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A COMPARISON OF STRENGTH PROPERTIES
OF HEAT TREATED AISI 1065 STEELS
AT HIGH STRENGTH LEVELS

BY

ROBERT L. HOLLENBECK -1938-

A

THESIS

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Approved by

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ABSTRACT

Six AISI C 1065 steels were heat treated and tensile tested in order to evaluate their ductility at high strength levels. Heat treating and tensile testing procedures were developed for use in working with these steels at tensile strengths of 300,000 psi and higher. The austenitizing procedure in the hardening operation was found to affect the strength and ductility of the high strength samples. Rapidly heating to the austenitizing temperature followed by an immediate quench produced better properties than slow heating followed by a soaking period before the quench. However, it was concluded that the carbon contents of the steels studied (0.64% - 0.72%) was too high to realize simultaneously very high strength and appreciable ductility.

ACKNOWLEDGEMENT

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The author also wishes to express his gratitude to Interlake Steel Corporation of Chicago, Illinois for donation of the steel used in this study.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES Page

LIST OF TABLES

I. INTRODUCTION

A study aimed at investigating the ductility of high strength plain carbon steels was undertaken. Six steels of the AISI C 1065 grade with carbon contents between 0.64% and 0.72% were studied.

Stronger materials are constantly required to meet the demands of modern technology. Often where high strength is required, alloy steels must be used because the particular application demands certain qualities such as high toughness, retention of strength at high temperature, corrosion resistance, weldability, etc. However, there are applications where high strength is required and the other requirements are less stringent. From the standpoint of economics in material usage, it is worthwhile to investigate plain carbon steels in order to determine their maximum useable tensile strength.

Plain carbon steels are commonly used in the slow cooled condition. In this study where very high tensile strength, 300 ksi (thousands of pounds per square inch) and higher, are of interest, the quenched and tempered condition was studied.

Chien (1)[1] and Kisslinger (2) have studied high strength, heat treated, plain carbon steels and found that tensile strengths of 300 ksi or higher can be obtained, but that some heats of steel lose their ductility when heat treated to high hardness.

The six steels that were available at the start of this work were studied in order to develop a heat treating procedure that would produce their best properties and to determine which, if any, of these steels was ductile at very high strength levels.

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[1] Numbers in parentheses refer to bibliographical entries.

II. LITERATURE REVIEW

A. TEMPERING OF MARTENSITE

Tempering of martensite has been a subject of importance to steel users since the discovery of the allotropic nature of iron. Light microscope and X-ray work served to remove much of the mystery of the hardening and subsequent tempering process of martensite. Not until the early 1950's, however, was much of the true mechanism revealed and adequately explained. In the early 1950's with the initiation of widespread use of the electron microscope, new in-roads were made to understanding the tempering process. Some discussion of the advances reported in the literature is considered necessary.

While there exist conflicting opinions concerning the exact nature of the tempering process, it is still customary to distinguish three general stages in tempering steels:

1. Decomposition of martensite and formation of epsilon carbide
2. Transformation of retained austenite
3. Transition of epsilon carbide to cementite.

In much of the literature attention is concentrated on the first and third stages, but no marked distinction is made.

Kelly and Nutting (3) show that the shear transformation of super-saturated austenite gives rise to two types of martensite: low-carbon martensite is in the form of needles or laths containing dense dislocation networks, while high-carbon martensite is in the form of internally twinned plates. Both of these substructures are known to exist simultaneously in quenched steels throughout the range of carbon contents. The extent to which either would exist in a steel of the carbon content being studied (approximately 0.70%) could conceivably be dependent on the degree of homogenization achieved in the austenitizing operation. How these substructures relate to the tempering process and subsequently affect the strength in quenched steels is discussed in the literature.

Tekin and Kelly (4) in their work with a twinned or high carbon form of martensite found that tempering occurred at temperatures as low as 70°F (20°C). Although too undeveloped to be definitely defined as carbide, they observed what appeared to be a precipitate lying between the twins after 18 months tempering. For more practical tempering times (25 hours) a precipitate first appeared at the temperature of 210°F (100°C), but it was not definitely identified. After tempering at 300°F (150°C) for 2 hours, this precipitate was identified as epsilon carbide by diffraction methods. They found that the epsilon carbide began to disappear when tempering was carried out at 390°F (200°C) and, simultaneously, cementite began to appear. This change from epsilon carbide to cementite did not occur as a direct transition, but the cementite precipitated at locations different from those of the original epsilon carbide. This last finding was corroborated by Eguchi et al (5) in transmission electron microscope work with a steel containing 0.40% carbon; however, Eguchi observed that epsilon carbide dissolved completely below 570°F (300°C) before cementite first appeared at 610°F (320°C).

In some of the earlier work, Lement et al (6) determined that the temperature ranges over which the carbide phases existed in the early stages of tempering overlapped. Working with high purity steels they indicated, in the case of a 0.80% carbon content, that the first stage of tempering ended at 350 to 400°F (175 to 200°C). Thereafter, progressive solution of the epsilon carbide network occurred in the third stage of tempering at 450 to 500°F (230 to 260°C). This solution of epsilon carbide occurred simultaneously with formation of cementite platelets and globules within the martensite subgrains and films at the subgrain boundaries. At least some overlapping of the existence of epsilon carbide and cementite, then, was indicated; whereas, Eguchi had noted a separation of the temperature ranges over which the two carbides existed.

In regard to the observation by Lement and his coworkers, it should be noted that they did not have the advantage of transmission microscopy techniques for their investigations and that use of replicas may not have revealed the specific nature of the carbides. Also, composition is known to affect carbide formation characteristics and could have been responsible for the varying observations.

Reisdorf (7) and Baker et al (8) have observed a marked retarding of carbide precipitation in high silicon steels at low tempering temperatures. Other elements have an effect on tempering rates, but no other element has been singled out which shows the marked retarding effect that silicon shows at low temperatures. Some evidence exists that indicates silicon is combined in the epsilon carbide. (7) Such being the case, silicon content could well be a controlling factor in the rate of dissolution of epsilon carbide.

The three stages of tempering stated at the beginning are a general discription of tempering martensite in the low temperature range. A more detailed description seems possible of the low temperature tempering process that can be expected in steels such as those in the AISI C 1065 grade being studied, because recent studies using the electron microscope have provided increased understanding of the nature of carbide formation in martensite.

The nature of carbide formation at low tempering temperatures is generally agreed upon. (3),(4),(5),(8) Agreement is less obvious with regard to temperatures at which the various carbides appear or disappear. The variation in compositions studied and in experimental techniques probably accounts, to some extent, for the disagreement on temperatures at which carbides appear and disappear.

As previously mentioned, both a twinned and a dislocation substructure can be present in a quenched plain carbon steel in the 0.70% carbon range, but a greater percentage of the twinned substructure is expected to be present. Tempering a twinned substructure in the vicinity of 400°F (200°C) can be expected to form a network of fine epsilon carbides lying in a direction across the twinned plates. At this same temperature the first cementite precipitates can be expected to appear along the twin boundaries. Tempering at higher temperatures of 500 to 570°F (260 to 300°C) can be expected to enlarge the cementite precipitates formed along the twin boundaries and to completely dissolve the epsilon carbides lying across the twins. Tempering at 750°F (400°C) should reduce the number of cementite precipitates, slightly enlarge the surviving precipitates, and reduce the number of twins present.

Any dislocation-substructured martensite present in a plain high carbon steel would be most affected in the temperature range below 500°F (260°C) where recovery would decrease the intensity of the dislocation tangles.

B. STRENGTHENING OF MARTENSITE

The precise mechanisms which influence the strength of martensite are perhaps no better understood than the tempering mechanisms. Much of the uncertainty stems from the multiplicity of factors available to produce strengthening and from the probability that many of these factors can be additive or cancelling when combined.

Kelly and Nutting (9) have studied the contribution that various factors make to hardness in martensite. Working with plain carbon steels of 0.20 and 0.80% carbon and iron-nickel-carbon alloys of 0.20 and 0.80% carbon, they were able to draw certain conclusions regarding the role of carbon in strengthening, as determined by hardness. They presented evidence showing that carbon in solid solution accounts for only about half of the strength observed in a fully hardened 0.80% carbon steel. It was assumed, then, that a large portion of the additional strength observed in martensite was provided by some form of carbide segregate and matrix substructure.

Carbide segregation is exceedingly dependent on carbon concentration and is manifest as precipitates in relation to either internal twins which predominate in high-carbon martensite or to dislocations which predominate in the needles or laths of low-carbon martensite. The internally twinned substructure in a plain carbon steel in the 0.70% carbon range is believed to affect strength properties more than is the dislocation substructure because of its affect on carbide morphology.

Carbide morphology was discussed in the previous section with regard to the early stages of tempering of high carbon steels. Various investigators (3),(4),(5),(8) have reported experimental data verifying the formation of carbides during tempering which lie both along twin boundaries and across the twinned plates. Twin boundary precipitates restrict the movement of dislocations and act as barriers to slip. For twinned martensite to deform, a slip system must be operative such that both the slip plane and slip direction are common to a pair of twinned plates. When carbide precipitates lie across, in addition to along the twin direction, they lock the only remaining deformation system. This presumably accounts for much of the hardness of high-carbon martensite after tempering in the region of 400°F (200°C). Kelly and Nutting (3) propose that the softening noted in the 400 to 750°F (200 to 400°C) range does not result from carbide growth, rather to removal of twins.

Hardening of dislocation-substructured, low-carbon martensite seems to occur by a mechanism quite different than that for twinned, high-carbon martensite. Experimental evidence (9) has shown that autotempering (carbide precipitation during the quench) is prevalent in plain, low carbon steels. The temperature at which a low-carbon austenite begins to transform to martensite is relatively high in comparison to the low range tempering temperatures. This is believed to promote the formation of a high density of fine carbides, because the density of the dislocations is high in this newly formed martensite and mobility of the dislocations is relatively high at the Ms temperature. As the dislocations sweep through the material, opportunity is provided for forming many nucleation sites. Thus, a high density of finely dispersed carbides is possible which would have a strengthening effect on the martensite. Work reported by Kelly and Nutting (9) showed autotempered martensite to be significantly harder than virgin martensite (carbon completely in solid solution) of the low-carbon type after both have been tempered in the same manner.

The strength of any steel is seen to result from a combination of various factors. Carbon solid solution strengthening accounts for approximately half of the strength of martensite tempered at low temperature. A large portion of the additional strength is due to carbide precipitates both of a coherent and noncoherent nature with dispersions commensurate with the particular substructure -- dislocations or internal twinning. Grain size and elements in substitutional solid solution are considered to play a relatively minor role. (9)

Carbon is known to have a greater hardening effect in the twinned substructure, both in solid solution and as carbide precipitate. Therefore, it is important to consider the degree of achievement of a twinned substructure in a given steel.

Austenite with 0.50% or higher carbon is considered necessary to produce a predominantly twinned martensite. The extent to which this substructure would be achieved in a 0.70% carbon, plain carbon steel should depend largely on the degree of homogenization achieved in the austenitizing treatment.

