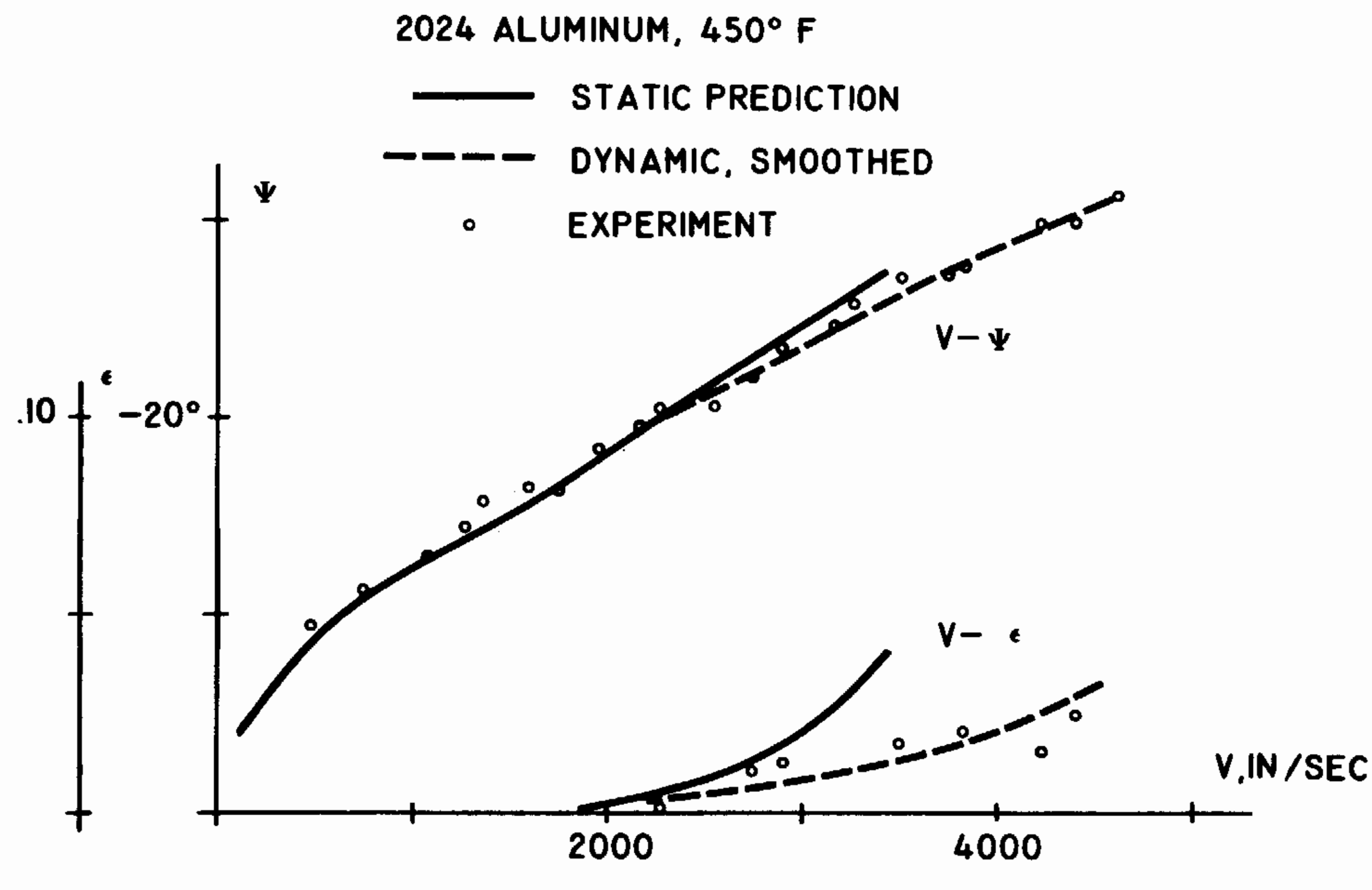

FIG. 12 EXPERIMENTAL OBSERVATIONS, 2024 ALUMINUM, 450°F

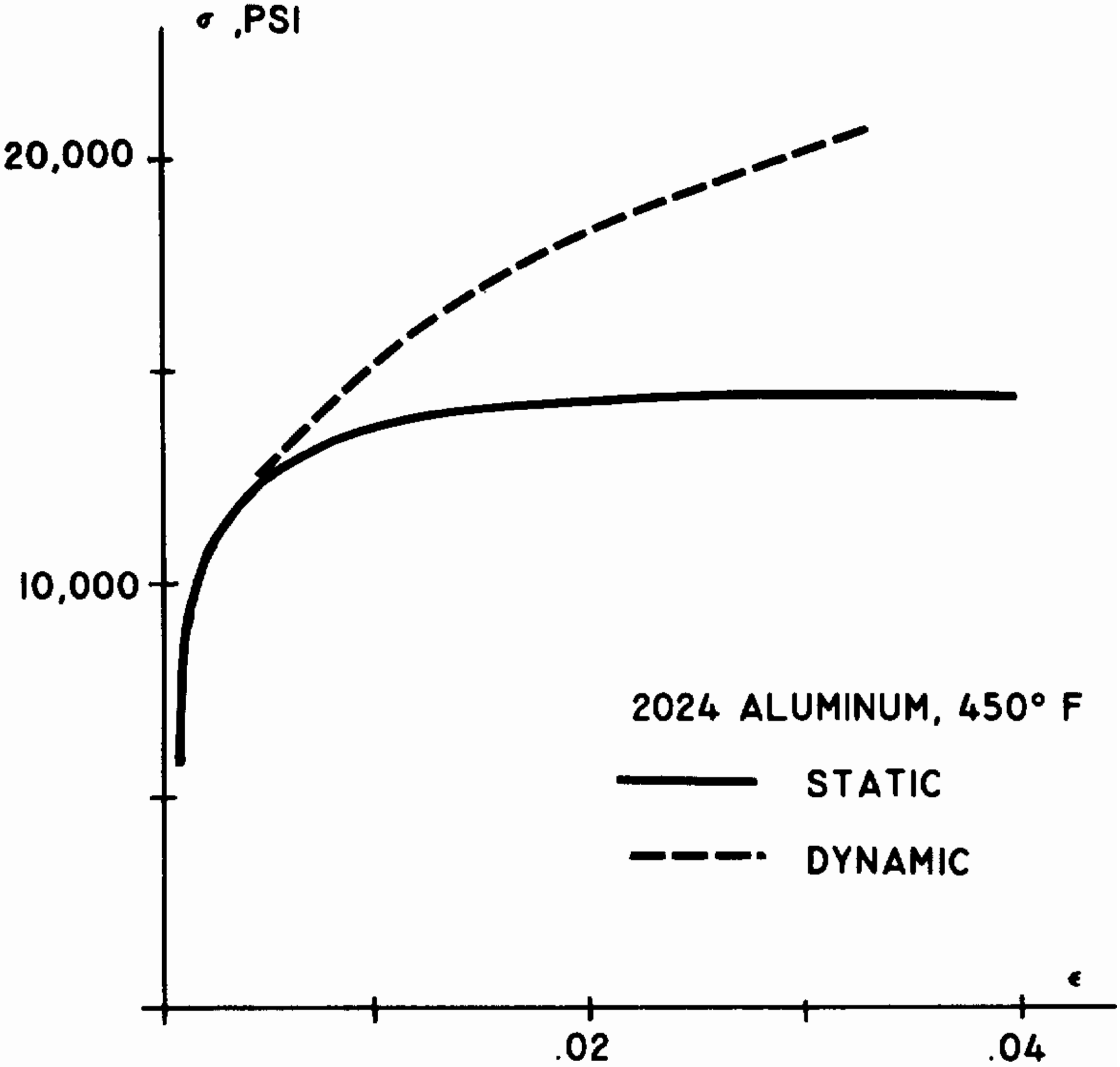

FIG. 13 STRESS-STRAIN DATA, 2024 ALUMINUM, 450°F

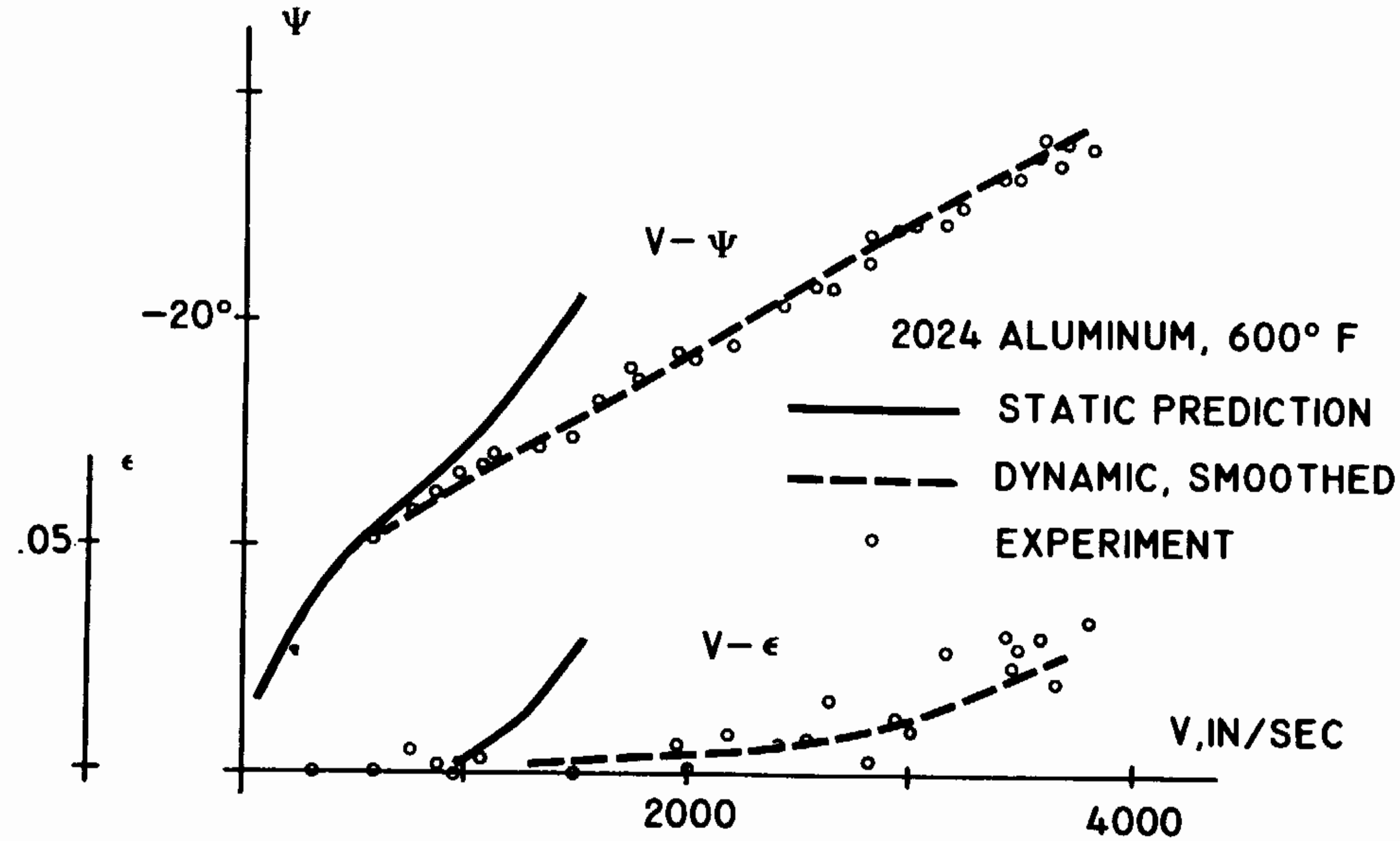

FIG. 14 EXPERIMENTAL OBSERVATIONS, 2024 ALUMINUM, 600°F

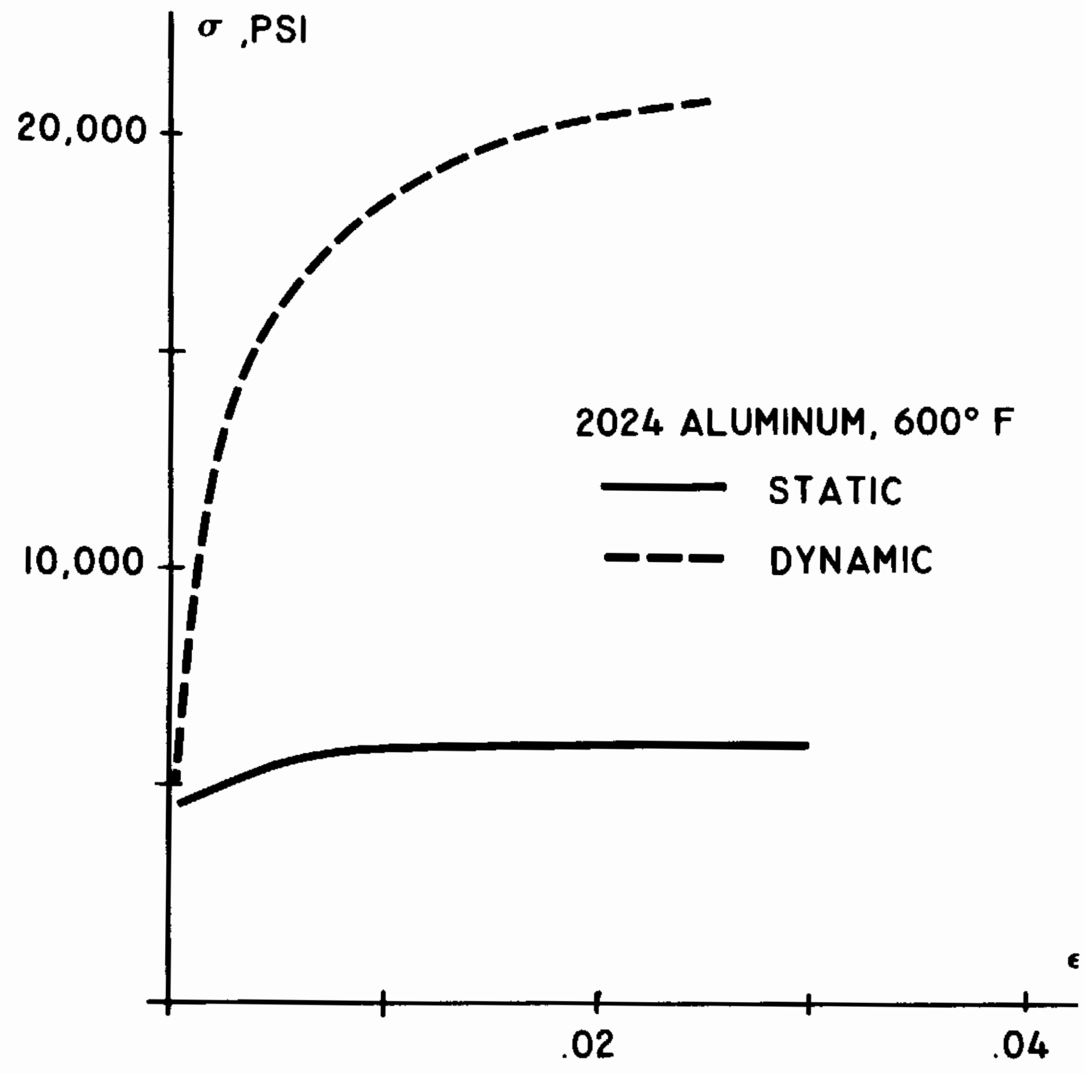

FIG. 15 STRESS-STRAIN DATA, 2024 ALUMINUM, 600°F

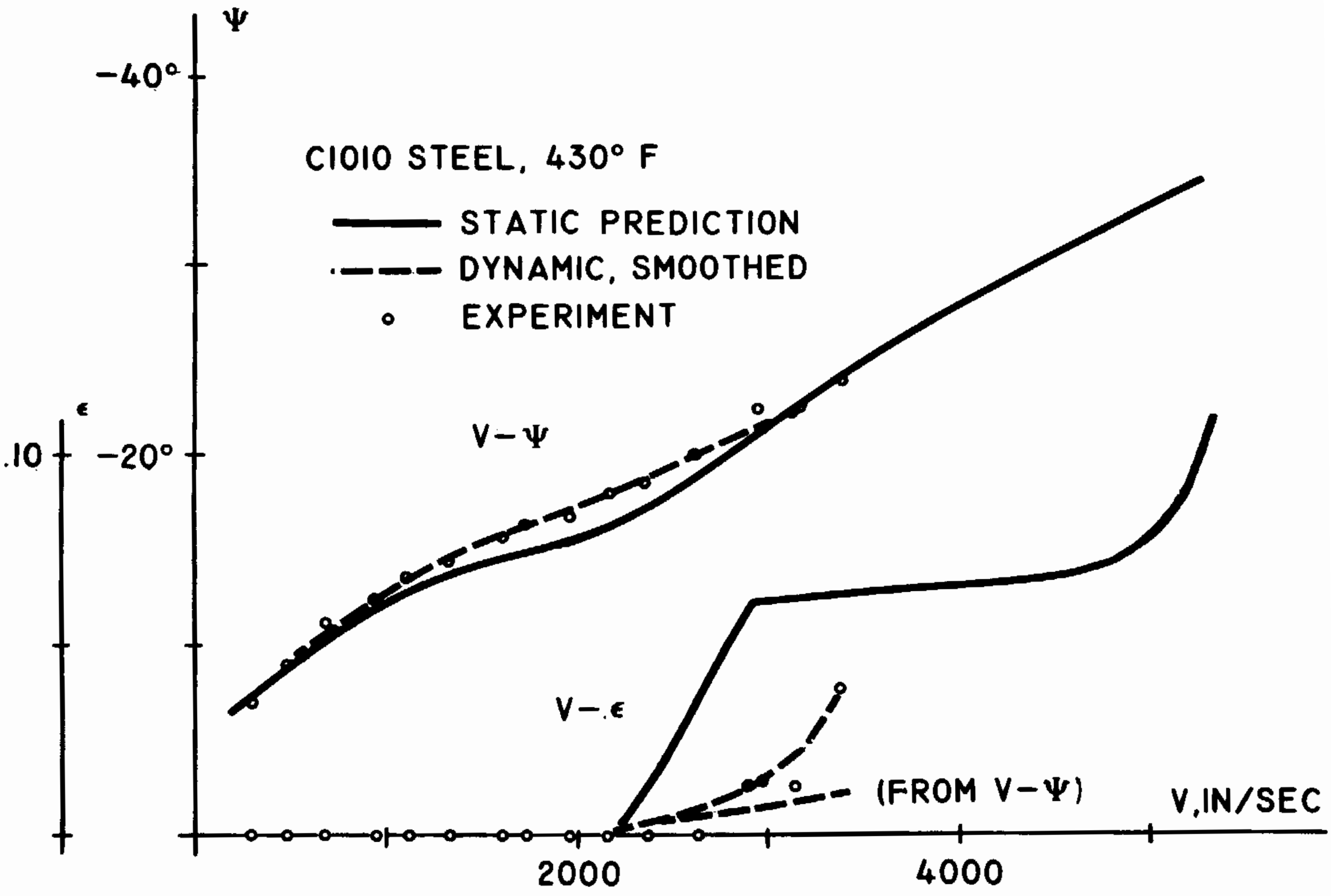

FIG. 16 EXPERIMENTAL OBSERVATIONS, C1010 STEEL, 430°F

