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THE POTENTIALITY OF AUSFORM STEELS FOR PRESTRESSING

by
V. F. Zackay* and W. W. Gerberich+

Abstract

Conventionally quenched and tempered martensitic steels are generally limited to structural applications which require yield strengths of 300,000 psi or lower. Steels having yield strengths greater than this are characterized by poor ductility and toughness. A new process designed to extend the limits of usefulness of these steels is described. By a thermal-mechanical treatment ductile martensitic steels having yield strengths between 300,000 and 400,000 psi can be obtained. The processing variables of alloy composition, deformation, and deformation temperature are discussed. The response of several proprietary alloys to this thermal-mechanical treatment is shown. Unusual room and elevated temperature properties, including strength and fatigue resistance are described. Some of the factors pertinent to the potential use of Ausform steels for prestressing are considered.

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INTRODUCTION

Patented high carbon cold-drawn steel wire has been successfully used for prestressed concrete applications at strength levels as high as 275,000 psi. In the opinion of leading manufacturers, the usable strength of this type of wire could be increased to about 300,000 psi by improvements in processing. At strength levels appreciably greater than this, it is generally held that finer diameter, and therefore more expensive, wires must be used.

A strength limitation also appears to exist for quenched and tempered martensitic steels. The strength and ductility of martensitic steels are inversely related. As the strength (equivalent to increasing the carbon content) is increased, the ductility decreases. At a strength level of about 300,000 psi, the ductility is diminished to levels considered unacceptable for most engineering applications. It is apparent that new means of obtaining high strength without sacrificing ductility are needed.

For the past eight years the Scientific Laboratory of Ford Motor Company has been conducting research on a process designed to move the useful strength limits of steel, now at about 300,000 psi, to higher levels. The process and the properties of steel made by this process are described in this paper. The information given has largely been taken from a previous publication.(1) The applicability of this process to the manufacture of high strength wire for prestressed concrete is briefly discussed.

THE AUSFORM PROCESS

Lips and Van Zuilen have described a new hardening technique whereby austenite is strain-hardened before transformation to martensite.(2) The ausform process which is based on this principle is perhaps best discussed by briefly reviewing the well-known relationship between the equilibrium and time-temperature-transformation diagrams of steel illustrated in Fig. 1.

The thermodynamic or equilibrium relationship of the proeutectoid, eutectoid, and hypereutectoid reactions of steel that are of interest here are shown by the left panel of Fig. 1. These reactions are time dependent and their kinetics are described by the isothermal transformation diagram shown in the right panel of Fig. 1. For simplicity, the eutectoid composition of a plain carbon steel is chosen for discussion. The interposition of plastic strain between the critical temperature, in this case Ae_1 and the martensite start temperature M_s, accelerates the decomposition of austenite to pearlite or bainite, depending upon the temperature of deformation. Attempts in this laboratory to apply the Lips and Van Zuilen technique to other than thin strip and wire were not successful owing to this onset of austenite decomposition.

By the appropriate use of carbide forming elements, such as chromium, a 'bay' may be developed in the metastable austenite which is sufficiently stable to resist decomposition. The isothermal transformation diagram of a hot work die steel type H-11, containing 0.40% C-5.0% Cr-1.30% Mo-1.0% Si-0.5% V is shown in Fig. 2.

The ausform process may be described as the strain-hardening of metastable austenite within the temperature region that exists in the 'bay' between the transformation bands of pearlite and bainite, quenching of the strain-hardened austenite to martensite, followed by tempering of the martensite so formed.

AUSFORM PROCESS VARIABLES

The strength of a strain-hardened metal is primarily dependent upon the amount of deformation and, to a much less extent, upon the temperature of deformation, and the time at temperature. The dependence of yield and tensile strengths upon the deformation temperature and the amount of deformation for a type H-11 vacuum melted steel is shown in Fig. 3. All of the data shown in this figure and in the remainder of this paper were obtained on vacuum melted steels deformed by rolling unless otherwise stated. The type H-11 steel was austenitized at 1900°F for one hour, air-cooled to the deformation temperature, deformed, oil quenched, and double tempered at 950°F. The tensile and yield strengths for this alloy in the nonausform condition are 310,000 lb/in^2 and 240,000 lb/in^2, respectively, for a tempering temperature of 950°F.

At a given level of deformation both the yield and tensile strengths decrease with increasing deformation temperatures for a range of 700° to 1200°F, as shown in Fig. 3. Deformations greater than 50% at 700°F, and 75% at 800°F were not possible due to excessive isothermal transformation. For a given deformation temperature both the yield and tensile strengths increase with increasing deformation within the range of temperature and deformation investigated, as shown in Fig. 3.

The ductility of this same steel as a function of deformation temperature and amount of deformation is somewhat more complicated, as shown in Fig. 4. Above a certain critical deformation temperature, in this case about 1000°F, any amount of deformation between 30% and 94% results in ductility equal to or greater than observed in the conventionally heat-treated condition. At lower deformation temperatures, however, about 75% deformation appears to be needed to obtain good ductility. The critical temperature and deformations for each alloy system must be established experimentally; however, there appears to be a dependence of these process variables upon the recrystallization and recovery temperatures of the alloy. The latter temperatures are primarily a function of the alloy content, being especially sensitive to the presence of strong carbide forming elements such as Mo, W, and V.

AUSFORM METALLURGICAL VARIABLES

Carbon content

The presence of carbon in ausform martensitic steels plays as vital a part in determining mechanical properties as it does in conventionally heat-treated steels. The strength and ductility of ausform steels are directly dependent upon the carbon content, with a given amount of deformation and at a given tempering temperature, as shown in Fig. 5 for a 3% Cr series of steels containing 0.30% to 0.60% C. These steels were deformed 91%, oil quenched to martensite, liquid nitrogen quenched to minimize retained austenite, and tempered at 625°F for one hour. The ausform steels show an increase of about 75,000 lb/in^2 in yield and tensile strengths relative to the conventionally treated steels. This response is relatively constant over the total range of carbon content investigated. The ductility is not significantly altered in the ausform steels even though the strength has been increased.

Tempering temperature

The response of ausform steels to tempering is unusual in several respects, namely, no visible evidence exists of secondary hardening, the strength and ductility are relatively insensitive to low and medium tempering temperatures, and in medium- and high-alloy steels, the resistance to 'over-tempering' is enhanced. The hardness dependence on tempering of ausform steels is illustrated in Fig. 6. The three steels investigated were 300M (a silicon-modified AISI 4340 steel) type H-11, and Vasco MA, a proprietary steel of the Vanadium Alloys Steel Corporation, containing 0.55% C and 12% alloying element (Cr, W, Mo, V). The hardness response to tempering in the low-alloy ausform steel (300M) appears similar to that of the conventionally treated, except, of course, for the overall increase in hardness. The hardness v. tempering curves of the ausform medium and high-alloy steels are relatively flat, give no evidence of secondary hardening, and exhibit enhanced resistance to over-tempering. With respect to the latter, both steels over-temper at a temperature about 150°F above that of the conventionally treated steels.

The effect of tempering on other mechanical properties of type H-11 steel in the ausform and conventional condition is shown in Fig. 7. For this alloy, the yield and tensile strengths are almost constant over the entire tempering range. Also the ductility is largely retained to relatively low tempering temperatures.

It is readily apparent from Fig. 7 that the strength of conventional high hardenability martensitic steels can be increased as much as 125,000 lb/in^2 by the ausform process. The ductility of these steels at the higher strength levels is generally equal to or greater than the same steel conventionally heat-treated. At a tempering temperature of 1000°F, the hot-work die steel type H-11 containing 0.40% C has a tensile strength of 400,000 lb/in^2, a yield strength of 375,000 lb/in^2, a Rockwell hardness of C 63, uniform elongation of 8%, and a reduction of area of 40%, as shown in Fig. 7.

ENGINEERING PROPERTIES OF AUSFORM STEEL

Cryogenic and elevated temperature properties

The increased resistance of ausform steels to over-tempering suggests that their elevated temperature mechanical properties might also be improved. The results of several elevated temperature tensile tests on type H-11 steels are shown in Fig. 8. At all temperatures investigated the strength of the ausform steel was superior to that of the conventional.

Fatigue strength of ausform steel

Borik has studied the fatigue strength of ausform type H-11 steel as a function of processing history.(3) The details of this work will be described in a future publication; however, some recent results may be briefly summarized here.