The Bain (10) and Osborn (11) studies on rates of carbon movement in spherodized and lamellar pearlitic steels indicate that approximately $\frac{1}{4}$-second is all the time that is required for carbon to diffuse the half lamellar distance in a coarse pearlite during austenitizing. Using a 0.68% carbon steel Mima and Hori (12) found that the hardness of martensite, formed from austenite which had been isothermally transformed from lamellar pearlite, was markedly dependent on austenitizing temperature and time. Approximately 40 seconds were required to develop full hardness at 1380°F (750°C) as compared to 2 seconds at 1470°F (800°C) and 1 second at 1560°F (850°C). Additionally, they showed that the time to completely austenitize lamellar pearlite at 1380°F is approximately 300 seconds and at 1470°F the time is 100 seconds.

III. EXPERIMENTAL PROCEDURE

A. STEELS STUDIED

Six coils of 3/4-inch wide by 0.035 inch thick steel strip were donated by Interlake Steel Corporation. Each of the six coils was taken from a different heat of steel approximating the AISI C 1065 composition range. The compositions provided by the supplier are listed in Table I.

Table I. Compositions Of Steels Studied.

Steel No.	1	2	3	4	5	6
% C	0.70	0.71	0.65	0.72	0.64	0.76
% Mn	.80	.68	.70	.67	.66	.75
% P	.009	.020	.014	.014	.014	.016
% S	.016	.040	.013	.008	.012	.012
% Si	.05	.04	.05	.05	.05	.05
% Cu	.01	.01	.01	.01	.01	.01
% Ni	.01	.01	.01	.01	.01	.01
% Cr	.01	.01	.01	.01	.01	.01
% Mo	.009	.005	.009	.005	.005	.005
% Sn	.020	.006	.008	.008	.007	.008
% Al	0.005	0.005	0.005	0.005	0.005	0.005

These steels were described as "semi-killed" and were hot rolled.

Metallographic examination revealed that the microstructures of the steels as-received were essentially completely pearlitic. Some proeutectoid ferrite was observed in Steels No. 3 and 5 which were slightly lower in carbon content relative to the other steels. A very thin, discontinuous layer of light etching ferrite was observed at the exterior surfaces of the strips. This indicated that some decarburization had occurred during hot rolling.

B. SAMPLE PREPARATION

1. Tensile

Samples were cut with a mechanical shear and identified by stamping appropriate numbers near one end. Samples were cut to two lengths: 8 inches and 10 inches. The 10-inch sample was used for tensile tests in all except some of the preliminary work to establish heat treating guidelines. The greater length permitted more accurate measurement of elongation. No surface preparation was performed since the material was received with smooth, uniformly oxidized surfaces.

Approximately 20 samples were tested with reduced sections machined to a width of ½-inch. Only these few samples were tested with reduced sections because no improvement was apparent in their test results. All other specimens reported in this thesis were straight strip samples with no reduced section.

2. Hardness

All of the tensile samples were tested for hardness with a Rockwell hardness testing machine. The ends of the samples were ground on a belt grinder before making hardness tests. These ground areas were in or beyond that portion of the sample gripped by the jaws during testing.

Some preliminary quenching experiments were done on 5-inch long samples. These were used for comparing different quench media and were hardness tested along their full length. No tensile tests were made on these samples.

Samples for microhardness testing were mounted and metallographically polished. A Kentron hardness testing machine with a Knoop indentor and 100 gram load was used.

C. HARDENING

1. Slow Heating

Samples were hardened by austenitizing in a preheated box type furnace and quenching in warm oil. A protective atmosphere was not used in the furnace.

The furnace was a Hevi-Duty electrically heated, resistance type furnace with internal dimensions: 8½ inches high, 13 inches wide, and 41 inches deep. Temperature was controlled by means of a variable temperature-band Wheelco controller which was found to maintain temperature to ±3°F at any given point in the work area. The maximum temperature variation along the length of a 10-inch sample was approximately 8°F.

Temperature was continuously monitored with a strip-chart recorder connected to a thermocouple with its hot junction placed on the hearth near the center of the sample. The recorder was checked against a portable potentiometer using the same thermocouple and a double-pole, double-throw switch connected to the thermocouple leads.

The oil quench bath was heated on a hotplate and maintained at 140 ±15°F.

A wire loop was attached to each sample to facilitate handling. The specimens were placed individually in the furnace on the clean hearth and removed individually for quenching.

2. Rapid Heating

Rapid heating during austenization was achieved by placing samples in the furnace when its temperature was higher than the desired austenitizing temperature. The temperature of the sample was continuously monitored during heating. As soon as the sample reached the desired austenitizing temperature, it was quickly removed from the hot furnace and quenched.

Special sample holders were prepared to implement the rapid heating. The holders were prepared by attaching thermocouple insulators to 3-foot long by 5/32-inch diameter steel rods. Chromel and alumel thermocouple wires were threaded through the insulators and used to hold the sample. One thermocouple wire was welded to each end of the sample. Thus, the sample was suspended by the wires and served as the hot junction of the thermocouple. Compensated lead wire was connected to the thermocouple wires at the handle end of the holder. The other ends of the lead wire were connected to a potentiometer. Temperature could be continuously monitored with this type holder as the sample heated.

The same box type furnace was used for both rapid and slow heating. However, the rapid heating procedure necessitated leaving the door up (partially open) approximately one inch while the sample was heating. Brick baffles were placed in the furnace between the open door and the area used for heating the samples in order to maintain a uniform temperature. The temperature within the heating chamber was found to vary no more than approximately 12°F with this arrangement.

The temperature of the furnace near the middle of the sample was monitored with a thermocouple and the recorder during the rapid heating experiments.

D. TEMPERING

Prior to tempering, loose scale and oil from the quench bath were wiped off the samples and some of the samples were checked on an area near their ends with a Rockwell hardness testing machine to insure that proper hardening had been achieved.

Tempering at the 350 and 400°F temperatures was performed in an oil bath tempering furnace. Temperature was found to be uniform throughout the oil bath and to vary ±3°F from the desired temperature during the control cycle.

Tempering at temperatures above 400°F was performed in a forced-circulation air furnace. Temperature variation was ±5°F from the desired temperature during the control cycle and the variation with position was negligible.

All samples were tempered on the same day that they were hardened unless specifically noted otherwise.

E. TENSILE TESTING

Static tensile testing was performed using a Baldwin hydraulic universal testing machine which was equipped with Templin grips. The machine had a load capacity of 20,000 pounds. The high range on this machine, full scale equal to 20,000 pounds load, was used for testing all of the tensile specimens since the loads required to break them were near 9,000 pounds.

For the majority of the tests, the jaws used to pull the samples were of a design with one gripping surface rigid and the opposite gripping surface free to rotate approximately 10 degrees about the sample axis. In this configuration a uniform "bite" was possible on the sample. The pulling bars were equipped with ball and socket joints to minimize any tendency to bend the samples during loading.

The regular jaws described above would not hold samples which were harder than about Rockwell C57 and these samples slipped during loading. A set of old jaws was modified to allow an insert cut from a file to grip the harder samples. A portion of the solid jaw was ground down to accommodate the insert (see Figure 1). In this manner with a coarse file as one of the gripping surfaces, the harder samples could be pulled.

For all except the softest samples, an expanding device was frequently necessary to set the jaw teeth into the sample before applying any load. The expanding device was merely a machine bolt brazed to a steel strap. By placing the head of the bolt on the butts of the jaws, as shown in Figure 2, and unscrewing the nut, the jaws were forced along the tapered slides in the grip assembly and forced to clamp the sample.

Load was applied to the sample at a rate of approximately 1500 pounds per minute. Testing was performed at room temperature.

F. ELONGATION

Prior to tensile testing, each sample was scribe marked. Lines were scribed across the sample at ½-inch intervals. A special templet which could be attached to the samples was made to facilitate this work.

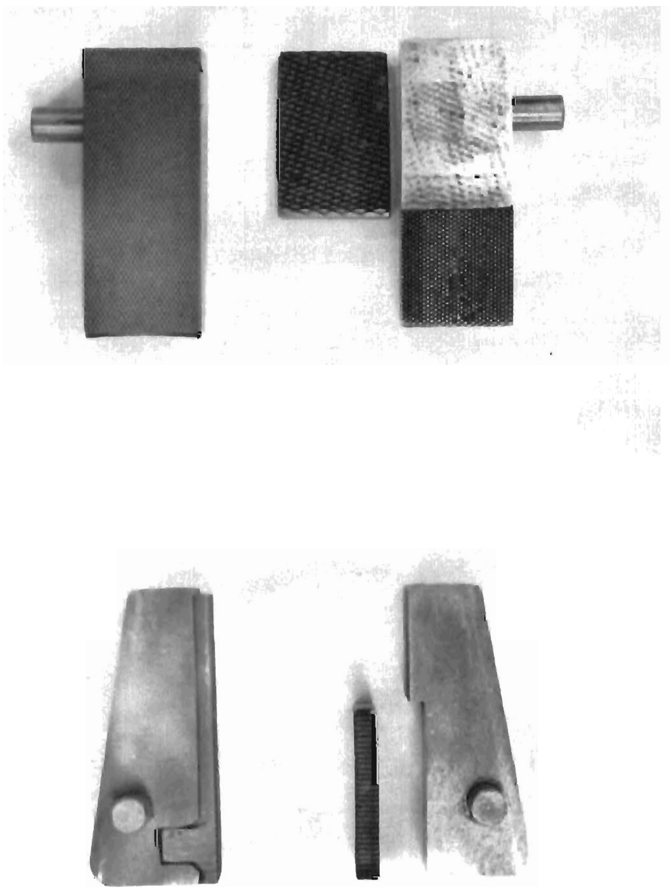

Figure 1. Modified Jaws: Top Shows Serrated Gripping Surfaces Without File Insert In Place On the Modified Solid Jaw, Bottom Shows Depth Of Ground-Out Portion Of Solid Jaw To Accommodate A File Insert.

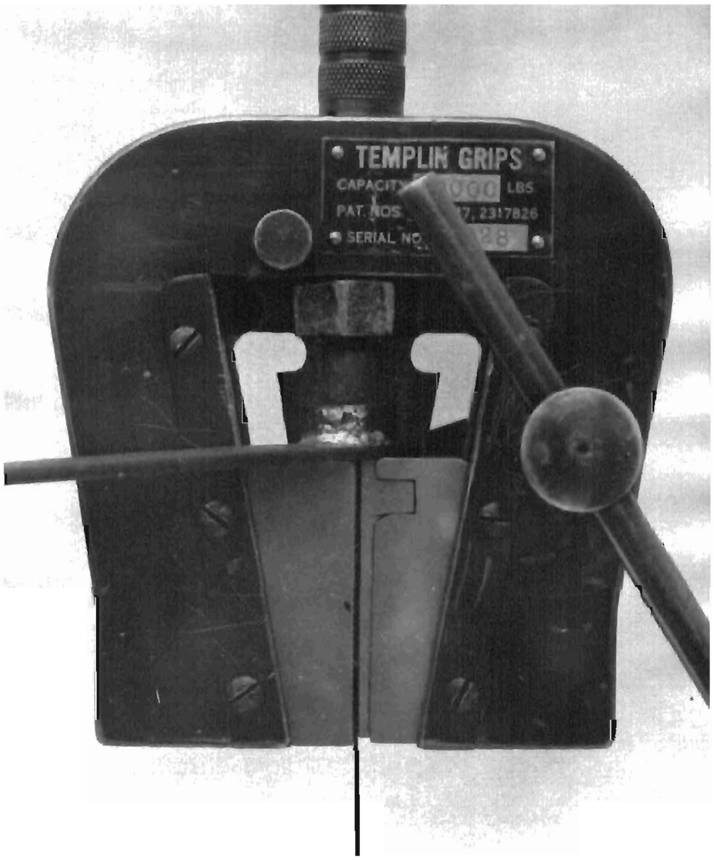

Figure 2. Templin Grip Assembly With Expanding Device In Place Against Butts Of Jaws.

