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TECHNICAL REPORT No. 25

**STRAIN AGING and RHEOTROPIC RECOVERY**

In Cooperation With  
The Office of Naval Research, U. S. Navy

NG-ONR-273/1

Project NR-031-049

February 1953

An Investigation of  
THE EFFECTS OF STRESS CONCENTRATION AND  
TRIAXIALITY ON THE PLASTIC FLOW OF METALS

Technical Report No. 25

STRAIN AGING AND RHEOTROPIC RECOVERY

By

E. J. Ripling

Conducted By  
METALS RESEARCH LABORATORY  
DEPARTMENT OF METALLURGICAL ENGINEERING  
CASE INSTITUTE OF TECHNOLOGY

In Cooperation With  
OFFICE OF NAVAL RESEARCH, U. S. NAVY

Contract N6-ONR-273/I

Project NR-031-049

Cleveland, Ohio  
February, 1953

METALS RESEARCH LABORATORY  
DEPARTMENT OF METALLURGICAL ENGINEERING  
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Technical Report No. 25

STRAIN AGING AND RHEOTROPIC RECOVERY

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# STRAIN AGING AND RHEOTROPIC RECOVERY\*

By

E. J. Ripling\*\*

## ABSTRACT

The rheotropic recovery produced in a steel heat treated to a high hardness level is shown to persist through a second tempering (or aging) treatment up to temperatures at least as high as the initial tempering temperature.

The rate at which the ductility of rheotropically recovered metal is lost at low aging temperatures and recovered again at higher temperatures, is far in excess of that found in the same metal under conditions in which the recovery is not necessary.

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\* This paper is based upon a portion of a research program conducted in the Metals Research Laboratory, Department of Metallurgical Engineering, Case Institute of Technology, Cleveland, Ohio in cooperation with the Office of Naval Research, U. S. Navy.

\*\* Assistant Professor, Department of Metallurgical Engineering, Case Institute of Technology.

# STRAIN AGING AND RHEOTROPIC RECOVERY

## INTRODUCTION

Cold deformation of a non-face-centered cubic metal under ductile conditions has been shown to partially alleviate the brittleness normally exhibited by these metals at low temperatures, high strain rates or under superimposed hydrostatic tensile stresses (1-5)\*. The strain-curable portion of the brittleness which these metals show under severe service conditions has been labeled "Rheotropic Brittleness". The rheotropic behavior exhibited by a typical non-face-centered cubic metal is shown schematically by the three dimensional model in Fig. 1. Curve A in Fig. 1 represents the ductility of the metal as a function of some embrittling variable while curve B indicates the fashion by which the initial low ductility,  $\epsilon_A$ , is overcome by prestraining under a ductile condition. The shaded portion immediately above curve B represents the rheotropic brittleness under one set of embrittling variables. The magnitude of the rheotropic brittleness at zero prestrain is given by the difference between the experimentally determined ductility value,  $\epsilon_A$ , and that obtained by extrapolating the ductile branch of curve A to this same testing condition,  $\epsilon_C$ , (2). Prestraining under the ductile condition eliminates the brittleness as shown by curve B, the ductility increasing from  $\epsilon_A$  to  $\epsilon_B$  (maximum). The magnitude of the prestrain necessary to completely overcome the rheotropic brittleness is labeled  $\epsilon_S$  in Fig. 1.

- - - -

\* Numbers in parentheses refer to Bibliography at the end of the Report.

investigation since a large amount of information was already available on the rheotropic behavior of this material. Specimens were prepared from the 3/4 inch diameter hot rolled "as received" rods as follows:

1. Normalize at 1675°F (913°C) for 1/2 hour and air cool.
2. Stress relieve at 1200°F (649°C) for 4 hours followed by a furnace cool.
3. Rough machine to the shape shown in Fig. 2.
4. Austenitize at 1525°F (830°C) for 45 minutes and oil quench.
5. Temper for 1 hour at 600°F (316°C) or 700°F (371°C) and air cool\*.
6. Finish machine to the specimen shape shown in Fig. 2.

Some of these specimens were then tested in tension over a variety of temperatures in order to obtain the transition temperature. Others were prestretched various amounts at room temperature after which they were aged before testing at the sub-transition temperature. A 3 1/2 (± 1/2) hour interval was used between prestraining and testing. Specimens aged above room temperature were held in the aging furnace for 1 hour followed by an air cool. During the other two hours, the specimens were measured and held at room temperature.

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\* This differs somewhat from the heat treatment previously used on SAE 1340 in that the specimens were water quenched from the temper in the earlier investigations (4,7). A few tests at room temperature and at one sub-transition temperature indicated that identical tensile results were obtained on either air cooling or quenching from these rather low tempering temperatures.

The low temperature tensile testing procedure has been given in some detail previously (7). Both prestrain and final ductility measurements were made by determining the specimen diameters on a micro-comparator before and after each straining operation.