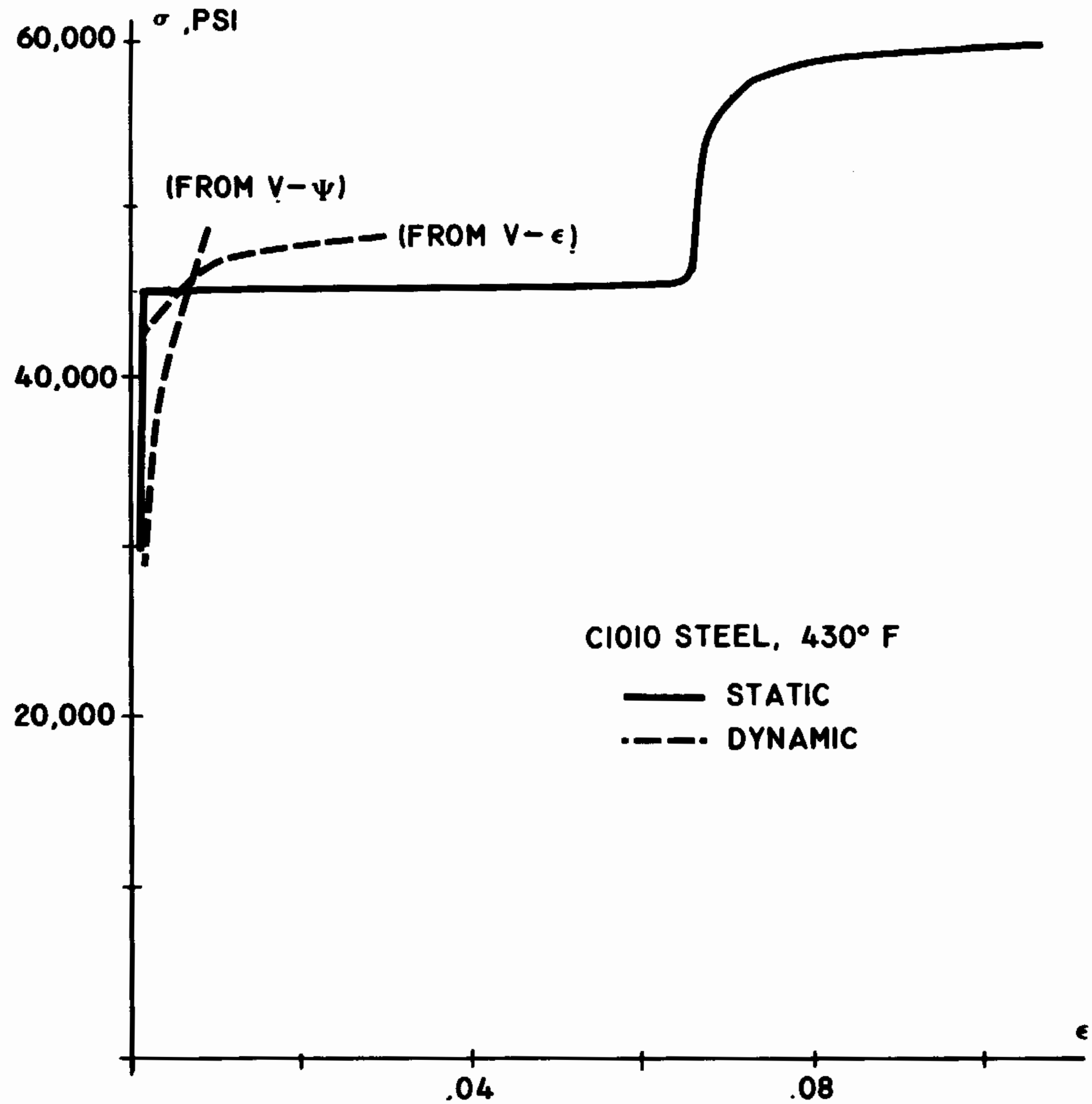

FIG. 17 STRESS-STRAIN DATA, C1010 STEEL, 430°F

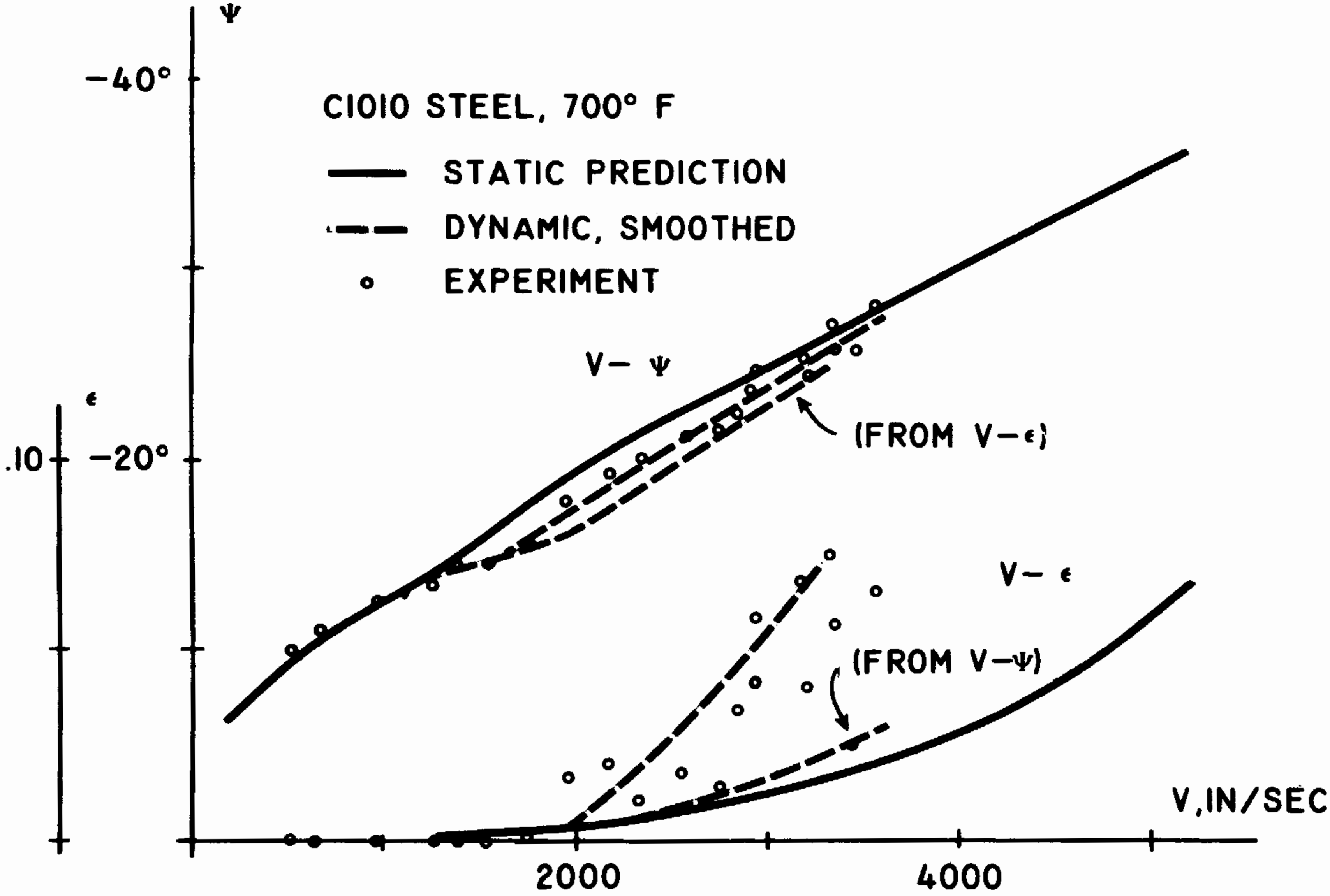

FIG. 18 EXPERIMENTAL OBSERVATIONS, C1010 STEEL, 700°F

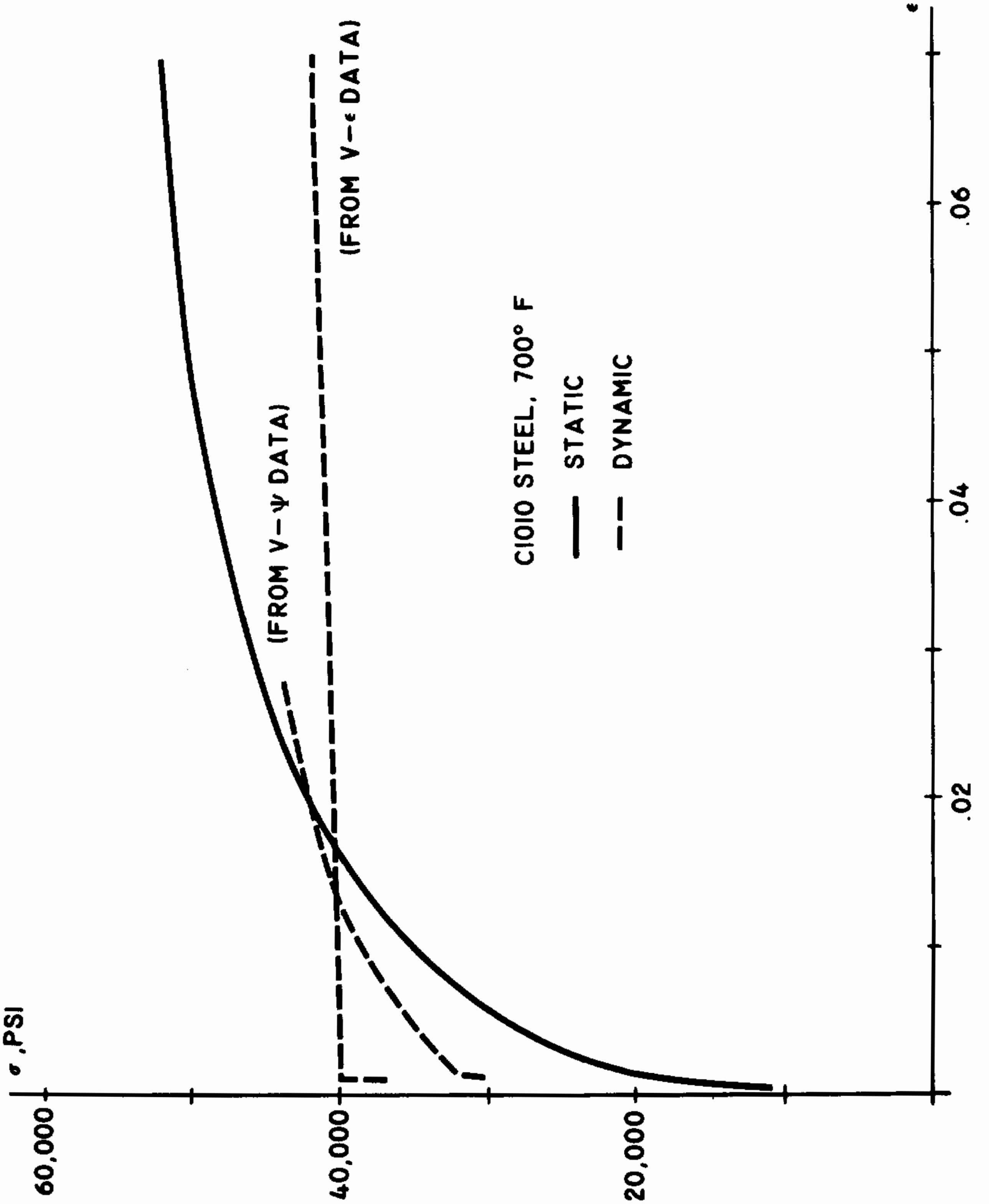

FIG. 19 STRESS-STRAIN DATA, C1010 STEEL, 700°F

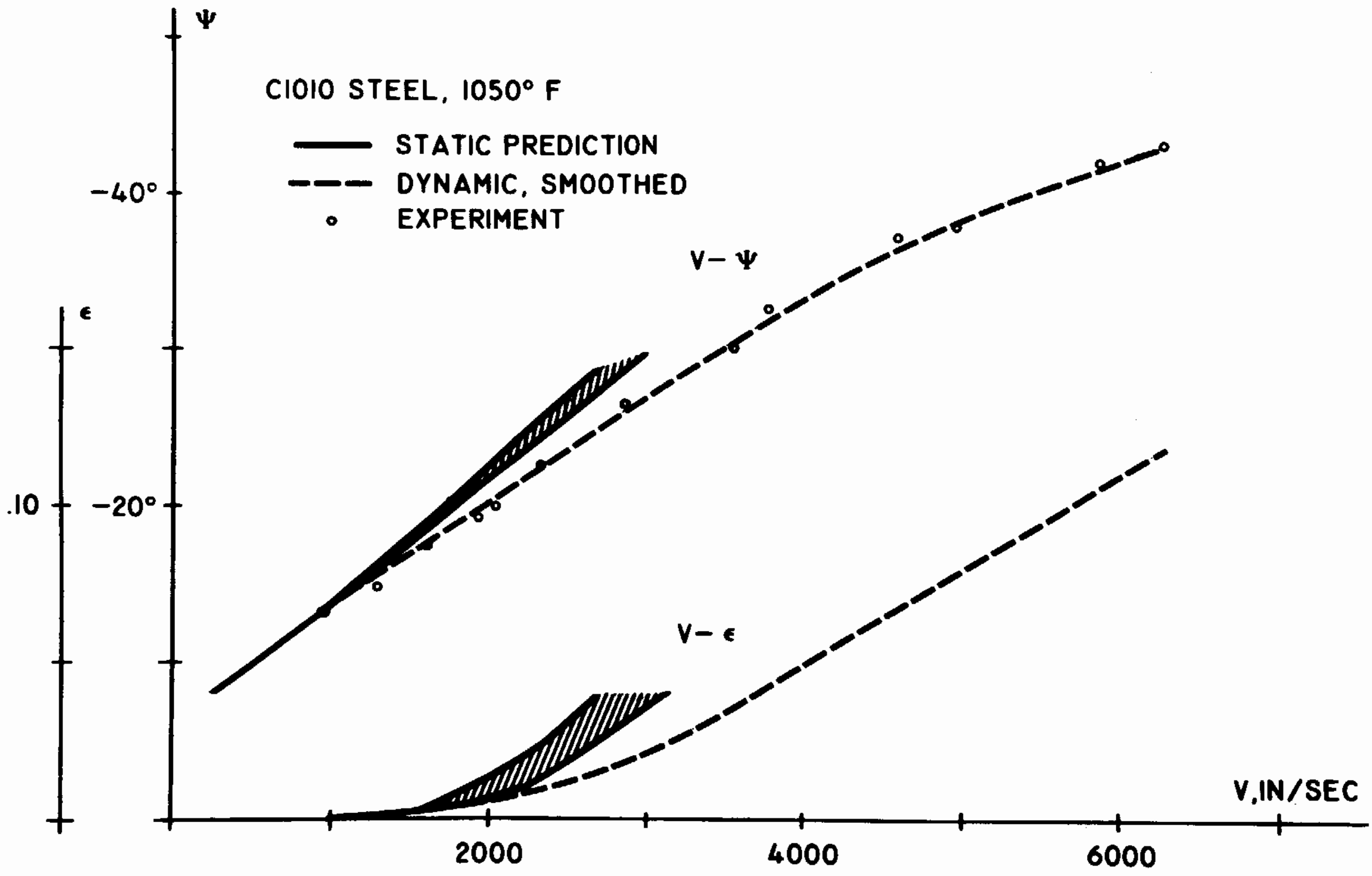

FIG. 20 EXPERIMENTAL OBSERVATIONS, C1010 STEEL, 1050°F

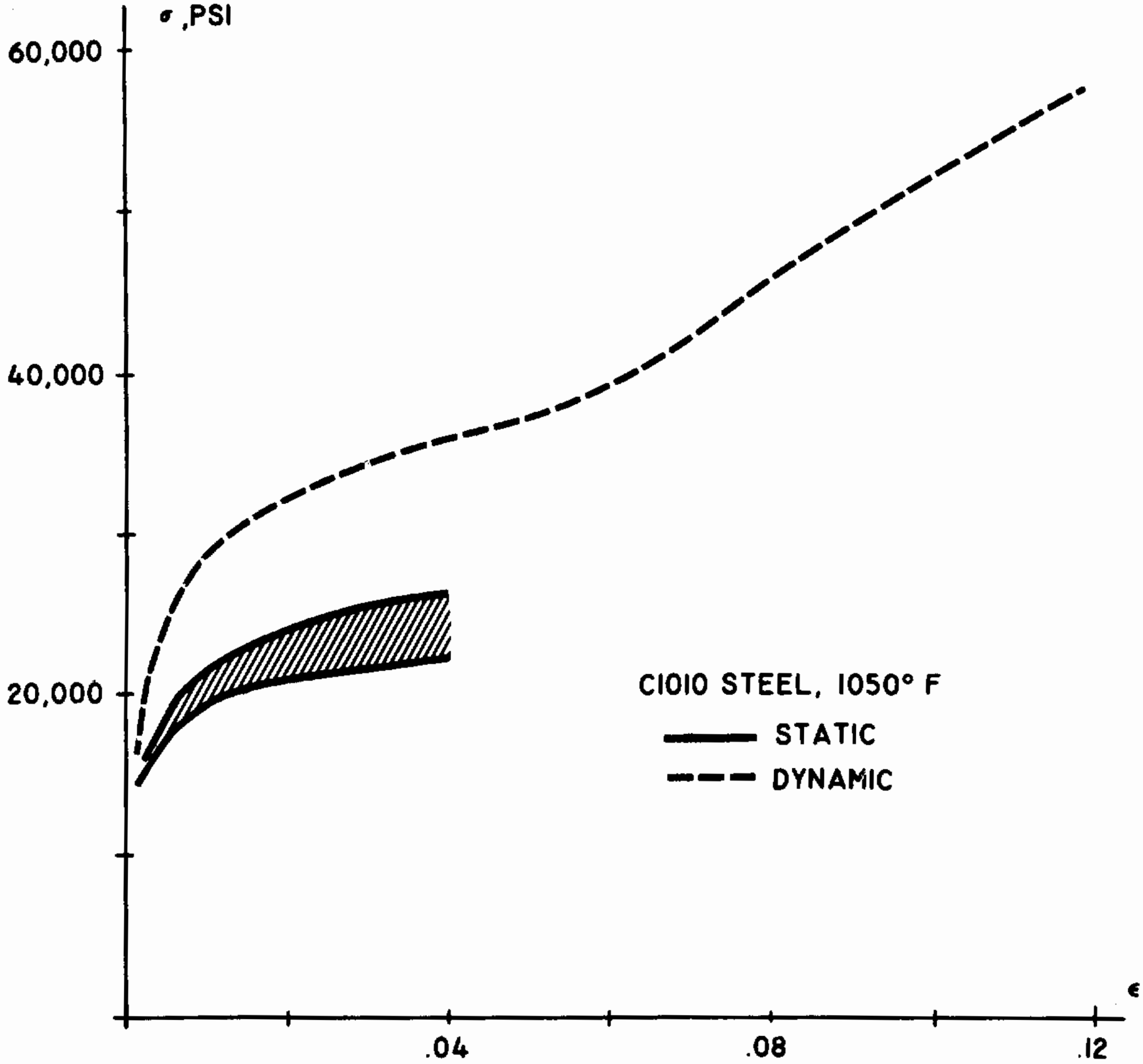

FIG. 21 STRESS-STRAIN DATA, C1010 STEEL, 1050°F

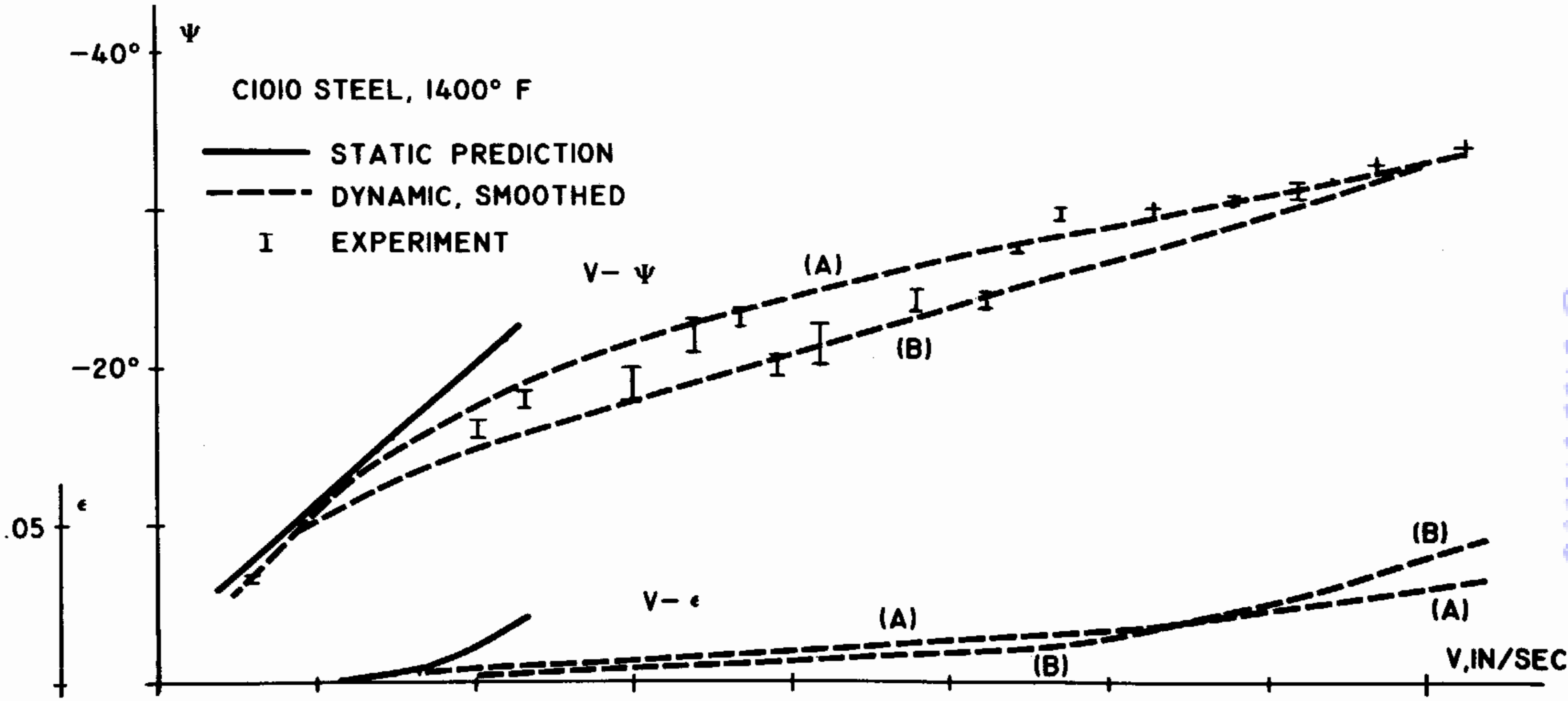