After tensile testing, elongation was measured on the broken sample using a beam trammel and a metal scale with 0.01 inch divisions. The longest distance between two scribed lines on the larger piece of the tested sample was measured and used to calculate elongation. The elongation did not include the fracture nor the localized deformation near the fracture. Therefore, all elongation data reported are uniform elongation outside the fracture area of the sample.

IV. RESULTS

A. STRENGTH PROPERTIES WITH SLOW HEATING

1. Hardness

Steel No. 5 was used in a preliminary study which determined the effect of austenitizing temperature and quenching medium on the hardening operation. Samples were austenitized for 15 minutes at temperatures ranging from 1425 to 1525°F and quenched with three different media: tap water at 70°F, oil at 70°F, and oil at 140°F.

Table II shows the average hardnesses found in these samples. Hardness was measured at five points along the length of each sample. Quenching in oil at 140°F produced the most uniform hardness throughout the range of temperatures studied. Quenching in water at 70°F produced the least uniform hardness. The variation of hardness along the length of these samples is shown in Figure 3. The more uniform hardness of the samples quenched in the warm oil is apparent in this figure.

The individual hardness values varied between Rockwell C63 and C66 for the samples quenched in oil at 140°F while they varied between C62.5 and C67 for the samples quenched in oil at 70°F. The water quenched samples had hardnesses between Rockwell C57 and C66. However, the water quenched samples that had been austenitized at 1425 and 1475°F were relatively uniform with hardness spreads of only about three points on the Rockwell C-scale.

The reason for the greater variation of hardness in some samples quenched in water is not known. This variation was observed in two separate runs. Water was ruled out as a suitable quenching medium on

Table II. Effect Of Quench Media And Austenitizing Temperatures On Average Hardness Of Steel No. 5

Quench Medium	Rockwell C Hardness Austenitizing Temperature				
	1425°F	1450°F	1475°F	1500°F	1525°F
Oil (140°F)	64.0	64.5	64.5	64.0	64.0
Oil (70°F)	65.0	65.5	65.0	63.5	63.5
Water (70°F)	64.5	60.5	64.5	62.0	62.5

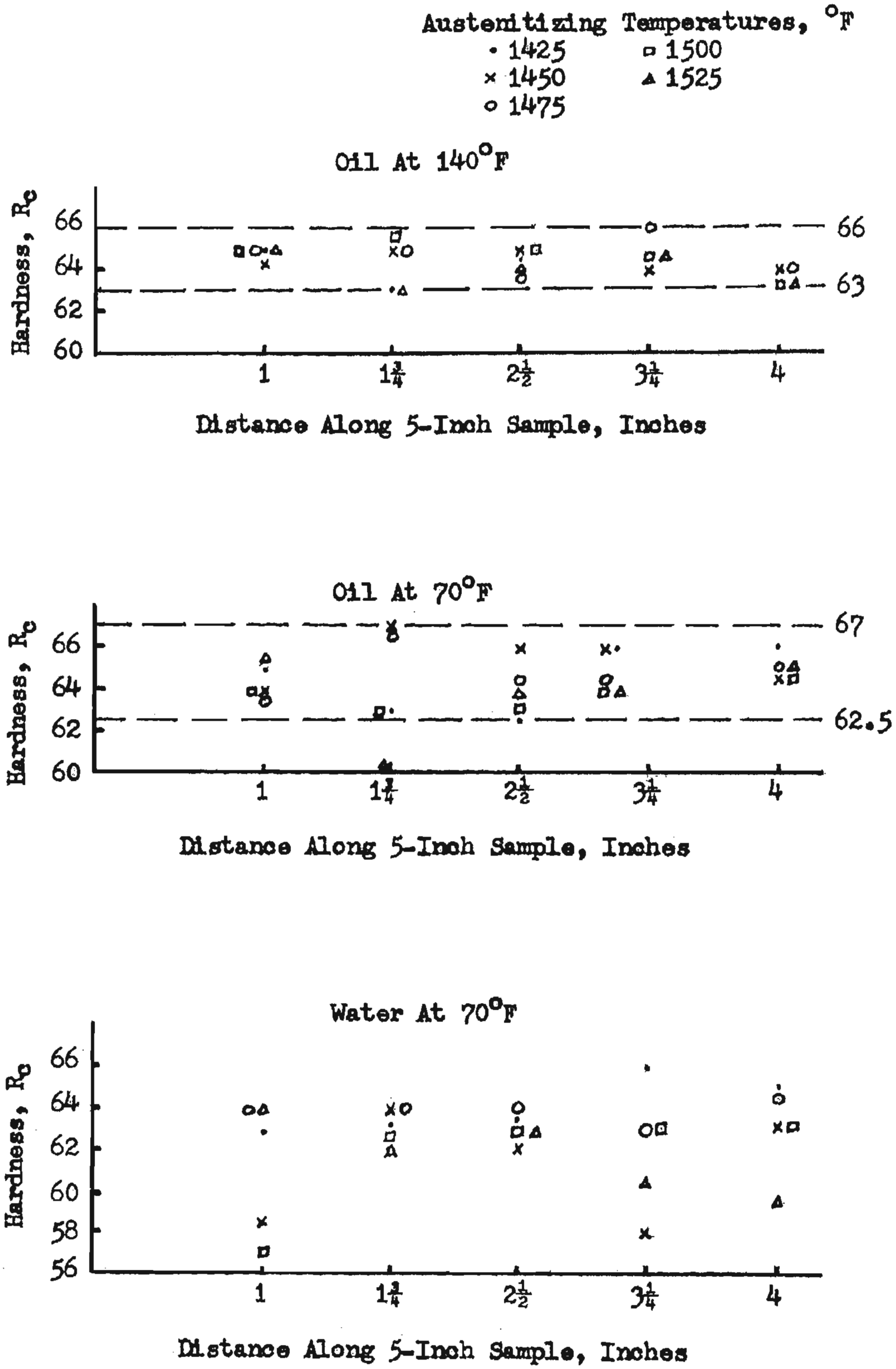

Figure 3. Hardnesses Of Samples Of Steel No. 5 Quenched From Various Austenitizing Temperatures Into 70°F Oil, 140°F Oil And 70°F Water.

the basis of these results.

Oil at both of the temperatures studied was able to produce maximum hardness, but oil at 140°F was selected for use in the later work because it seemed to produce a more uniform hardness.

During the course of the later work, all six steels were found to develop maximum hardness when quenched in oil at 140°F. Samples were spot checked before tempering and were consistently found to have hardnesses of Rockwell C62 or higher.

2. Tensile Strength And Ductility

a. Exploratory Treatments. Table III shows the results of exploratory hardening and tempering treatments of the six steels. This work was intended primarily to determine which of the six steels was relatively ductile when heat treated to high tensile strengths. For this work samples were austenitized at 1500°F for 15 minutes and quenched in warm oil. This austenitizing treatment was used to insure that proper hardening would be achieved in all of the steels even though the previous work on hardening showed that Steel No. 5 could be fully hardened with lower temperatures.

Samples were tempered at 600°F for 1, 2 and 4 hours. Figure 4 shows that Steels No. 3, 4, 5 and 6 developed tensile strengths of approximately 250 ksi (thousands of pounds per square inch) after tempering for 1 hour and for 4 hours. Steel No. 1 was noticably lower in strength than were Steels No. 3, 4, 5 and 6 after tempering for 1 and 4 hours. The tensile strength of Steel No. 2 tended to be much lower than that of the others for each of the three tempering times.

Some of the steels, viz. 2, 4, 5 and 6, gave their lowest strength

Table III. Effect Of Austenitizing And Tempering Treatments On Strength Properties With Slow Heating.

			Steel No. 1			Steel No. 2			Steel No. 3			Steel No. 4			Steel No. 5			Steel No. 6		
Hardening[a]	Tempering		TS[b]	F[b]	El[b]	TS	F	El	TS	F	El	TS	F	El	TS	F	El	TS	F	El
Austenitize, 1500°F - 15 min	600°F	1 hr	221	s	0	217	c	0	240	s	0	245	s	0	253	s	1.0	246	c	0
		2 hr	243	s	0	160	c	0	242	s	0.5	224	s	0	233	s	0	210	c	0
		4 hr	220	s	0	200	c	0	233	s	0	242	s	1.5	243	s	1.5	238	c/s	0
	500°F	2 hr	114	c	0	54	c	0	176	c	0	175	c	0	167	c	0	127	c	0
		4 hr	210	c	0	146	c	0	219	c	0	209	c	0	191	c	0	142	c	0
		7 hr	197	c	0	75	c	0	202	c/s	0	250	c	0	248	c	0	198	c	0

[a] All samples were quenched in oil at 140°F.

[b] TS - Tensile Strength, 1000 psi
F - Fracture
c - cleavage
s - shear
c/s - more cleavage than shear
s/c - more shear than cleavage
El - Per cent uniform elongation outside the fracture zone.