### RESULTS AND DISCUSSION

The dependence of ductility\* on the testing temperature for the two tempering temperatures used in this investigation are shown in Fig. 3. These tempering temperatures were selected since they are known to produce a rather high transition temperature. These curves are somewhat different from those previously presented on SAE 1340 which was also quenched and tempered at 700° and 600°F (4) (8). In addition to the data obtained on specimens subjected to a single temper at 600 or 700°F, other specimens were retempered or aged at temperatures less than or equal to the tempering temperatures. As shown in Fig. 3, the second temper (or aging treatment) did not change the properties of the steel.

Data obtained on the specimens quenched and tempered at 600°F, followed by prestretching at room temperature, aging, and final testing at a subtransition temperature (-210°F) are shown in Fig. 4. Similar data obtained on the specimens quenched and tempered at 700°F are

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\* All the ductility values used in the report are in terms of the maximum natural strain and is defined as:

$$\epsilon = \ln \frac{\text{original area}}{\text{final area}}$$

shown in Fig. 5. In both of these figures, the room temperature aging curves are taken to represent the basic rheotropic behaviors. Consequently, these curves are replotted with each of the aging curves for comparison.

In an earlier publication on rheotropic brittleness (2), it was suggested that retained ductility-prestrain curves of the type shown in Figs. 4 and 5 were the result of some rheotropic impediment in the unstrained metal. Increasing prestrains under a ductile condition over the range of prestrains between zero and the prestrain ( $\epsilon_S$ ) necessary to reach the retained ductility peak in Figs. 4 and 5 attenuate this impediment. The metal when strained beyond  $\epsilon_S$  then was said to be unimpeded or stabilized.

An extrapolation of the stable portion of the retained ductility-prestrain curve back to zero prestrain is of special interest since it yields the ductility value that the unstrained metal would possess in the absence of rheotropic brittleness (2). These extrapolated ductility values at zero prestrain have been shown to be the same as those obtained by extending the ductile branch of the ductility-testing temperature curve to this same temperature,  $\epsilon_C$ , in Fig. 1. It is apparent from Figs. 4 and 5 that the unimpeded low temperature ductility ( $\epsilon_C$ ) decreases with low aging temperatures and then increases again in a manner characteristic of an aging phenomena. The specimens quenched and tempered at 700°F showed a higher stabilized or unimpeded ductility after aging at 700°F than did the unaged (aged at room temperature)

material. Unfortunately, for both test groups (tempered at 600 or 700°F) the maximum aging temperature was limited to the initial tempering temperature. Aging at temperatures higher than the tempering temperature presumably produces property changes other than those resulting simply from strain aging. In order to make aging at a higher temperature possible, a number of specimens were quenched and tempered at 800°F. This higher tempering temperature had to be abandoned, however, since it produced a transition temperature below that of boiling nitrogen.

Aging effects are characterized not only by a ductility minimum, but also by a strength (or hardness) peak. The most convenient strength property to evaluate in test series was the low temperature (conventional) tensile strength. Since the steel tempered at the temperatures used here exhibits a rather low maximum load strain, the tensile strength, when plotted as a function of the prestrain, is approximately equal to the low temperature flow-stress curve. As can be seen in Fig. 6, low aging temperatures produced the highest strength at any constant prestrain.

Since strain aging was found to be so effective in changing the unimpeded low temperature properties, a few specimens quenched and tempered at 700°F were prestrained at room temperature, aged at various temperatures, and then tested at room temperature. As seen in Fig. 7, low aging temperatures again produced a strength maximum and a ductility minimum. Room temperature in these test was above

the transition temperature so that the data in Fig. 7 indicate the effect of strain aging on unimpeded ductility at a super-transition temperature. Apparently strain aging has considerably less effect on unimpeded ductility at the elevated testing temperatures where no rheotropic impediment is involved than it has at the sub-transition temperatures.

The effect of strain aging on unimpeded ductility at a sub-transition and super-transition temperature are compared in Fig. 8. For the steel quenched and tempered at 700°F, a prestrain of  $\epsilon_1 = 0.31$  is capable of producing a complete rheotropic recovery at a testing temperature of -321°F for all of the aging temperatures investigated (see Fig. 5). Of course, at room temperature the steel experiences no rheotropic impediment at any prestrain. Consequently, the unimpaired ductility at the sub- and super- transition temperature can be compared by comparing the retained ductility at the high and low temperatures after a prestrain of  $\epsilon_1 = 0.31$ , as shown in Fig. 8a. In addition these two curves, the ductility of the steel at -321°F after a room temperature prestrain of  $\epsilon_1 = 0.31$  if no rheotropic recovery were effected, is also shown as a horizontal line in Fig. 8a\*. The shaded area between these two curves represents the rheotropic recovery as a function of aging temperature.