Carefully polished specimens were tested on standard R. R. Moore machines at 10,000 complete stress reversals per minute. The endurance limits for 10^7 cycles of stress reversal were established for ausform and conventional type H-11, and conventional SAE 5160, as shown in Fig. 9. The endurance limits for the ausform steel represent the highest ever recorded for any known material. There is an improvement of about 20% in endurance limit for the ausform steel over its conventional counterpart.

Experimentally, it is known that the ratio of the fatigue endurance limit to the tensile strength of steels is about 0.5 for tensile strengths up to 250,000 lb/in^2. Above this strength level, the ratio decreases for most low-alloy steels, as shown in Fig. 10. The ratio remains high, however, for conventionally heat-treated type H-11 steel reflecting its excellent fatigue strength at 300,000 lb/in^2, and the ausform steel maintains a similar ratio at a strength level of 360,000 lb/in^2.

THE STRAIN AGING OF AUSFORM STEELS

The proportional limit and the yield strength of ausform steels can be significantly increased without loss of ductility by a strain aging treatment. The treatment consists of plastically straining the quenched and tempered ausform steel and then aging it at a temperature substantially lower than the prior tempering temperature.

Two ausform alloys are being investigated for their response to strain aging, viz., type H-11 steel and Ladish D6-AC. The latter is of special interest because of its relatively low alloy content (0.42% C, 0.72% Mn, 0.63% Ni, 1.05% Cr, 0.94% Mo, 0.08% V). The type H-11 steel in the form of rolled ausform sheet was purchased from Vanadium Alloy Steel Corporation, while the Ladish D6-AC steel was prepared by the authors in the form of both rolled sheet and forged bar.

The initial preparation of the Type H-11 steel consisted of 65 per cent deformation by rolling at a temperature of 1000°F. After quenching from the deformation temperature the steel was tempered twice at 1000°F for a total of four hours. After room temperature straining, all specimens were aged one hour at 500°F.

The response of Type H-11 steel to strain aging with varying amounts of strain is shown in Fig. 11. The proportional limit and yield strength of strained and aged ausform Type H-11 steel are increased by about 40 per cent and 15 per cent, respectively, for strains greater than 0.2 per cent. The ductility, as measured by reduction of area, is increased; this unexpected effect is most apparent at strains less than 0.5 per cent. The uniform elongation of ausform strained and aged steel is monotonically decreased with increased strain, as expected.

The partial stress-strain curves of strain aged and conventionally heat-treated ausform Type H-11 steel are shown in Fig. 12. The striking increase in proportional limit for the strained and aged specimen is clearly evident. Also obvious is the change in the rate of work hardening occasioned by strain aging. Although the proportional limit has been appreciably increased, the accompanying decrease in the rate of work hardening, as shown by the flat portion of the stress-strain curve, may be an undesirable feature in certain structural applications. In such instances, it may be preferable to increase the proportional limit and yield strength by plastically deforming one-half to one per cent without aging. The resultant increase in strength is not as great, of course, as that induced by strain aging. The mechanical properties of ausform Type H-11 in the conventional and strain aged condition, are summarized in Table I.

Table I

The Mechanical Properties of Strain Aged Ausform Type H-11 Steel

Condition	Proportional Limit, ksi	0.2% Offset Yield Stress, ksi	Ultimate Tensile Stress, ksi	Elongation in 2 inches, per cent	Reduction in area, per cent
Ausformed,* oil quenched, tempered (twice) at 1000°F for a total four hours	166	297	361	6.5	33.0
Same plus 0.20% strain, aged at 500°F for one hour	278	345	369	6.5	38.1
Same plus 1.10% strain, aged at 500°F for one hour	300	372	373	4.5	31.6
Same plus 1.74% strain, aged at 500°F for one hour	310	374	374	4.0	35.9

* Deformed 65% in the metastably austenitic state.

Much of the research effort, to date, on the mechanical properties of ausform steels has been on medium and high alloy steels. The relatively high alloy content of these steels, compared to that of plain carbon steels, is economically disadvantageous. The excellent response of a low alloy steel, Ladish D6-AC, to the ausform process is therefore of interest.

Rolled and forged Ladish D6-AC rod were deformed 50 and 55 per cent, respectively, in the metastably austenitic state, oil quenched, and double tempered. The yield and tensile strengths, and the proportional limit are — shown for various tempering temperatures in Fig. 13. Although the strain aging experiments are still in progress, it appears that proportional limits about 300,000 psi and yield strengths of about 325,000 psi are attainable for ausform specimens tempered at 400°F and appropriately strain aged. The uniform elongation and reduction in area of the ausform rolled sheet, tempered at 400°F, were 7 and 27 per cent, respectively. There would be, therefore, sufficient ductility after strain aging for many engineering applications of this steel.

MODES OF FABRICATION OF AUSFORM STEELS

A number of fabrication techniques shown listed in Table II have been evaluated for the production of ausform steels. In general, ausform steel produced by the various types of fabrication exhibited the same improvement in strength and ductility as that reported for rolling. The rate of deformation is an important processing variable, as shown in the extrusion studies of Faunce.(4)

Table II

Modes of Fabrication of Ausform Steels

Type	Shapes
Rolling	Rod, bar, plate, sheet
Extrusion	Rod
Shear spinning	Tubes (up to 13 in. dia.)
Forging (hammer)	
Explosive forming	Tubes (up to 3 in. dia.)
Deep drawing	Tubes (up to 12 in. dia.)

SUMMARY AND CONCLUSIONS

The current useful strength limit of steel, either in the patented cold-drawn or martensitic condition, appears to be of the order of 300,000 psi. A need exists for strengthening processes designed to substantially increase this limit without sacrificing ductility and toughness. One such thermal-mechanical process, called "ausforming" by its developer, the Ford Motor Co., is described.

The influence of several ausform process variables including those of deformation, deformation temperature, carbon content and tempering temperature is established. The unusual strength, ductility and fatigue resistance of steels produced by this process are described.

The proportional limit and yield strength of quenched and tempered ausform steels may be increased by straining, or by straining and subsequent aging. The ductility remaining after this post-ausform processing is adequate for many engineering applications.

Although some manufacturing aspects of the process are still in the developmental stage, no insuperable difficulties are presently foreseen that will bar the adoption of the process to parts requiring high tensile and fatigue strengths. The requisite precise control of ausform process variables, such as deformation, rate of deformation and deformation temperature implies that automated manufacturing procedures, much like those currently employed for making prestressed wire, are appropriate.

The anticipated demand for higher strength prestressed wire coupled with the proven ability of the ausform process to produce ductile steels with strengths in excess of 300,000 psi suggests that this process be given further consideration as a potential wire source.

Acknowledgment

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2. E. M. H. Lips and H. Van Zuilen, Met. Prog., 1954, <u>66</u>, 103.
3. F. Borik, Private communication.
4. R. Faunce, Private communication.

Figure Captions

1. The relationship between the equilibrium and isothermal transformation diagrams of a eutectoid steel.
2. The isothermal transformation diagram of a hot work die steel, Type H-11.
3. The dependence of the yield and tensile strength of a Type H-11 steel on the deformation temperature and the amount of deformation.
4. The dependence of the ductility of a Type H-11 steel on the deformation temperature and the amount of deformation.
5. The dependence of strength and ductility of ausform 3% Cr steels, deformed 91%, upon carbon content at a tempering temperature of 625°F.
6. The hardness dependence of ausform 300 M, Type H-11, and Vasco MA steels on tempering temperature.
7. The response to tempering of the mechanical properties of Type H-11 steel in the ausform and conventionally heat-treated conditions.
8. The cryogenic and elevated temperature strength and ductility of ausform and conventional Type H-11 steel.
9. The endurance limits of ausform Type H-11 steel and conventional Type H-11 and SAE 5160 steels at various survival levels.
10. The endurance limit-tensile strength ratio for several ausform and conventionally treated steels.
11. The effect of strain aging on the tensile properties of ausform Type H-11 steel, tempered at 1000°F, strained as indicated, and aged at 500°F.
12. Stress-strain curves for ausform (a) and strain aged ausform (b) steels. Ausform steel prepared by deforming 65% in austenitic state, quenching, and tempering at 1000°F. Strain aged specimen deformed 1.74% and aged at 500°F for one hour.
13. The mechanical properties of ausform Ladish D6-AC as a function of tempering temperature.