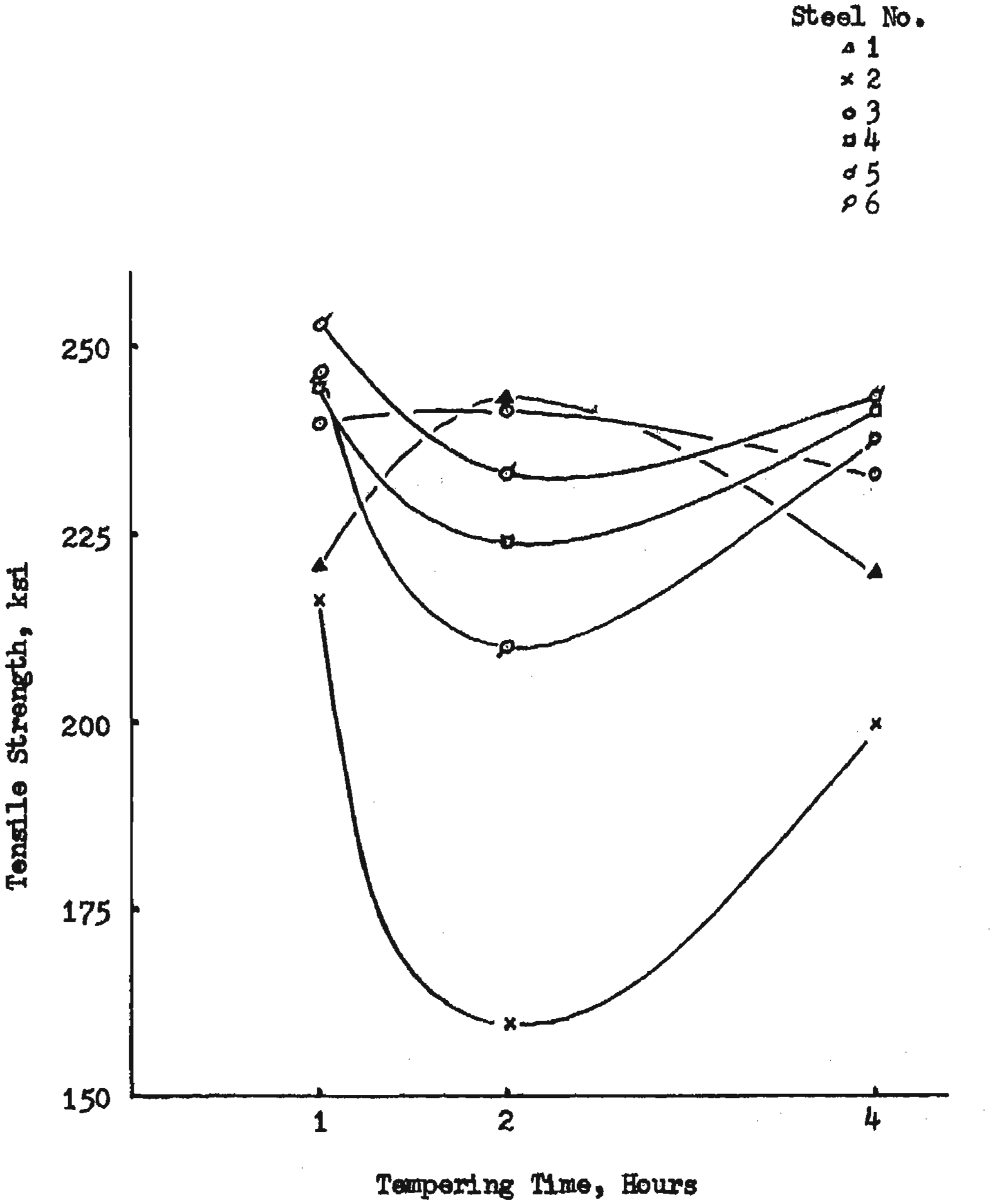

Figure 4. Tensile Strength Of Six Steels Austenitized At 1500°F For 15 Minutes And Tempered At 600°F.

after 2 hours tempering while the others gave their highest strength after 2 hours tempering. The reason for this was not clear.

Since tempering at 600°F achieved strengths of only about 250 ksi, the second set of samples was tempered at 500°F in an attempt to achieve higher strengths. Tempering times were increased to include 7 hours because the work at 600°F indicated the strength of some of the steels might be higher after longer tempering. The data for these samples are shown in Table III.

Figure 5 shows the results of tempering at 500°F. Scatter was more pronounced at this temperature than at 600°F. The most significant feature of these data was the apparent separation of the material into two groups. Steels No. 1, 3, 4 and 5 showed higher strength than did Steels No. 2 and 6 for a given tempering time. Also, the strength data were relatively linear and increased with increasing tempering time. Strengths of approximately 250 ksi were developed in Steels No. 4 and 5 after tempering 7 hours, and appeared probable in Steels No. 1 and 3. The samples of Steels No. 1 and 3 broke in the tensile tester jaws at lower values.

As indicated in Table III, a change occurred in the appearance of the fracture surfaces between the 500 and 600°F tempering treatments. All samples fractured in the cleavage mode at 500°F; whereas, the mode of fracture was predominantly shear at 600°F. Significantly, only Steels No. 2 and 6 displayed a cleavage fracture at 600°F.

b. <u>Austenitizing Treatments.</u> On the basis of the exploratory work, Steels No. 3, 4 and 5 were selected for use in evaluating the effect of austenitizing treatments. A treatment was desired which

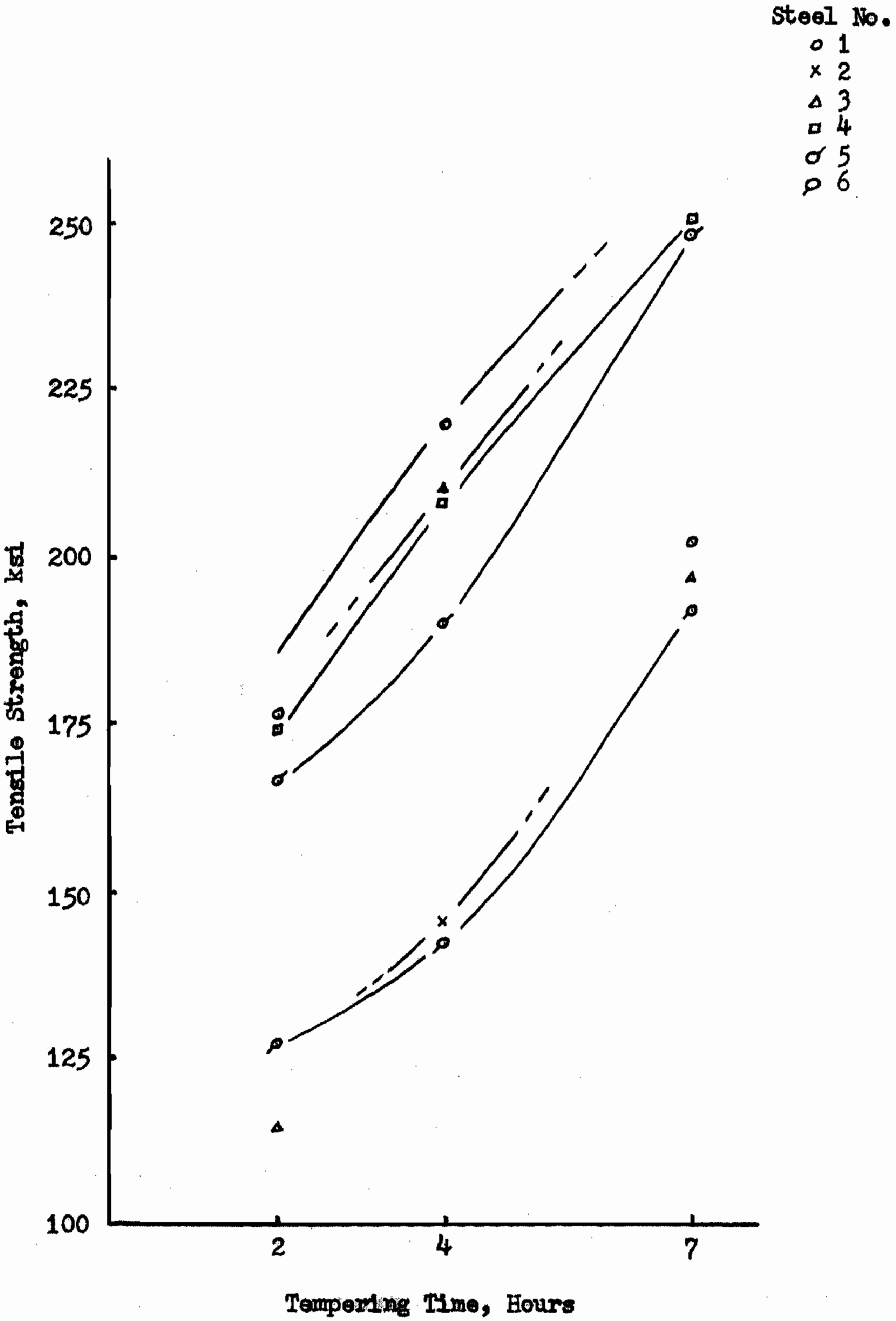

Figure 5. Tensile Strength Of Six Steels Austenitized At 1500°F For 15 Minutes And Tempered At 500°F.

would develop tensile strengths of 300 ksi or more and uniform elongations of at least 3%.

Table IV lists the data generated with samples quenched from six austenitizing temperatures ranging from 1375 up to 1500°F using three austenitizing times: 10, 20 and 30 minutes. Lower austenitizing temperatures were included here than were studied in the above work on hardening. The preliminary hardening work had not completely established the lowest possible austenitizing temperature, nor did it show the effect of austenitizing temperature on the ductility of the steel. All samples were tempered at 600°F for 4 hours.

Figures 6, 7 and 8 present tensile strength and elongation data plotted against austenitizing time at the various temperatures. The highest tensile strengths were achieved in samples from Steel No. 4 and were obtained by austenitizing at 1450°F. Steels No. 3 and 5 also showed their highest strength when austenitized at 1450°F. Slightly more than 3% elongation was achieved by austenitizing at 1425°F for 20 minutes in each of the three steels studied, and austenitizing at 1450°F for 20 minutes produced more than 3% elongation in Steels No. 3 and 4.

Table IV shows that for the above series of tests in which austenitizing treatment was studied the mode of fracture was shear for all three steels. Mode of fracture correlated to some extent with the amount of elongation observed. Shear was associated with ductile samples and cleavage with samples showing little or no elongation.

c. <u>Tempering Treatments.</u> The above study of austenitizing treatments indicated that the best hardening treatment might use 20 minutes

Table IV. **Effect Of Austenitizing Treatments On Strength Properties With Slow Heating.**

		Steel No. 3			Steel No. 4			Steel No. 5		
Hardening	Tempering	TS	E	El	TS	E	El	TS	E	El
Austenitize,										
1375°F - 10 min	600°F 4 hr	250	s	1.2	252	s	1.4	220	s	0
20 min		252	s	1.2	240	s	0	211	s	0
30 min		249	s	1.8	251	s	1.2	245	s	1.6
1400°F - 10 min		244	s	-	260	s	2.3	257	s	3.1
20 min		250	s	2.1	257	s	2.3	251	s	2.1
30 min		242	s	2.3	253	s	1.6	249	s	2.3
1425°F - 10 min		254	s	2.3	258	s	2.3	251	s	3.1*
20 min		246	s	3.1	254	s	3.1	256	s	3.1
30 min		256	s	2.3	250	s	1.6	252	s	2.3
1450°F - 10 min		258	s	2.6	266	s	2.1	258	s	1.5
20 min		247	s	3.1	266	s	3.1	257	s	2.3
30 min		241	s	2.3	267	s	2.0	255	s	2.1
1475°F - 10 min		247	s	3.3	264	s	2.3	255	s	3.1
20 min		241	s	1.3	257	s	2.7	252	s	2.1
30 min		244	s	2.5	253	s	2.5	249	s	2.3
1500°F - 10 min		251	s	2.1	260	s	1.9	252	s	2.3
20 min		245	s	1.6	258	s	1.9	253	s	2.5
30 min		242	s	3.1	249	s	3.1	246	s	2.1

* Sample was tempered for 8 hours.