FIG. 22 EXPERIMENTAL OBSERVATIONS, C1010 STEEL, 1400°F

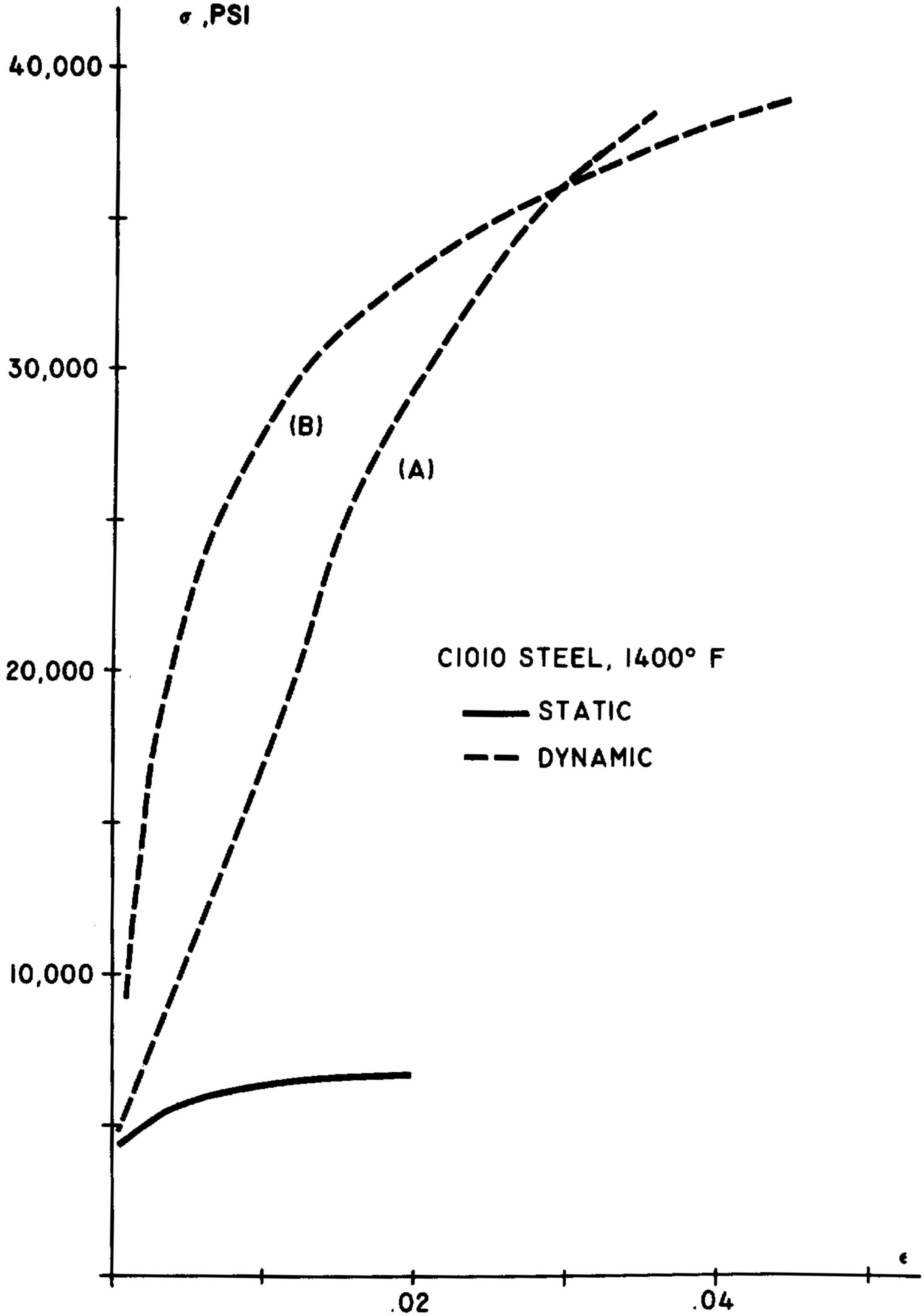

FIG. 23 STRESS-STRAIN DATA, C1010 STEEL, 1400°F

TABLE I SUMMARY OF RESULTS

MATERIAL	CRITICAL TRANSVERSE VELOCITY, IN/SEC			CRITICAL LONG. VELOCITY, IN/SEC			ULTIMATE STRAIN			ULTIMATE STRESS, 10^3 PSI		
	STATIC	DYN.	DYN./STATIC	STATIC	DYN.	DYN./STATIC	STATIC	DYN.	DYN./STATIC	STATIC	DYN.	DYN./STATIC
1100 ALUMINUM												
200° F	4300	4300	1.0	−1620	−1470	.91	.20	.075	.38	9.4	10.8	1.15