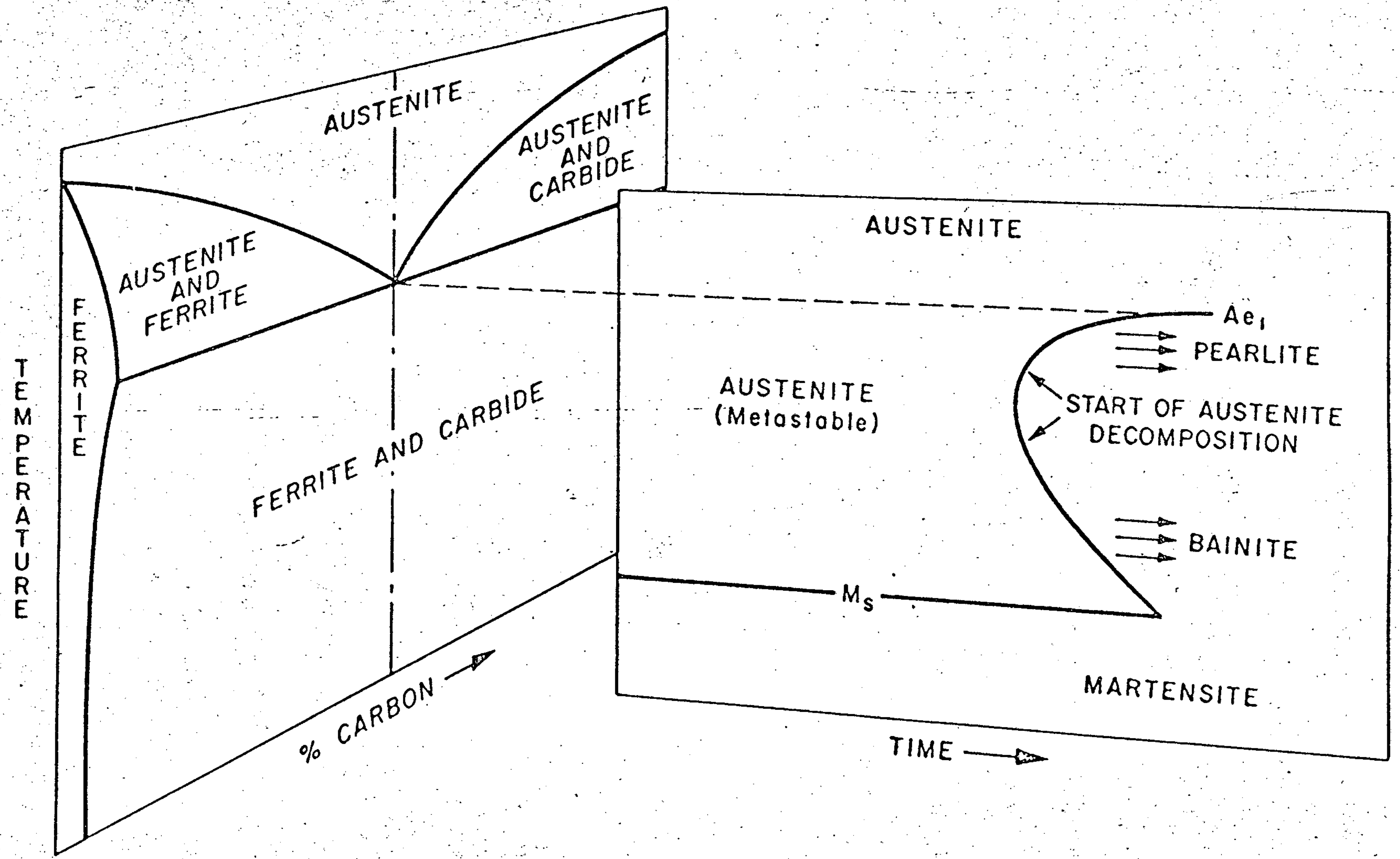

Fig. 1

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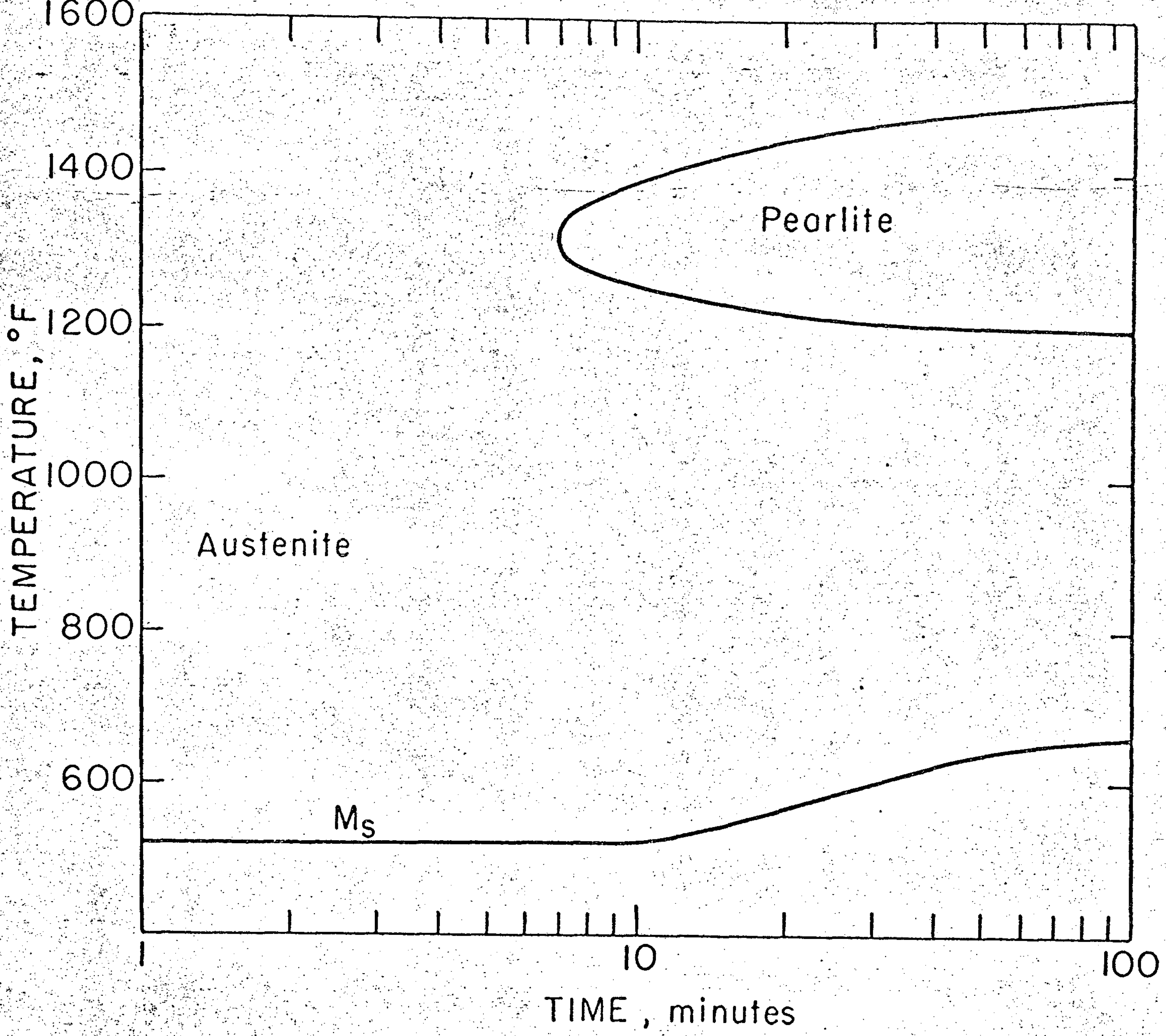