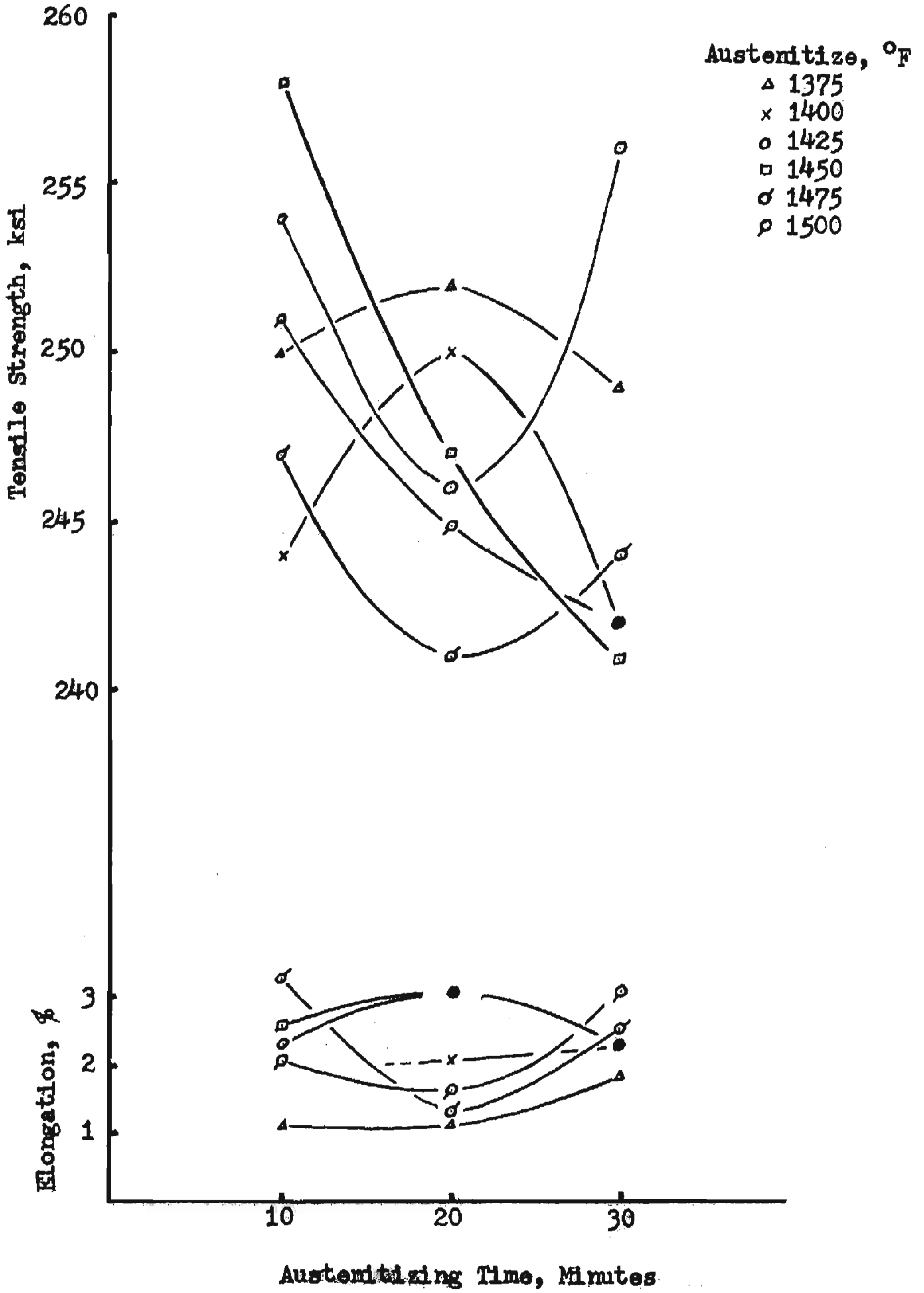

Figure 6. Tensile Strength And Elongation On Samples From Steel No. 3 With Various Austenitizing Treatments. All Samples Were Tempered At 600°F For 4 Hours.

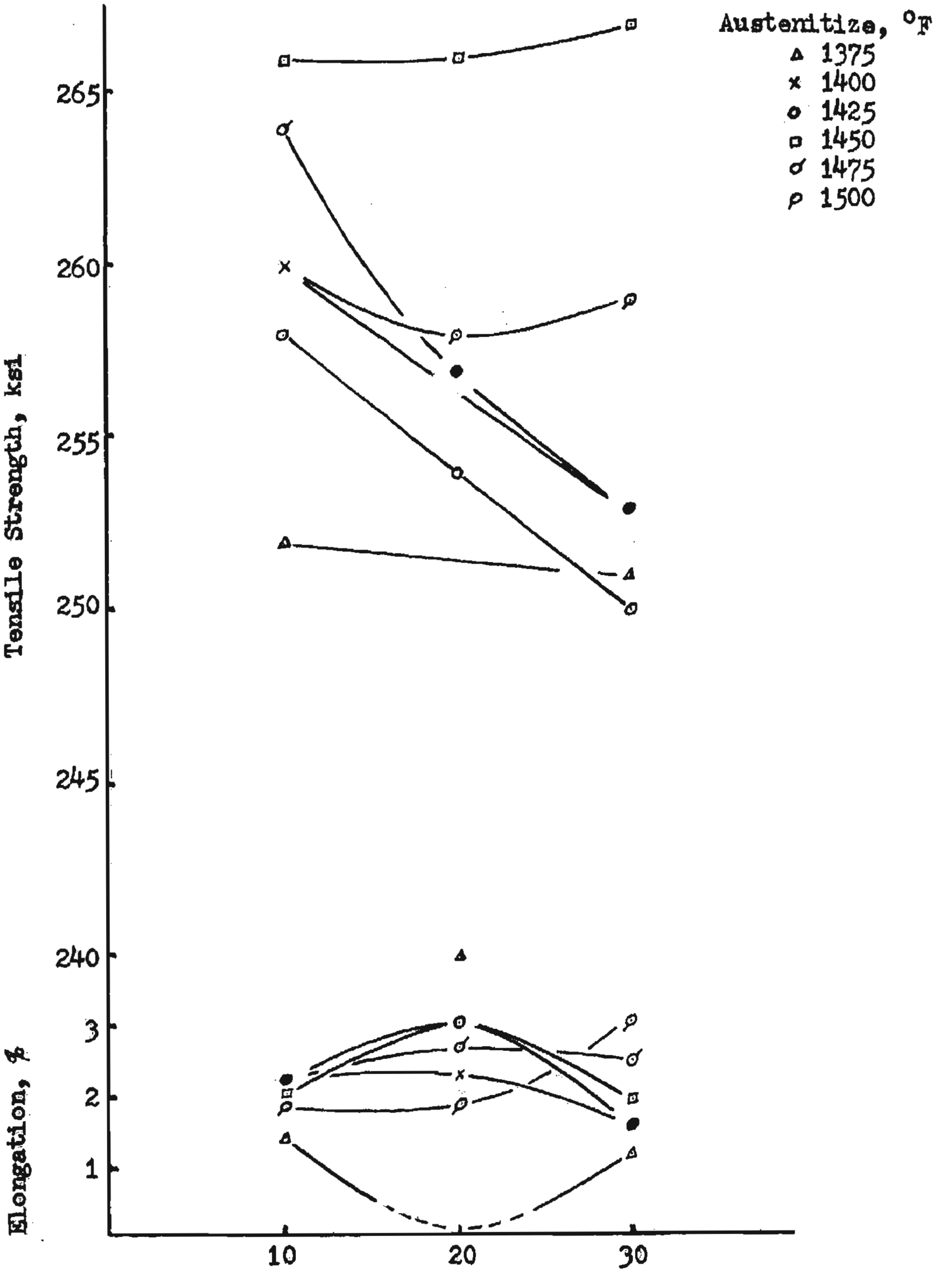

Figure 7. Tensile Strength And Elongation On Samples From Steel No. 4 With Various Austenitizing Treatments. All Samples Were Tempered At 600°F For 4 Hours.

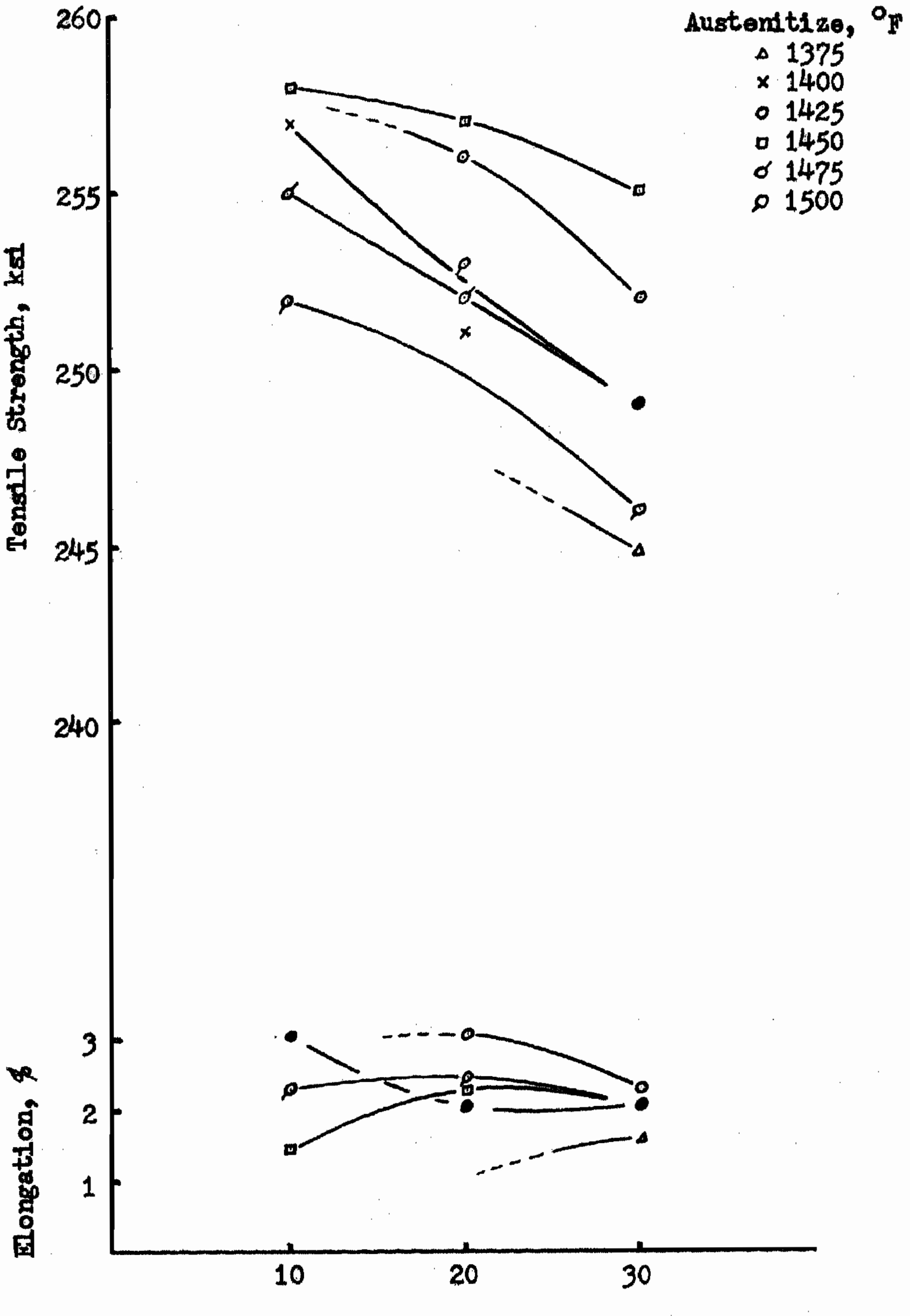

Figure 8. Tensile Strength And Elongation On Samples From Steel No. 5 With Various Austenitizing Treatments. All Samples Were Tempered At 600°F For 4 Hours.

at 1450°F. Therefore, this was adopted as the austenitizing treatment in a series of experiments intended to show how the tempering treatment affected strength properties. Steels No. 2, 3, 4, 5 and 6 were used in these experiments and the results are shown in Table V.