350° F	2570	3200	1.16	−760	−1020	1.3	.09	.044	.49	4.5	7.8	1.7
550° F	1500	2800	1.9	−350	−790	2.3	.05	.03	.60	2.7	6.7	2.5
800° F	1050	2700	2.6	−200	−860	4.3	.02	.064	3.2	1.8	4.8	2.7
2024 ALUMINUM												
200° F	6800	4800	.71	−2340	−1380	.59	.077	.05	.65	28.0	20	.71
450° F	3400	4500	1.3	−830	−1440	1.7	.04	.033	.82	14.5	20.5	1.4
600° F	1500	3700	2.5	−280	−940	3.4	.03	.025	.83	6.0	20.8	3.5
C1010 STEEL												
430° F	5300	3400	.67	−1640	−740	.45	.11	.03	.28	45 (FLOW)	48	1.07
700° F	5200	3600	.69	−1720	−703	.41	.07	.07	1.0	52	42	.81
1050° F	3000	6300	2.1	−800	−2500	3.1	.04	.12	3.0	24	57	2.4
1400° F	1150	4100	3.9	−230	−1260	5.5	.02	.044	2.2	6.5	39	6.0

unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Board of Trustees of the University of Illinois Box 4348, Chicago, Illinois 60680	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
Dynamic Behavior of Metals Under Tensile Impact
Part I: Elevated Temperature Tests

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Summary Report - 1 March 1967 to 28 February 1969

5. AUTHOR(S) (First name, middle initial, last name)
Albert B. Schultz

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1969	36	11

8a. CONTRACT OR GRANT NO. F33615-67-C1283 b. PROJECT NO. 7351 c. TASK NO. 735106 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFML-TR-69-76 Part I

10. DISTRIBUTION STATEMENT This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Metals and Ceramics Division (MAM), Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Materials Laboratory Research and Technology Division, Air Force System Command, Wright-Patterson AFB, Ohio

13. ABSTRACT

The mechanical behavior of metals subjected to uniaxial tensile impact at elevated temperatures is reported. Tests were conducted on annealed 1100 aluminum at 200°, 350°, 550°, and 800°F; annealed 2024 aluminum at 200°, 450°, and 600°F; and annealed C1010 steel at 430°, 700°, 1050°, and 1400°F. The materials exhibit a wide range of dynamic behavior, including some in which the stress required to produce a given level of strain is significantly lowered by dynamic loading. The ratios of the dynamic ultimate stresses to the static are found to range from 0.71 to 6.0.

This abstract is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Metals and Ceramics Division (MAM), Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Plastic wave propagation						
Dynamic material behavior						