Fig. 2

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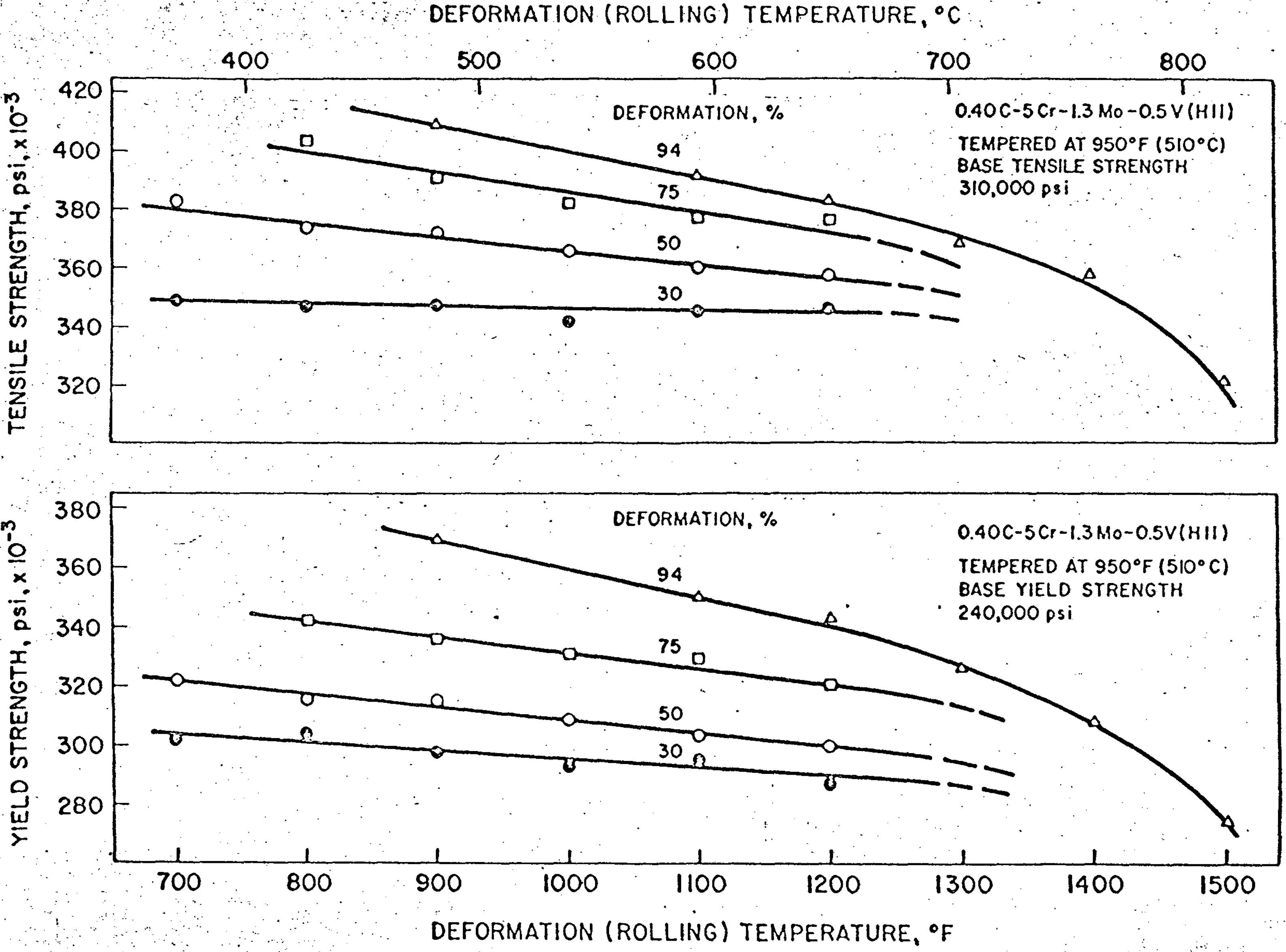

Fig. 3

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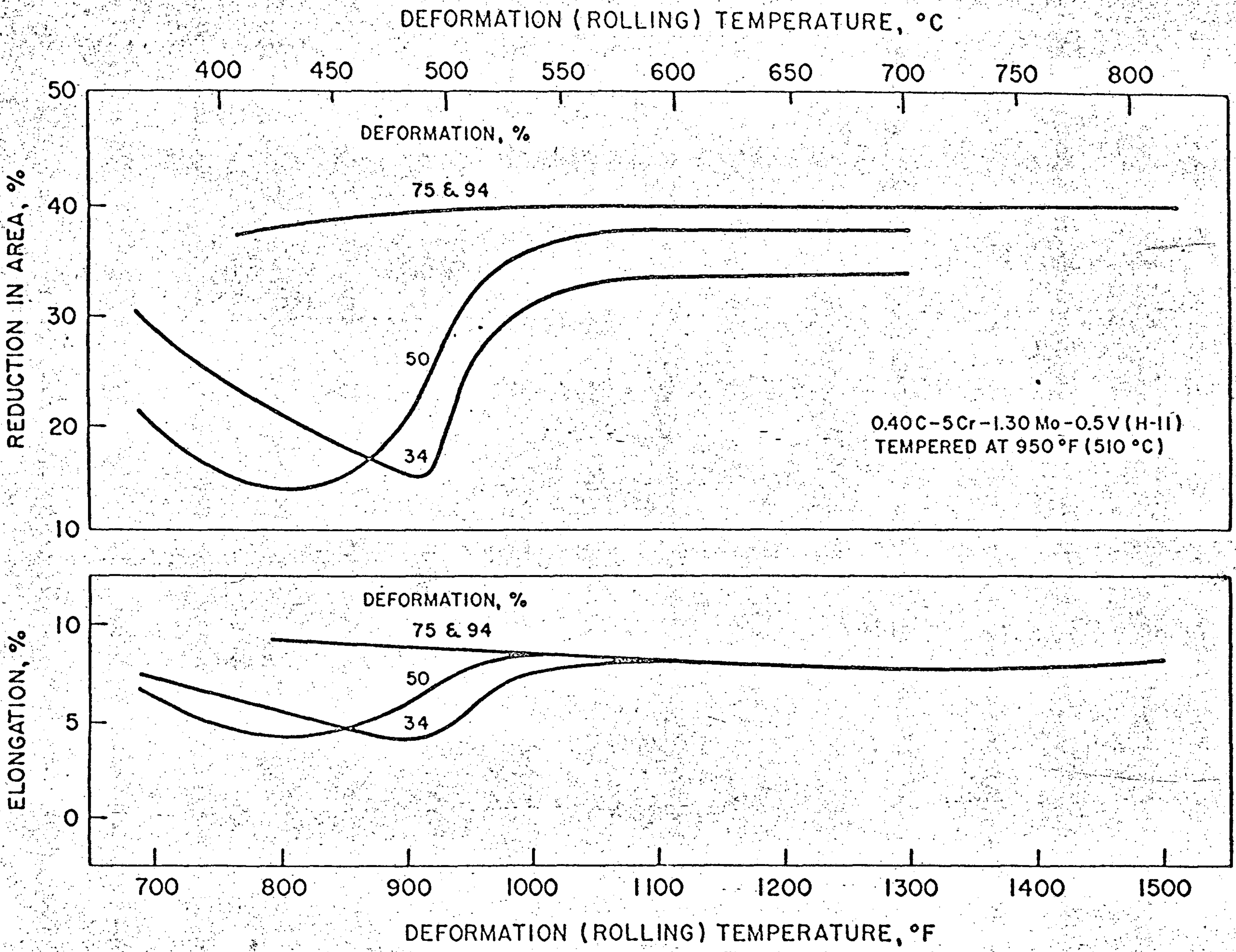