Since the results of the work reported in the exploratory treatments (Table III) indicated that strength improvement might be expected with tempering times longer than the 7 hours used there, a study was made of the effect of tempering at 450°F for times up to 128 hours. Tempering at 450°F was expected to yield higher strengths than were achieved with tempering at 500 and 600°F in the exploratory work. Figure 9 shows the tensile strength data obtained with samples from Steels No. 3, 4, 5 and 6.

Higher strength was obtained in Steels No. 3 and 4 than in Steels No. 5 and 6 throughout the range of tempering times. All steels showed a decline in tensile strength with increasing tempering time except Steel No. 3 which showed its highest strength of approximately 275 ksi after tempering 128 hours.

Elongation was nil for all samples except those of Steel No. 3 tempered 16 hours and longer at 450°F, as shown in Table V. The sample from Steel No. 3 tempered 128 hours was the only one of the series which showed more than 1% elongation. This particular sample also showed the highest strength of the series.

The increase of tensile strength with increased elongation might have been an indication that the material was notch sensitive at low tempering temperatures. Therefore, the effect of tempering in the range of temperatures from 550 to 700°F for times up to 1 hour was studied. Steels No. 2 and 3 were selected for this work since on the

Table V. Effect Of Tempering Treatments On Strength Properties Of Samples Hardened With Slow Heating.

Hardening	Tempering		Steel No. 2			Steel No. 3			Steel No. 4			Steel No. 5			Steel No. 6		
			TS	F	El	TS	F	El	TS	F	El	TS	F	El	TS	F	El
Austenitize, 1450°F - 20 min	450°F	8 hr				176	c	0	261	c	0	242	c	0	118	c	0
		16 hr				268	c	0.5	239	c	0	167	c	0	193	c	0
		32 hr				252	c	0.5	267	c	0	213	c	0	173	c	0
		64 hr				189	c/s	0.5	250	c/s	0	186	c	0	152	c	0
		128 hr				276	c/s	1.7	225	c/s	0	185	c	0	160	c	0
	550°F	10 min	150	c	0	278	c/s	0									
		20 min	109	c	0	268	s/c	0									
		30 min	164	c	0	272	s	1.5									
		60 min	137	c	0	265	s	1.0									
	600°F	10 min	214	c	0	255	s	0									
		20 min	234	c	0	268	s	1.5									
		30 min	148	c	0*	257	s	1.0									
		60 min	178	c	0	257	s	1.0									
	650°F	10 min	196	c	0	250	s	1.5									
		20 min	215	c	0	248	s	1.2									
		30 min	257	c/s	1.2	246	s	1.2									
		60 min	255	s	2.0	246	s	2.0									
	700°F	10 min	263	s/c	1.7	244	s	2.0									
		20 min	251	s	3.3	240	s	2.0									
		30 min	246	s	2.5	240	s	1.7									
		60 min	170	s	0*	231	s	2.5									

* Sample was cracked.

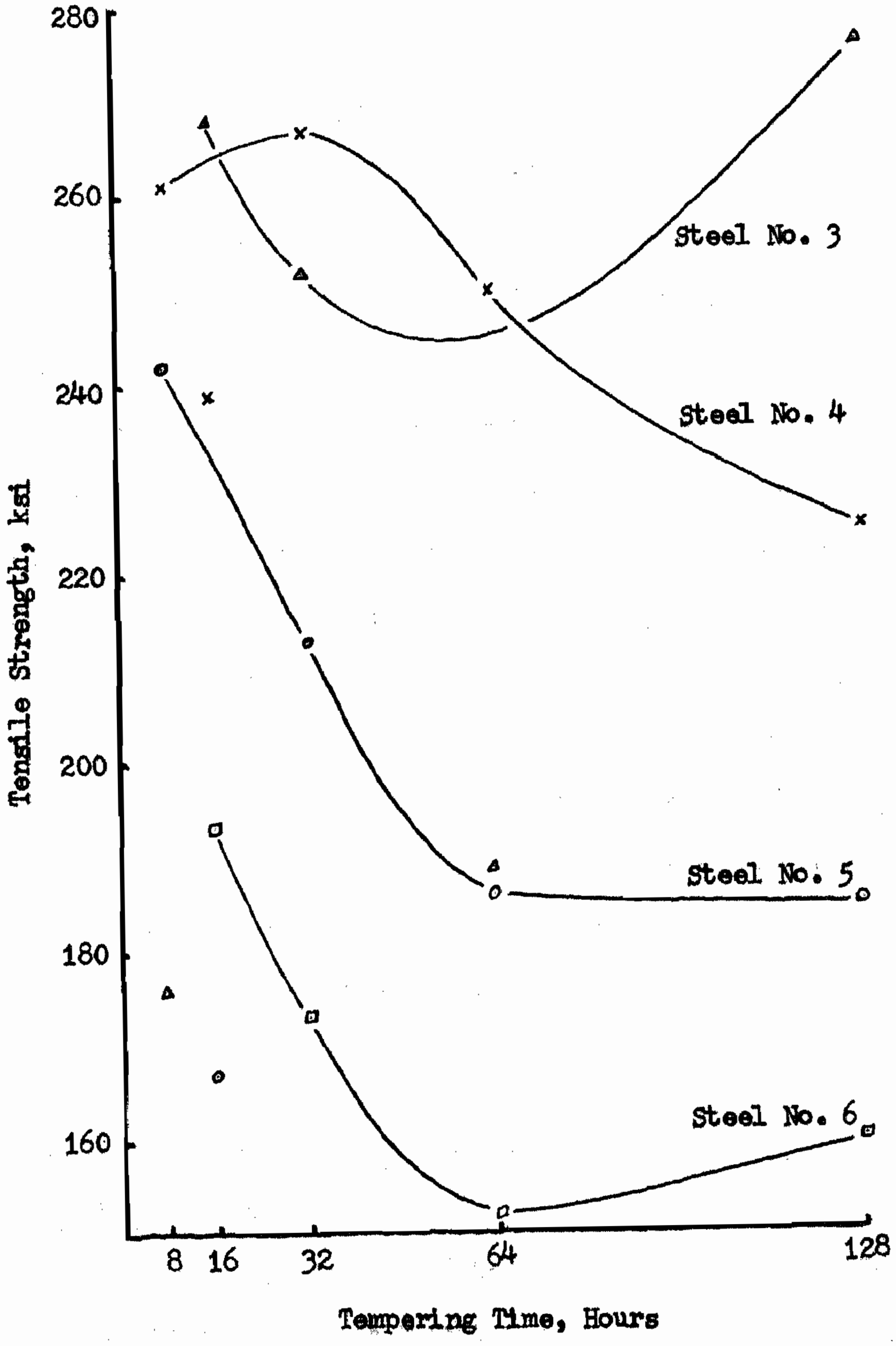

Figure 9. Effect Of Tempering Time On Tensile Strength Of Steels Tempered At 450°F. All Samples Were Austenitized At 1450°F For 20 Minutes.

basis of the previous work Steel No. 2 tended to show the least elongation and Steel No. 3 tended to show the highest elongation of the six steels.

The data from Steel No. 2 had a large amount of scatter, as shown in Table V, and are considered to be of questionable value.

The data from Steel No. 3 are plotted in Figure 10 and show that tensile strengths in the vicinity of 275 ksi were obtained by tempering at 550°F. A relatively small decrease in strength was noted with increasing tempering time at each tempering temperature. Elongation varied between 1 and 2.5% except at the 550°F temperature where no elongation was measured even though tensile strength was high.

The data in Table V indicated that no tempering treatment was likely to produce very high tensile strengths together with appreciable ductility in samples hardened according to what appeared to be the best treatment with slow heating. If the desired higher properties could be produced in these steels, it appeared that the hardening procedure would have to be improved. For this reason further work was done on the austenitizing treatment and some work was done on pretreatments.

B. STRENGTH PROPERTIES WITH RAPID HEATING

1. <u>Austenitizing Treatments</u>

Steels No. 3 and 4 were selected for further study of the effect of austenitizing treatment on tensile properties of high strength steel. Steel No. 3 had the lowest carbon content (0.65%) relative to the other steels. Furthermore, it had been most thoroughly studied in the above work on hardening and tempering. Steel No. 4 was highest in

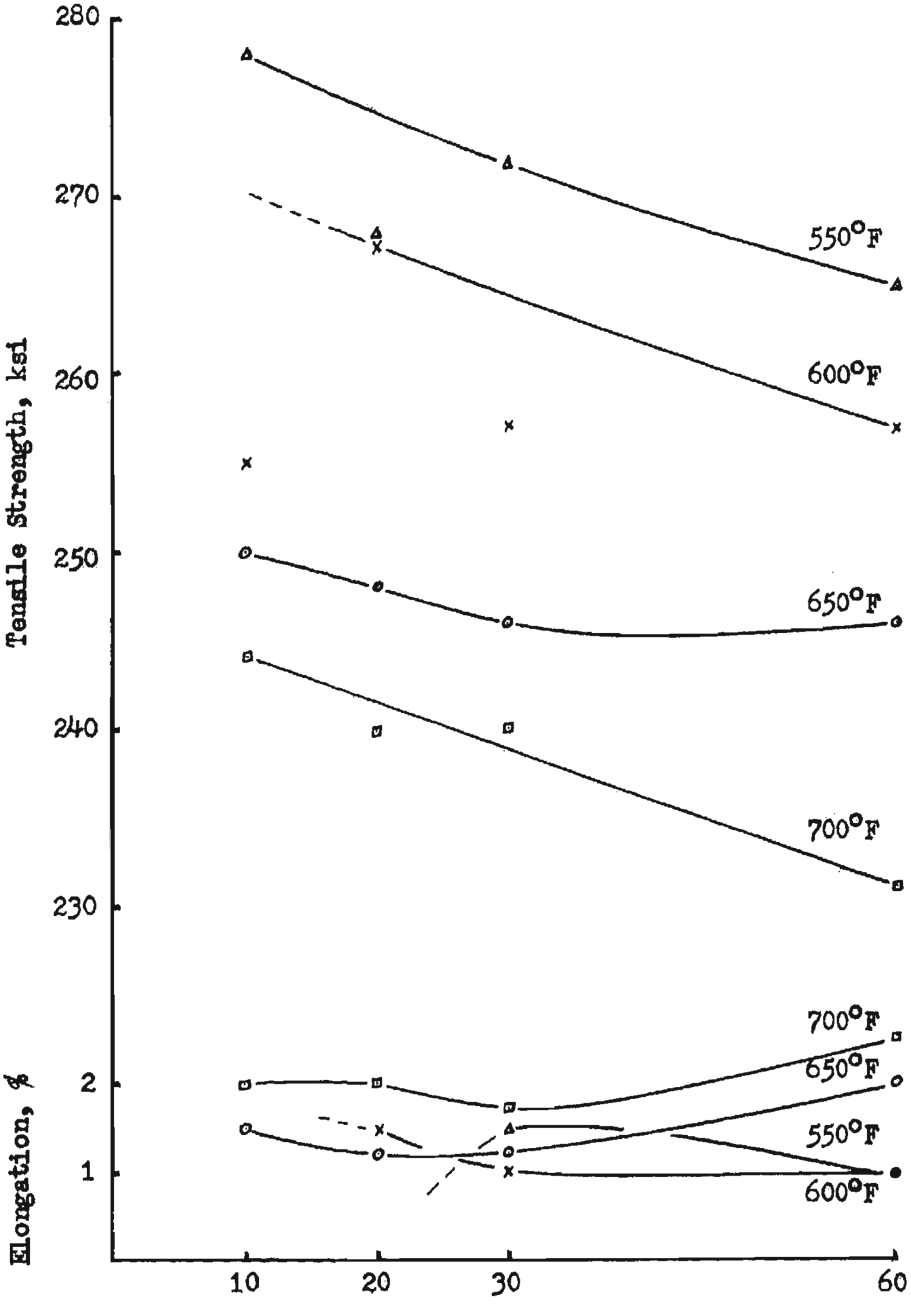

Figure 10. Effect Of Tempering Treatments On Strength Properties Of Steel No. 3. All Samples Were Austenitized At 1450°F For 20 Minutes.

carbon content (0.72%). Both steels showed comparable tensile strength and elongation in the above work and both had shown somewhat better properties than the other steels. It was assumed that these two steels were most likely to respond to any improvement in the heat treating procedure.