The upper two curves in Fig. 8a are re-plotted in Fig. 8b so that the ductility after the aging treatments is plotted as a fraction of the ductility in the absence of aging (actually aged at room temperature). The area

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\* This value is readily calculated from the equation  $\epsilon_r = \frac{\epsilon_B}{\epsilon_A} (\epsilon_A - \epsilon_p)$  given in Reference (2).

between these curves is a measure of the strain aging sensitivity of the rheotropically recovered steel that is in excess of the ordinary or super-transition temperature strain aging. So far as ductility is concerned, no strain aging takes place at room temperature (see Fig. 7). Consequently, it must be assumed that the relatively high ductility recovery obtained on aging at 700°F (Fig. 8b) is not overaging in the ordinary sense, which could be considered a secondary behavior superimposed on the rheotropic recovery; but it appears that these two phenomena are interdependent.

The magnitude of the prestrain ( $\epsilon_S$ ) necessary to affect a complete rheotropic recovery depends on the relative positions of the testing temperature and the transition temperature. The lower the testing temperature with respect to the transition temperature, the greater is this value of  $\epsilon_S$  (3). Since strain aging is known to lower the notch impact transition temperature (6), one would expect the values of  $\epsilon_S$  to show a maximum at the aging temperatures which show a minimum in Fig. 8. The values of  $\epsilon_S$  have been plotted as a function of aging temperature in Fig. 9. Although both of these curves show maxima at low aging temperatures, the change in  $\epsilon_S$  as a function of the aging temperature is rather slight. This suggests that aging produces only mild changes in the transition temperature (when the criterion is ductility in a tensile test) and major changes in the unimpeded low temperature ductility. It might be added that Jones and Worley (9) found that strain aging had a negligible influence on the transition

temperature of a semi-killed steel, and increased the transition temperature of the rimmed steel only to a minor degree when the transition temperatures were evaluated by means of tensile tests conducted over a wide range of strain rates with specimens having a variety of notch shapes.

#### SUMMARY

1. The rheotropic recovery produced in a high strength steel is not eliminated by re-heating the steel at least up to the initial tempering temperature.
2. The ductility of the rheotropically recovered metal is far more sensitive to strain aging than the same metal at a super-transition temperature when it is not rheotropically embrittled.
3. Strain aging appears to have only a mild effect on the tensile ductility transition temperature of the heat treated SAE 1340 used in this investigation.

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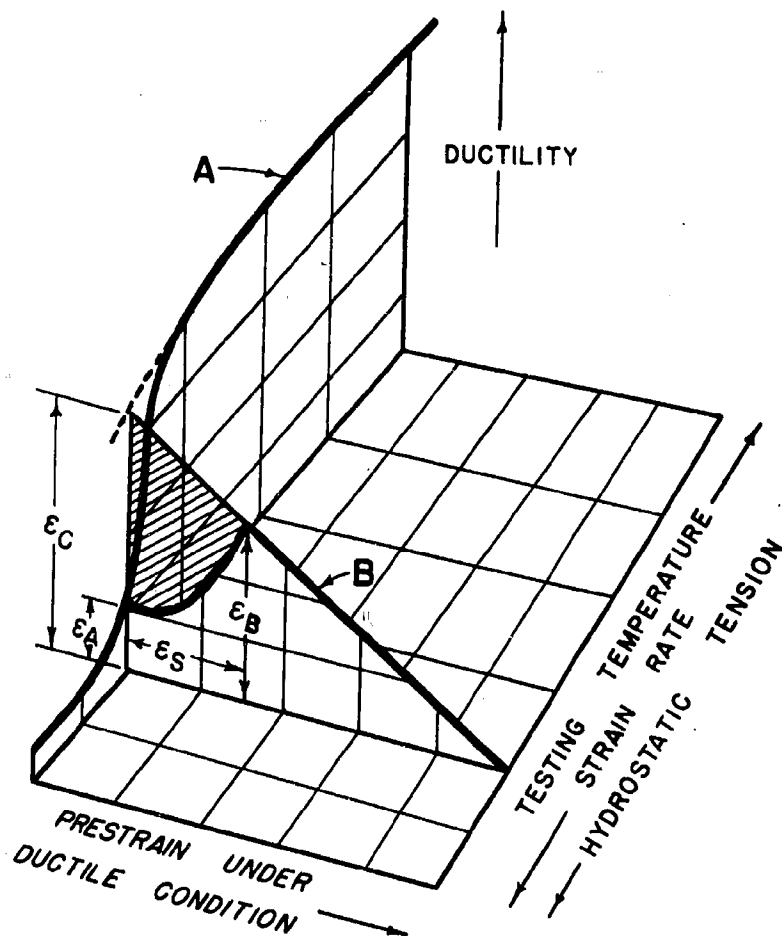


FIG.1: SCHEMATIC RELATIONSHIP BETWEEN DUCTILITY, TESTING CONDITIONS AND PRESTRAIN.