Fig. 4

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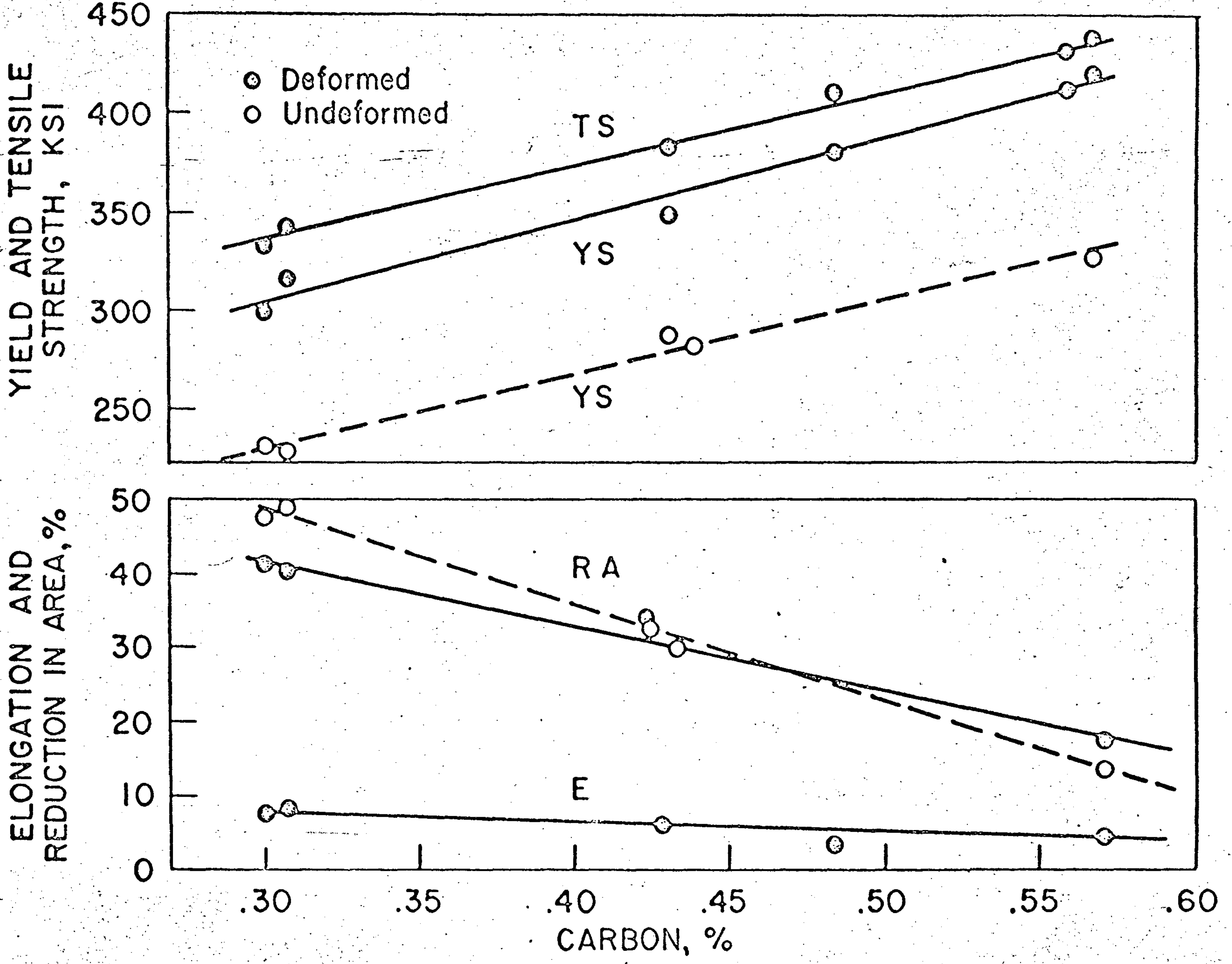

Fig. 5

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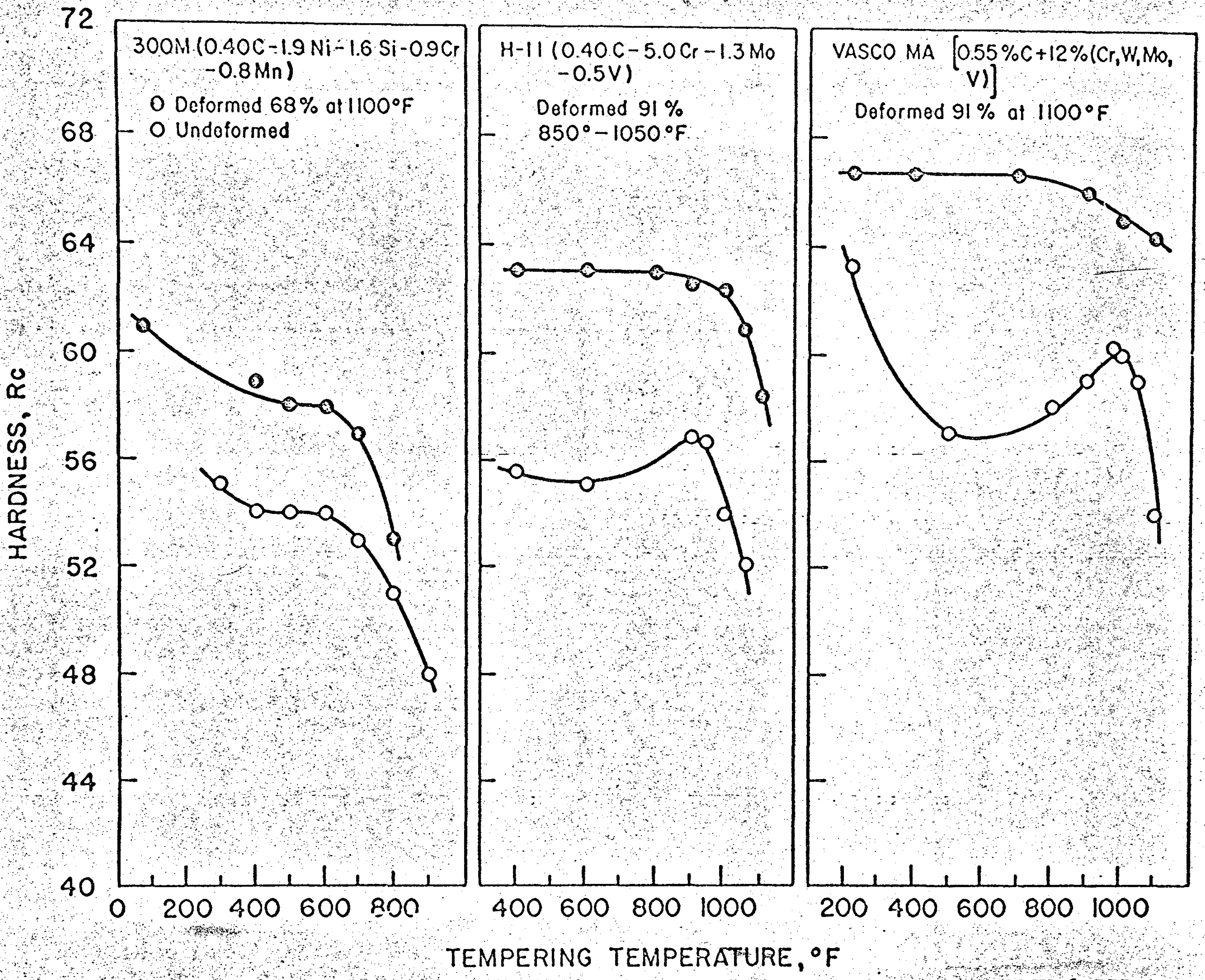