The heating rate was studied to determine its effect on properties. This was done by heating to the austenitizing temperature in a furnace at a temperature above the austenitizing temperature. Table VI gives the tensile strength and elongation of samples heated rapidly to temperatures of 1425, 1450 and 1500°F with the furnace at 1550°F. Tables VII and VIII give the tensile data for samples austenitized at temperatures of 1450, 1500 and 1550°F with the furnace at 1650 and 1750°F, respectively.

For the 1550°F furnace temperature, the highest austenitizing temperature studied was 1500°F since higher temperatures began to give too slow heating. Austenitizing at 1425°F was included in the series with the furnace at 1550°F to provide heating times comparable to those obtained at the higher furnace temperatures. The time required for a sample to heat to the austenitizing temperature was a function of both furnace temperature and difference between furnace temperature and the desired austenitizing temperature.

a. Furnace At 1550°F. Samples of Steel No. 3, when rapidly heated to temperatures of 1425, 1450 and 1500°F in a furnace at 1550°F and tempered at 550°F after warm oil quenching, developed tensile strengths in the range from 270 to 290 ksi, as shown in Figure 11. A maximum strength of 292 ksi was obtained by austenitizing at 1450°F

Table VI. Strength Properties With Rapid Heating In Furnace At 1550°F.

Hardening		Tempering		Steel No. 3			Steel No. 4		
				TS	F	El	TS	F	El
Austenitize,									
1425°F	35 sec[a]	550°F	10 min	288	s	2.0	307	s	1.8
			20 min	289	s	1.5	280	s/c	0
			60 min	278	s	1.0	284	s	0
1450°F	40 sec		10 min	292	s	1.0	302	s/c	1.8
			20 min	287	s/c	1.3	297	s/c	0.8
			60 min	282	s	1.7	286	s	1.3
1500°F	50 sec		10 min	290	s	1.4	294	c/s	0
			20 min	284	s	2.0	304	s/c	1.5
			60 min	271	s	1.0	294	s	1.5

[a] Approximate time to heat to austenitizing temperature.

Table VII. Strength Properties With Rapid Heating In Furnace At 1650°F.

Hardening		Tempering		Steel No. 3			Steel No. 4		
				TS	F	El	TS	F	El
Austenitize,									
1450°F	25 sec[a]	550°F	10 min	293	s	1.3	304	s	0.7
			20 min	277	s	0.9	291	s	0.6
			60 min	276	s	1.8	292	s	1.5
1500°F	30 sec		10 min	293	s	1.3	308	s	0.8
			20 min	282	s	1.3	301	s	1.3
			60 min	273	s	1.5	292	s	1.0
1550°F	35 sec		10 min	289	s	1.7	248	s	0
			20 min	277	s	2.0	298	s	1.1
			60 min	269	s	2.0	290	s	1.5

[a] Approximate time to heat to austenitizing temperature.

Table VIII. Strength Properties With Rapid Heating In Furnace At 1750°F.

Hardening		Tempering		Steel No. 3			Steel No. 4		
				TS	F	El	TS	F	El
Austenitize, 1450°F	22 sec[a]	550°F	10 min	288	s	1.0	321	s	1.0
			20 min	281	s	1.0	303	s	1.7
			60 min	277	s	2.4	291	s	2.0
1500°F	25 sec		10 min	287	s	1.3	313	s/c	1.3
			20 min	276	s	1.7	304	s	1.7
			60 min	273	s	2.3	291	s	2.3
1550°F	30 sec		10 min	290	s	1.7	214	c/s	0
			20 min	275	s	1.7	305	s	1.7
			60 min	266	s	1.7	289	s	1.0

[a] Approximate time to heat to austenitizing temperature.

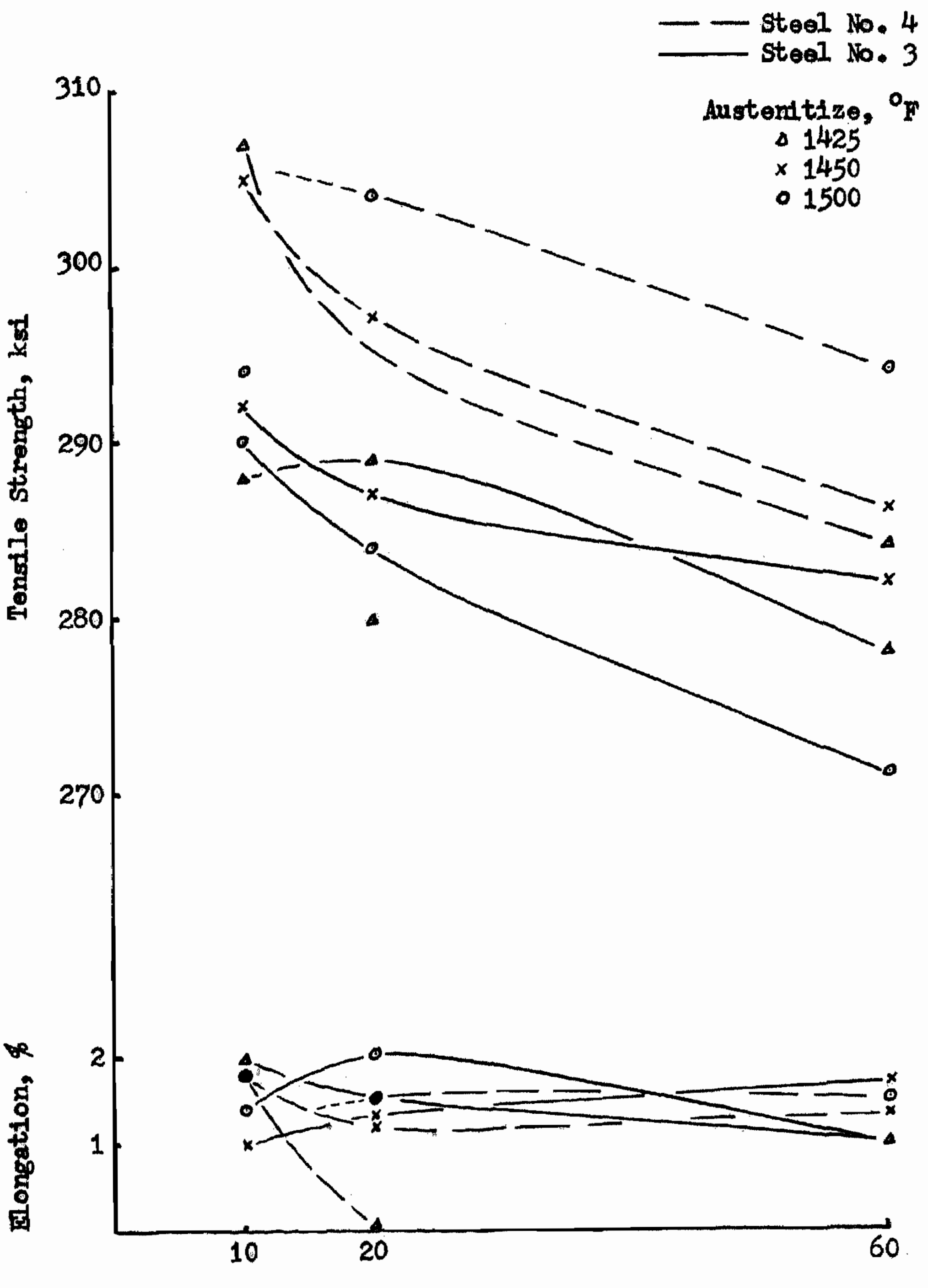

Figure 11. Tensile Strength And Elongation On Samples From Steels No. 3 And 4 Hardened With Rapid Heating In Furnace At 1550°F. All Samples Were Tempered At 550°F.

and tempering 10 minutes at 550°F. This strength can be compared directly with the strength shown in Figure 10 for the same austenitizing temperature with slow heating. Such a comparison indicates that Steel No. 3 improved by approximately 5% in tensile strength when hardened by rapid heating.

An improvement in the elongation of Steel No. 3 also was obtained by rapid heating. Between 1 and 2% elongation was obtained, compared to no elongation with slow heating, for the shorter tempering times. Elongation tended to decrease from the values obtained at 10 and 20 minutes when tempering was continued for an hour in samples austenitized at 1425°F and 1500°F; whereas, elongation increased continuously with tempering time in samples austenitized at 1450°F.

A difference in fracture appearance between the rapidly heated and slowly heated samples of Steel No. 3 was observed at the 10-minute tempering time at 550°F. Rapid heating produced a predominantly shear fracture while with slow heating the fracture was predominantly cleavage

Rapidly heating samples of Steel No. 4 to the austenitizing temperature in a furnace at 1550°F produced a greater increase in the tensile strength than that observed in Steel No. 3. Figure 11 shows that tensile strengths over 300 ksi were obtained with Steel No. 4 after 10 minutes tempering. Direct comparison of slowly and rapidly heated samples of Steel No. 4 was not possible since no samples of Steel No. 4 were tempered at 550°F in the work on slow heating. However, comparing the strengths shown in Figure 11 with those in Figure 4, where tempering was done at 600°F instead of 550°F, indicates that tensile strength improvement might have been of the order of 20%. The tensile strength of the sample rapidly heated to 1500°F and tempered 1 hour at 550°F was

294 ksi, compared to 245 ksi for the sample slowly heated to 1500°F and tempered 1 hour at 600°F.

Elongation in samples of Steel No. 4 was between 1 and 2% except on the samples austenitized at 1425°F and tempered for 20 and 60 minutes which showed no elongation.

b. <u>Furnace At 1650 And 1750°F.</u> Figures 12 and 13 show the mechanical properties obtained with samples of Steels No. 3 and 4 when rapidly heated to the austenitizing temperature in a furnace at 1650 and 1750°F, respectively. At these higher furnace temperatures, which gave faster heating rates, the austenitizing temperatures investigated were 1450, 1500 and 1550°F.