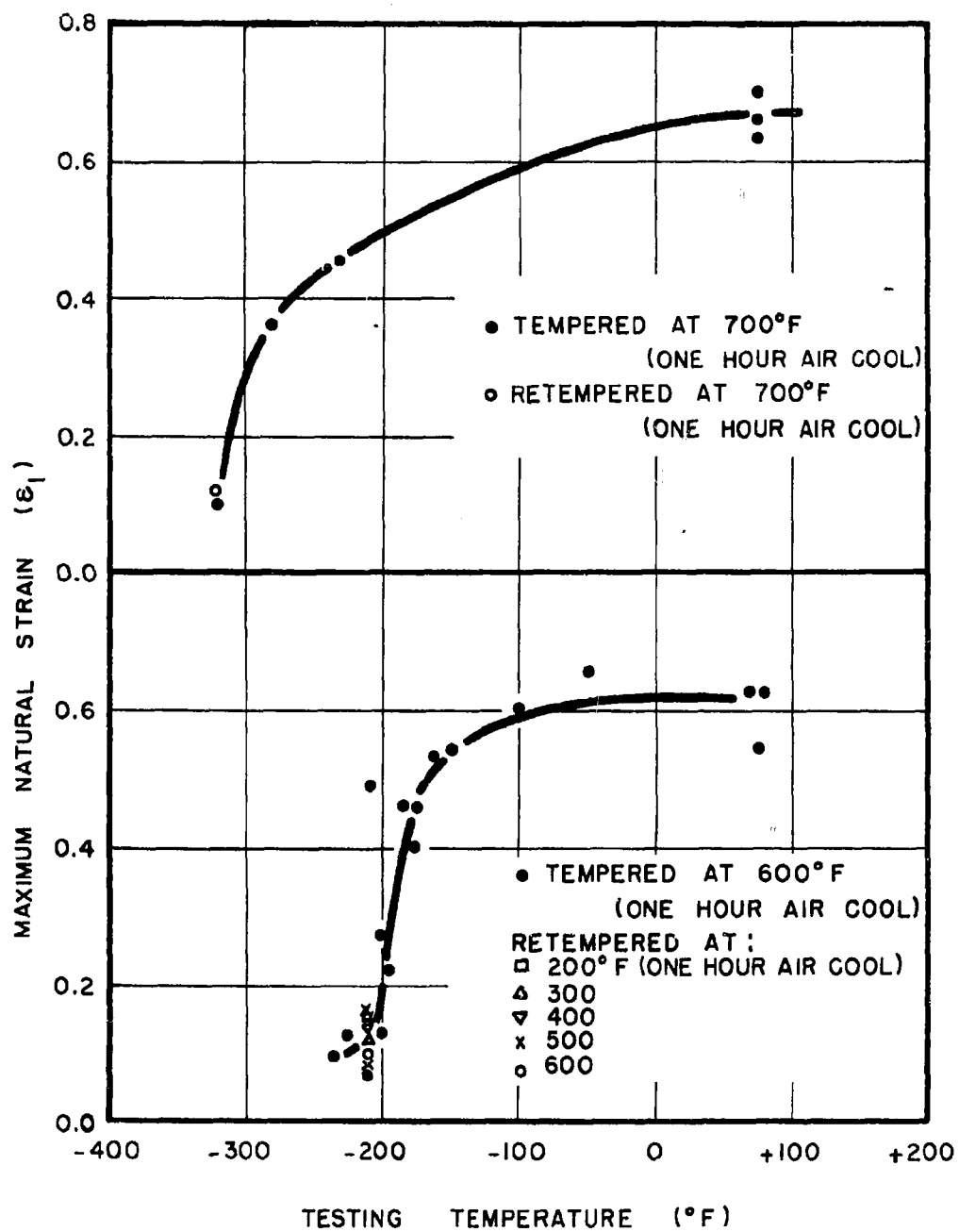


FIG. 3: TRANSITION TEMPERATURE OF SAE 1340  
QUENCHED AND TEMPERED AT 700 AND 600°F.