Fig. 6

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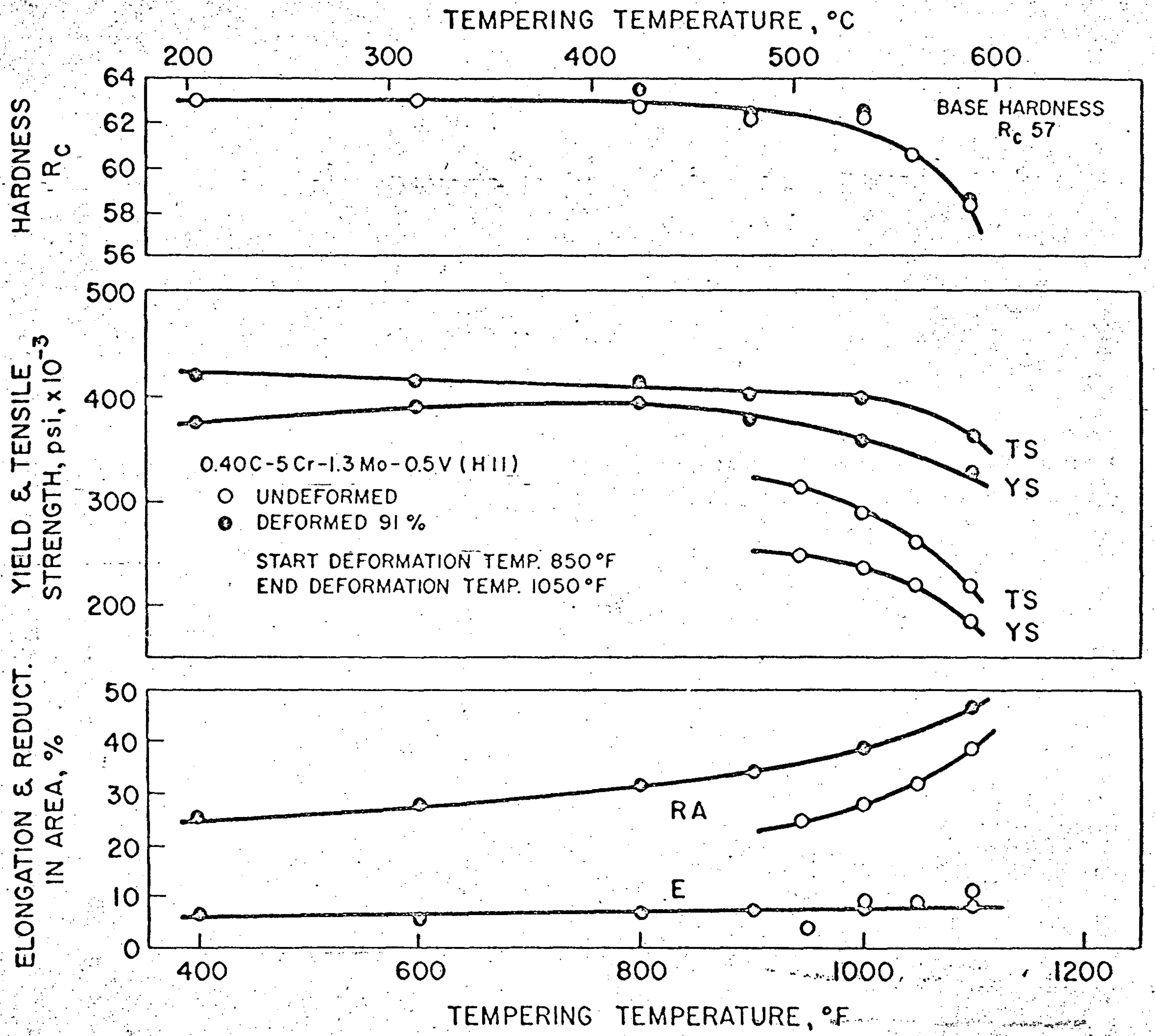

Fig. 7

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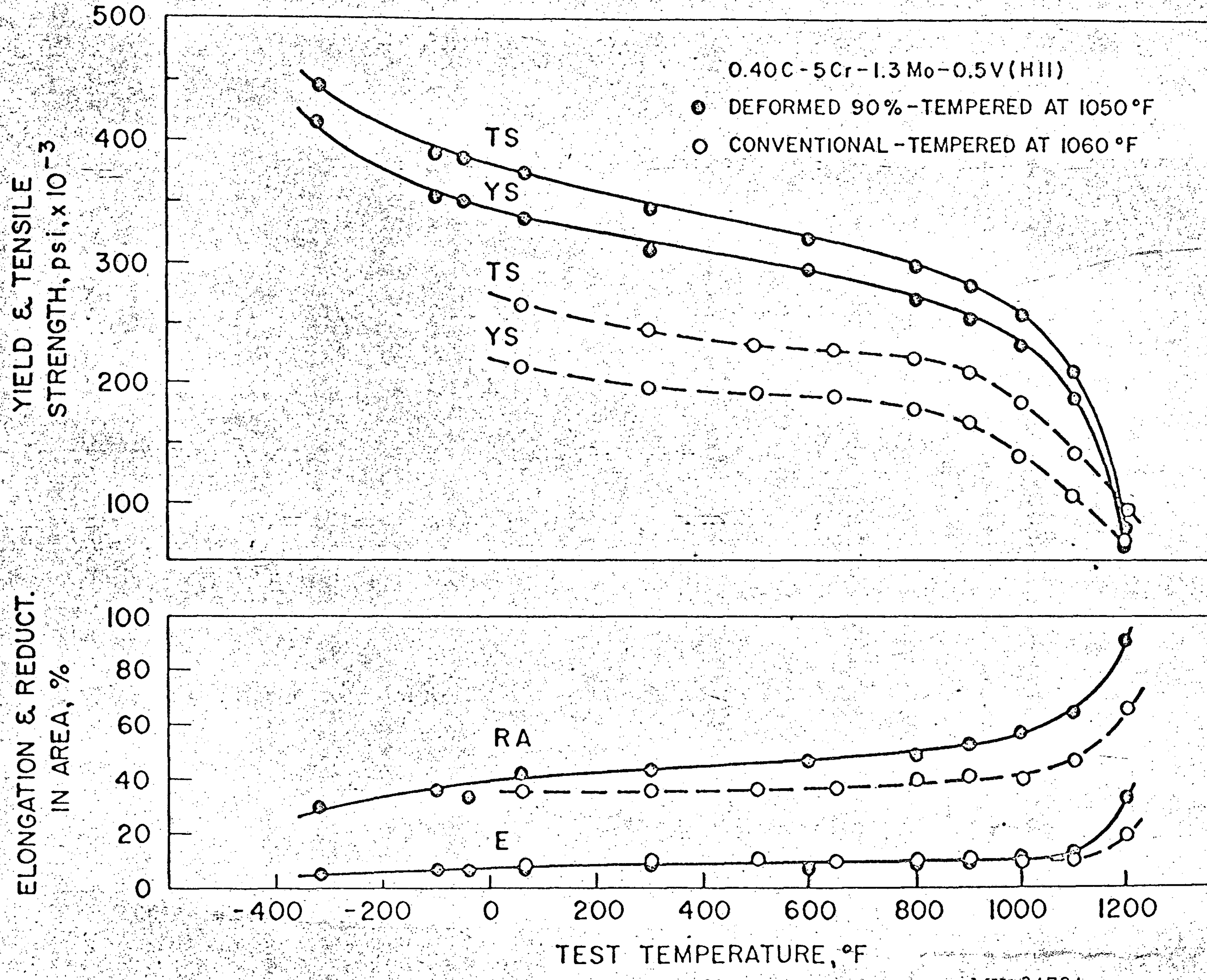

Fig. 8

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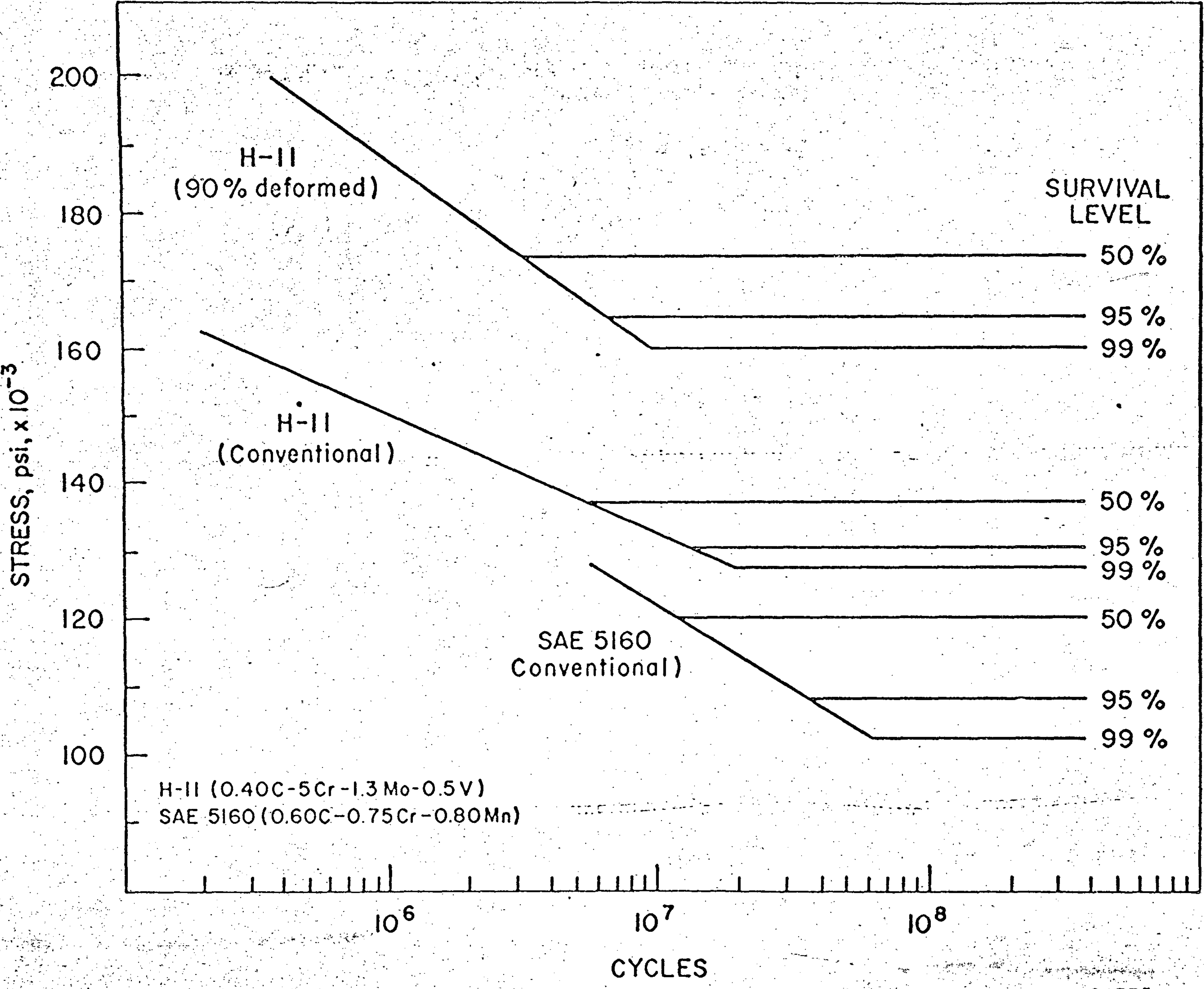