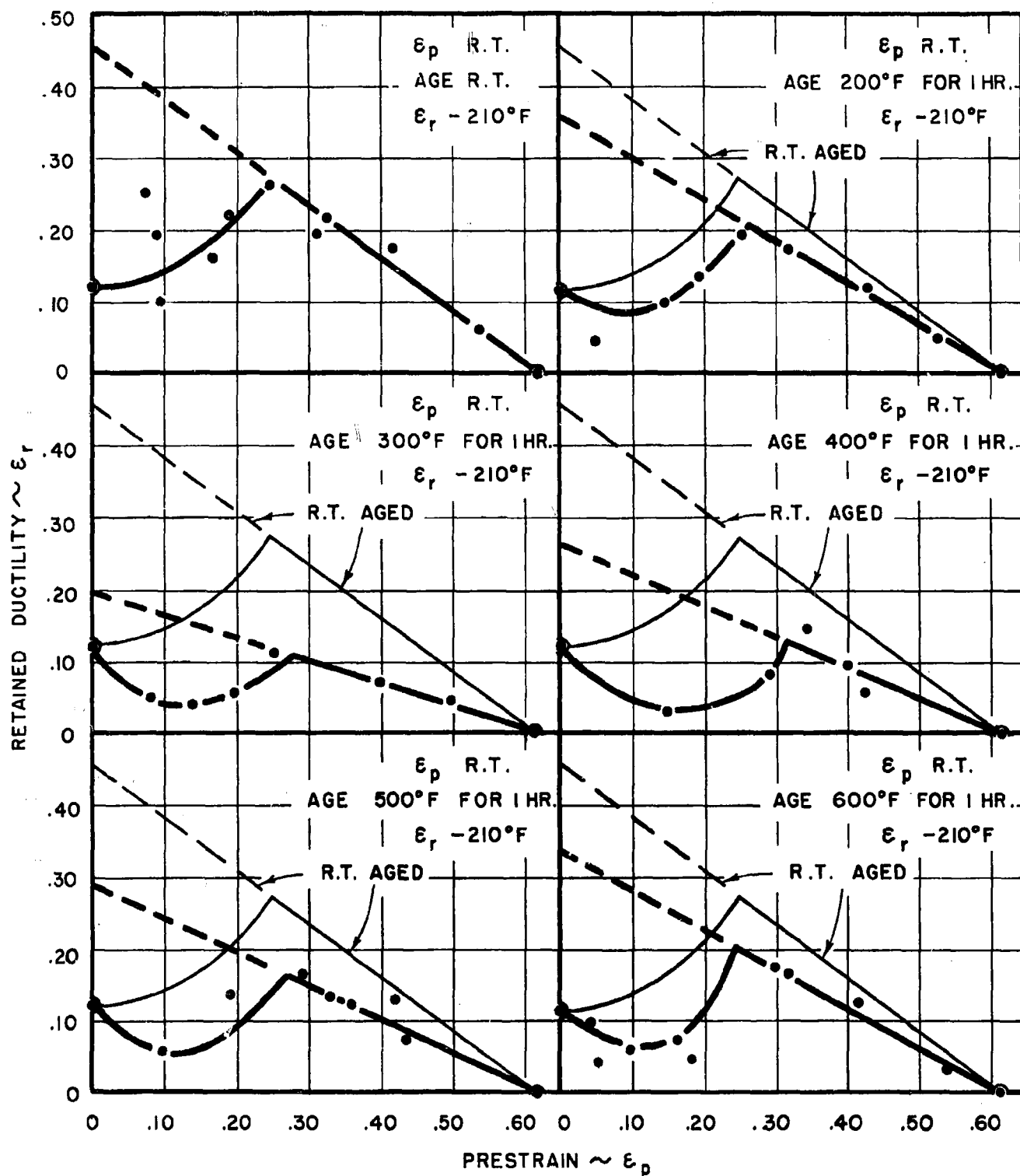


FIG. 4: RHEOTROPIC RECOVERY OF SAE 1340 QUENCHED AND TEMPERED AT  $600^\circ\text{F}$  PRODUCED BY PRESTRETCHING AT ROOM TEMPERATURE, AGING AT THE INDICATED TEMPERATURE AND TESTING AT  $-210^\circ\text{F}$ .