Fig. 9

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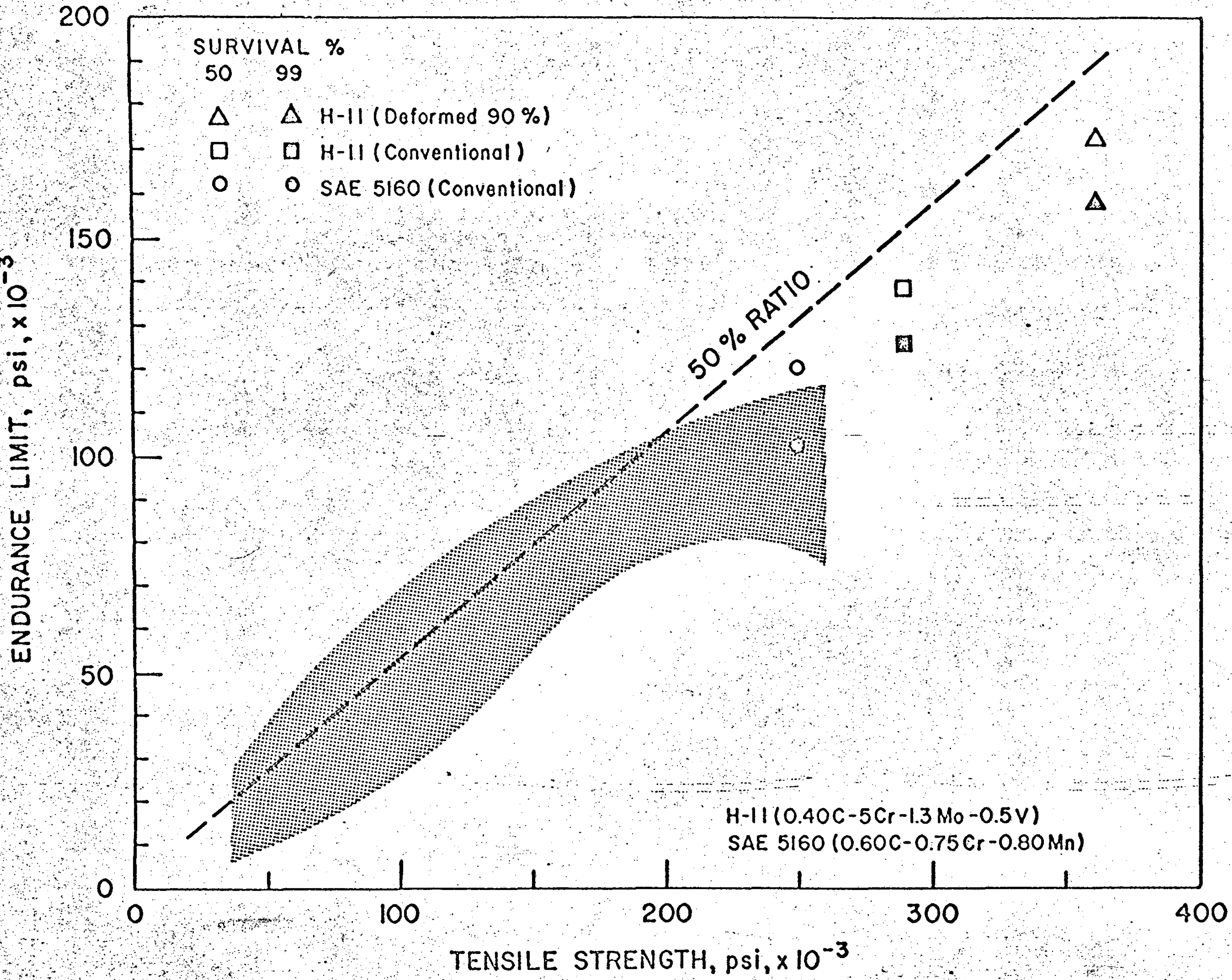

Fig. 10

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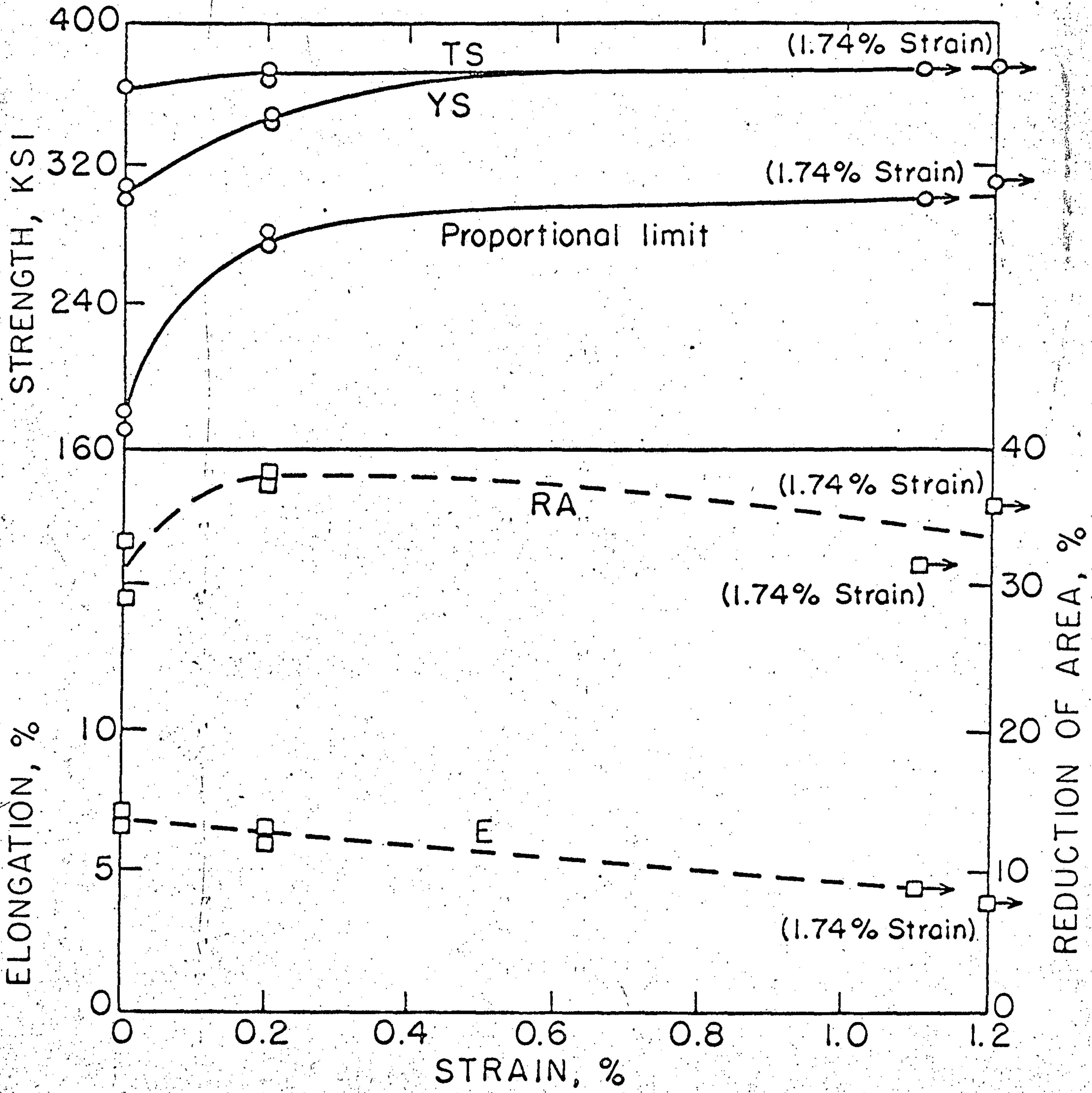