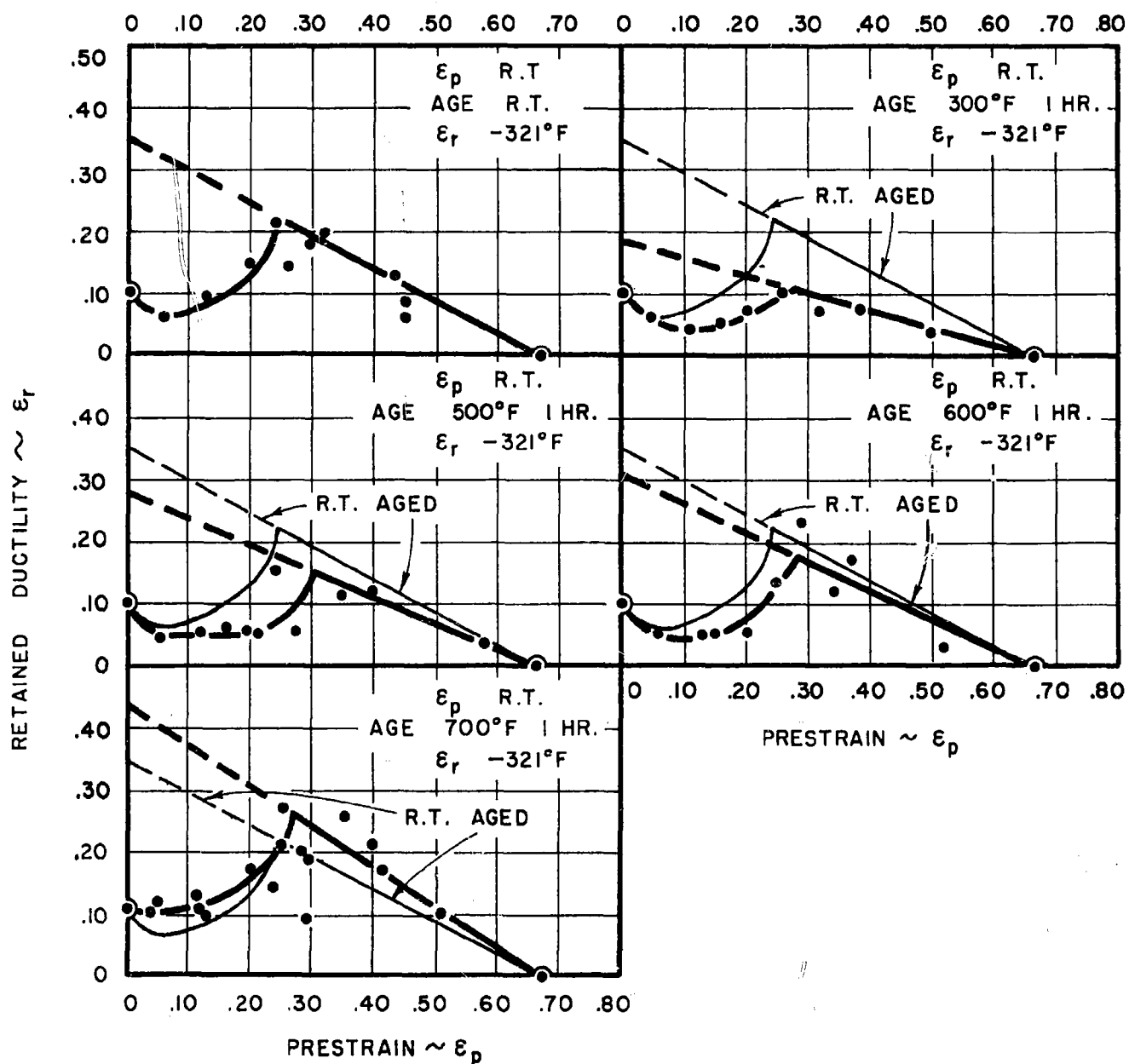


FIG. 5: RHEOTROPIC RECOVERY OF SAE 1340 QUENCHED AND TEMPERED AT 700°F PRODUCED BY PRESTRETCHING AT ROOM TEMPERATURE, AGING AT THE INDICATED TEMPERATURE, AND TESTING AT -321°F.