Fig. 11

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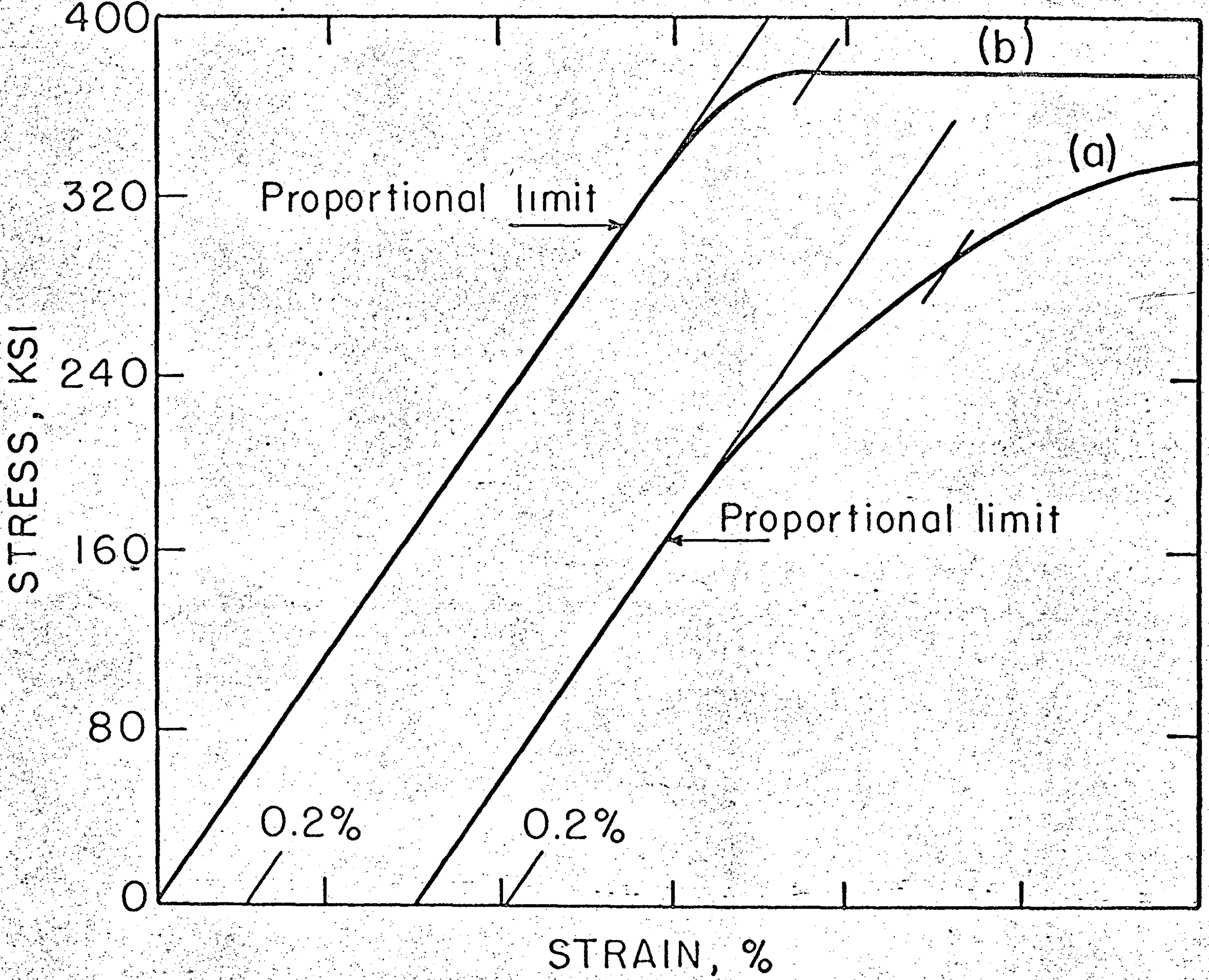

Fig. 12

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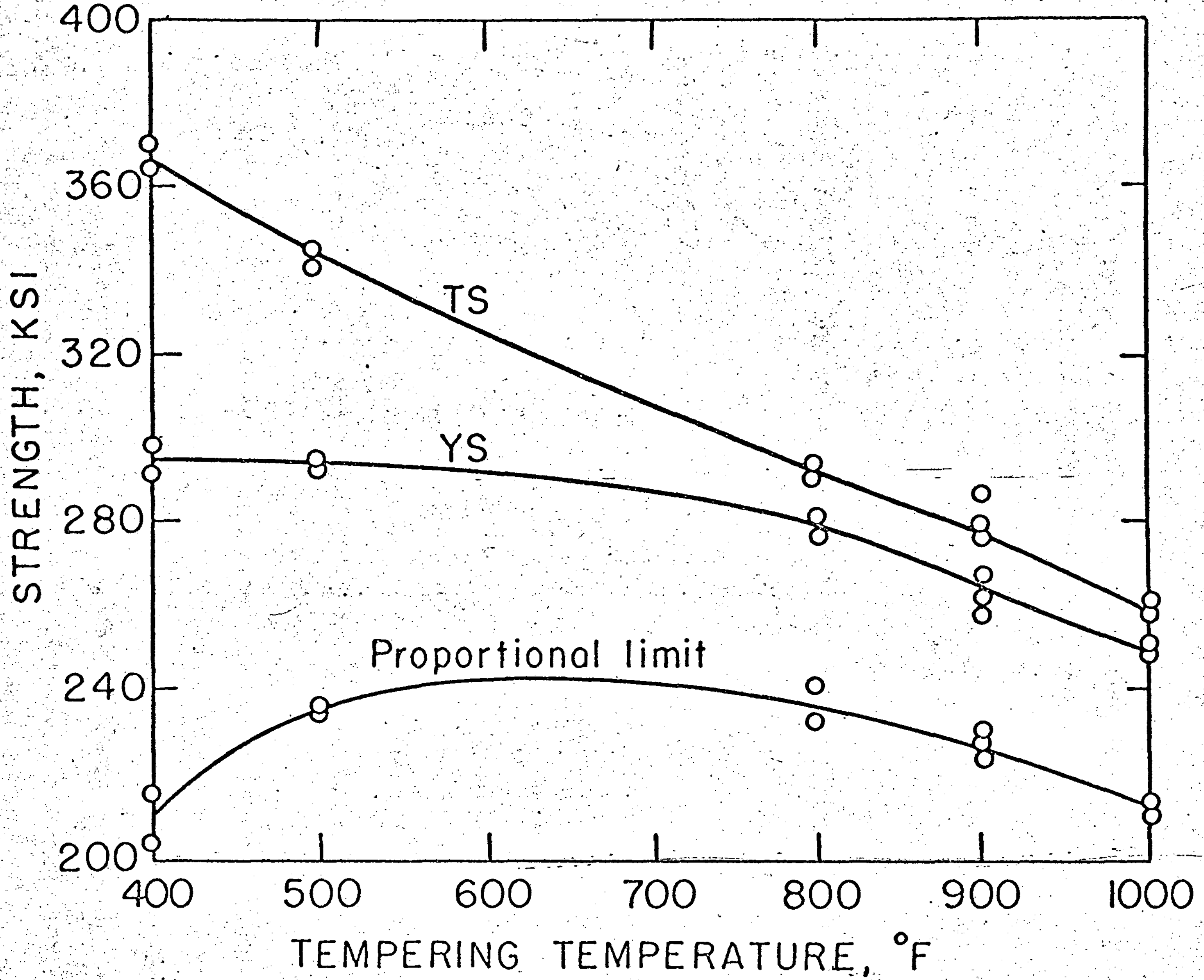

Fig. 13

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