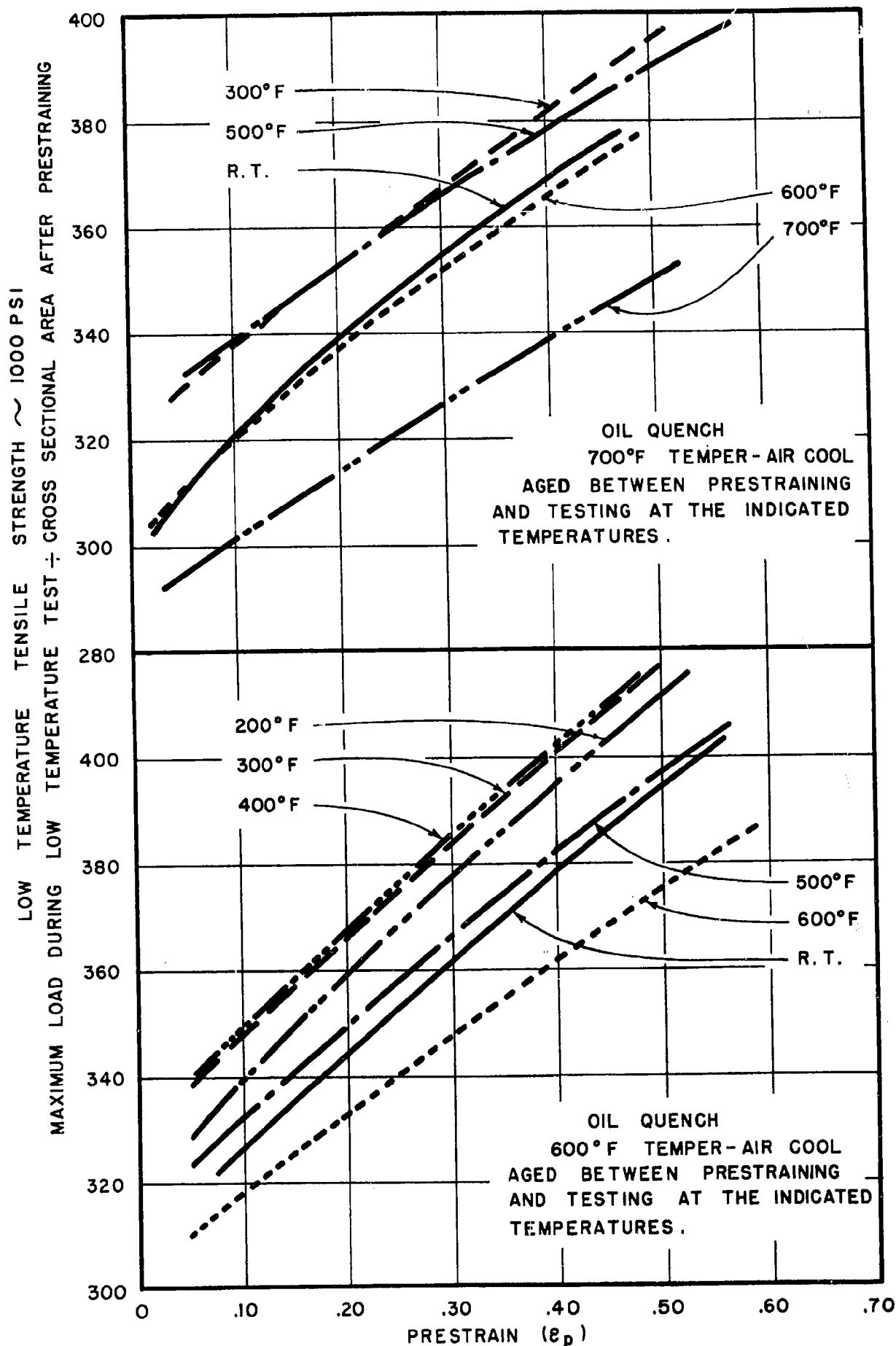


FIG. 6: LOW TEMPERATURE TENSILE STRENGTH AS A FUNCTION OF THE ROOM TEMPERATURE PRESTRAIN.

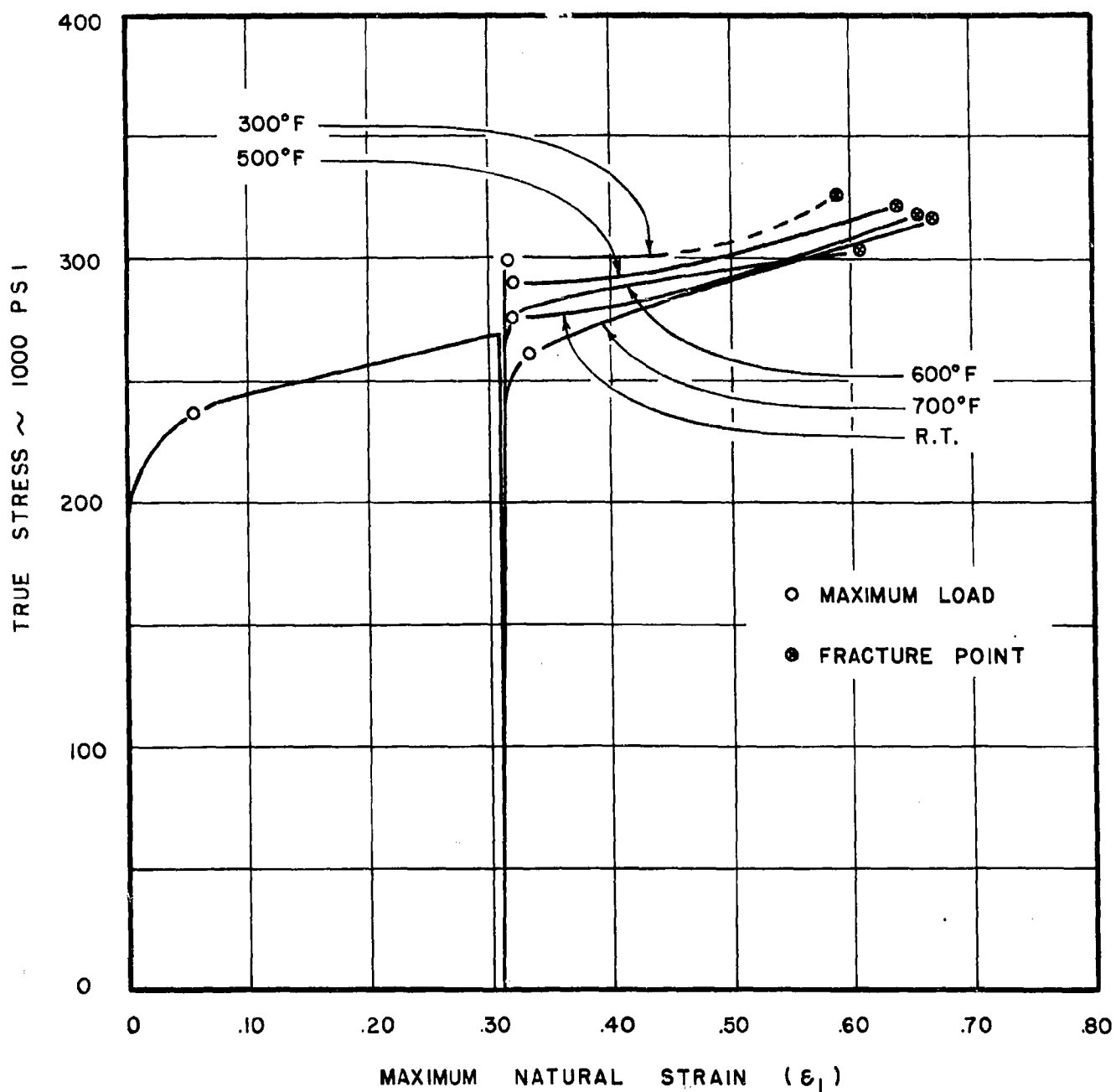


FIG. 7: TRUE STRESS — STRAIN CURVES FOR SAE 1340 QUENCHED AND TEMPERED AT 700°F OBTAINED BY PRESTRaining AT ROOM TEMPERATURE TO AN  $\epsilon_p = 0.31$ , AGING ONE HOUR AT THE INDICATED TEMPERATURES AND FINAL TESTING AT ROOM TEMPERATURE.

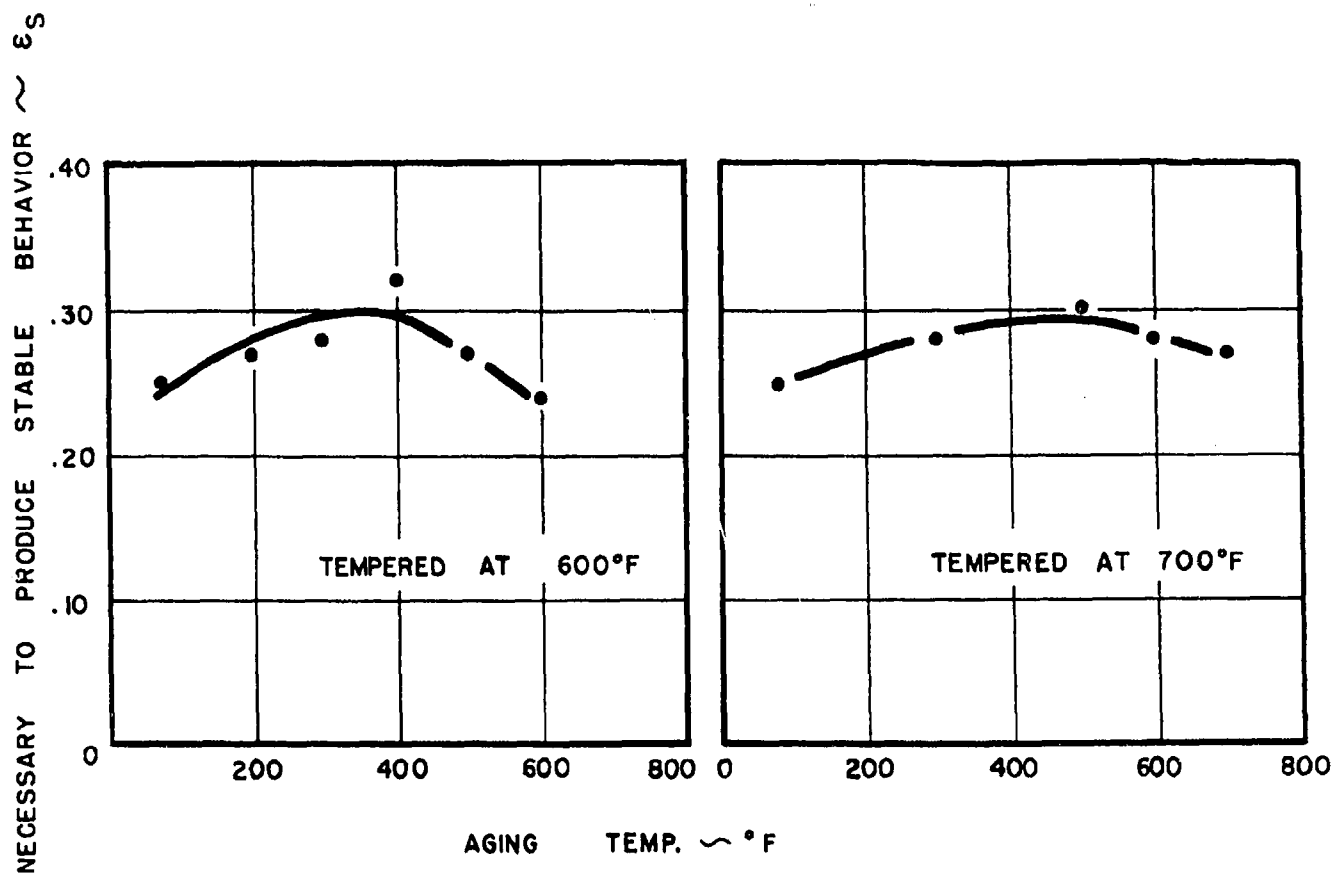


FIG.9: MAGNITUDE OF THE PRESTRAIN NECESSARY TO EFFECT A RHEOTROPIC RECOVERY AS A FUNCTION OF AGING TEMPERATURE.

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