Steel No. 3 responded much the same in these treatments as it did at the lower furnace temperature of 1550°F. The highest tensile strengths were observed in samples tempered for 10 minutes and were in the vicinity of 290 ksi. Elongation ranged between 1 and 2% except for the sample austenitized at 1450°F and tempered for 1 hour, which showed 2.5% elongation.

With Steel No. 4, the increased heating rates brought about by the higher furnace temperatures tended to increase strength. Samples austenitized at 1450 and 1550°F in a furnace at 1650°F and tempered 10 minutes at 550°F obtained tensile strengths of 308 ksi. Heating Steel No. 4 in a furnace at 1750°F to each of the three austenitizing temperatures and tempering at 550°F for both 10 and 20 minutes produced tensile strengths in excess of 300 ksi.

Figures 11, 12 and 13 show an upward trend in the tensile strength of Steel No. 4 with faster heating rates. Also, as the heating becomes

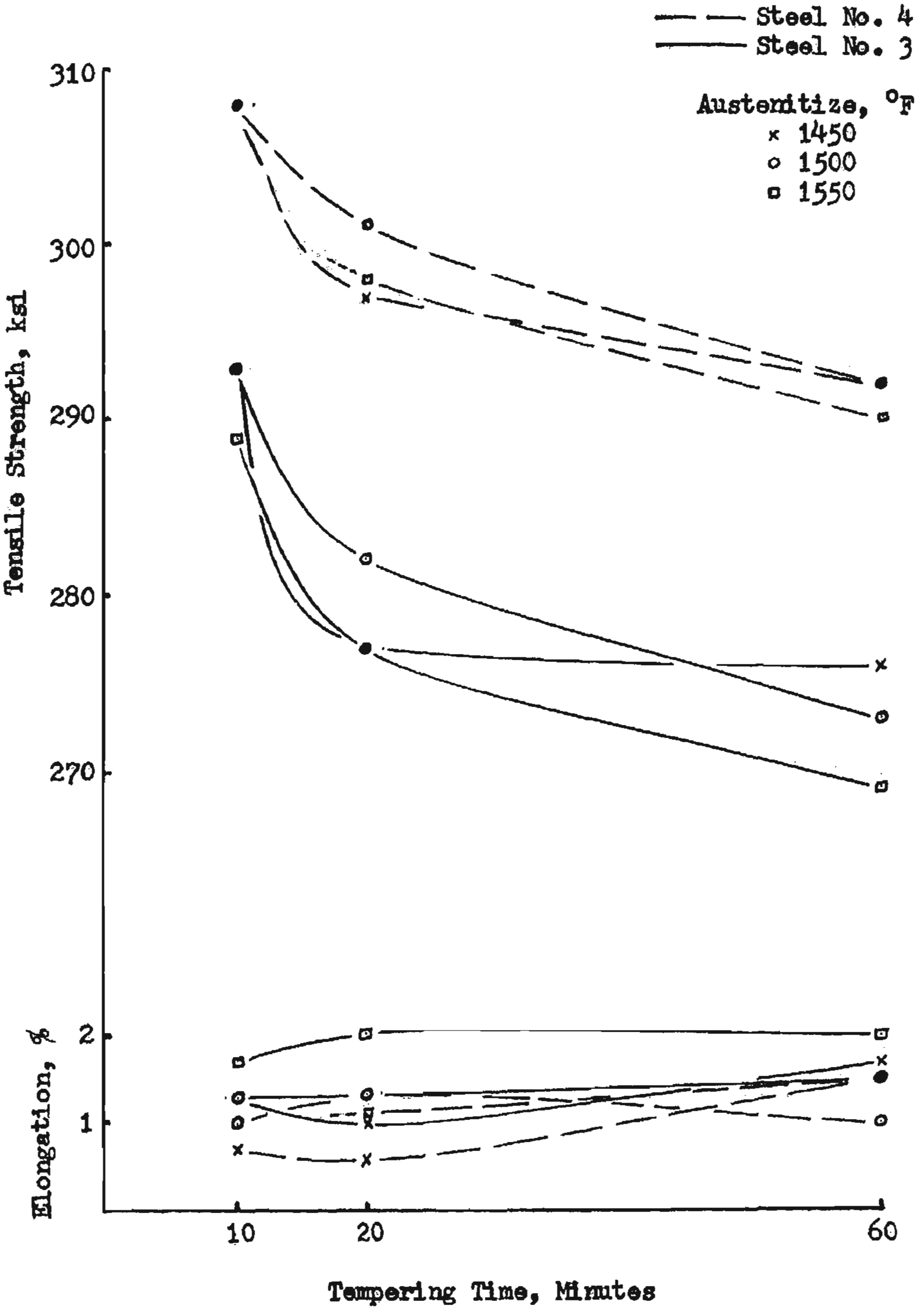

Figure 12. Tensile Strength And Elongation Of Samples From Steels No. 3 And 4 Hardened With Rapid Heating In Furnace At 1650°F. All Samples Were Tempered At 550°F.

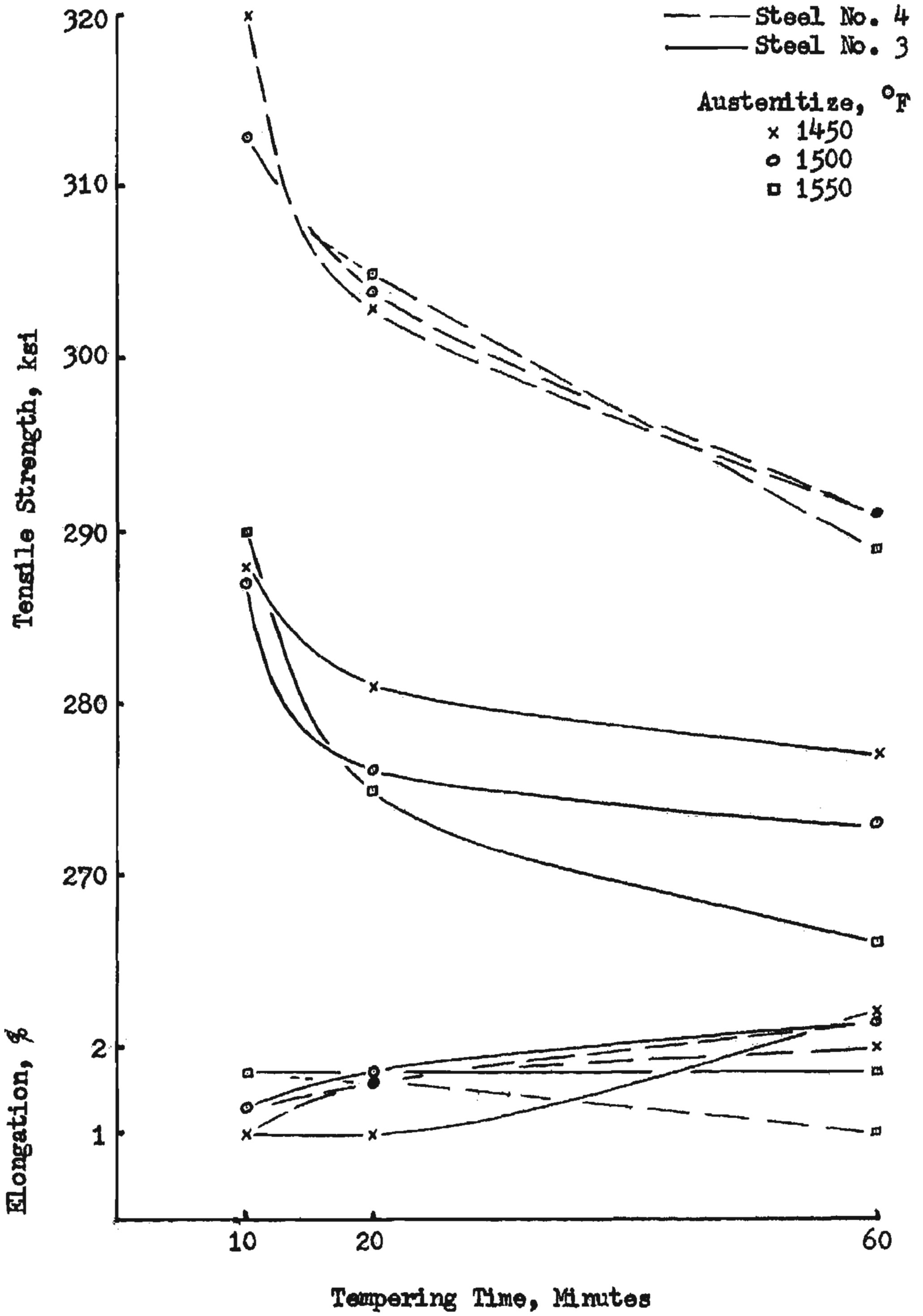

Figure 13. Tensile Strength And Elongation Of Samples From Steels No. 3 And 4 Hardened With Rapid Heating In Furnace At 1750°F. All Samples Were Tempered At 550°F.

more rapid, the values for tensile strength fall into an increasingly more narrow band which indicates a decrease in the effect of austenitizing temperature.

Elongation was not affected as much by furnace temperature, or rate of heating, as was tensile strength. The values were mainly between 1 and 2% for samples heated in a furnace at each of the three temperatures. Some of the samples of both Steel No. 3 and 4 heated in the furnace at 1750°F, however, had elongations of approximately 2.5% when tempered for 1 hour.

Elongation did appear to be affected by austenitizing temperature. Austenitizing samples of both Steel No. 3 and 4 at the lower temperature for each furnace temperature, tended to produce highest elongation with the 60-minute tempering time while austenitizing at the higher temperature tended to produce highest elongation with the 20-minute tempering time.

Steels No. 3 and 4 did not develop their best combination of properties with the same austenitizing treatment. Steel No. 3 gave its best tensile strength and elongation when austenitized at 1450°F in a furnace at 1550°F while Steel No. 4 gave its best properties when austenitized at 1450°F in a furnace at 1750°F.

All of the samples used to study the effect of austenitizing treatments were tempered at 550°F. In general, tensile strength decreased and elongation increased with increasing tempering time. However, for several austenitizing temperatures the sample tempered for 20 minutes was more ductile than the sample tempered for 60 minutes.

2. Tempering Treatments

Rapidly heating to the austenitizing temperature was shown in the previous section to produce a significant improvement in the strength of Steels No. 3 and 4. Tensile strengths in excess of 300 ksi were obtained in Steel No. 4 with tempering at 550°F, but elongation was relatively low. Therefore, the effect of tempering treatment on ductility of the rapidly heated samples was studied. The best hardening treatments, as given for Steels No. 3 and 4 in the previous section, were used for these samples.

Table IX gives the tensile strength and elongation of Steels No. 1, 3 and 4 hardened by rapidly heating to 1450°F and tempered for 20 minutes at temperatures in the range from 400 to 800°F. The samples of Steels No. 1 and 3 were heated in a furnace at 1550°F, and the samples of Steel No. 4 were heated in a furnace at 1750°F.

Figure 14 shows that Steel No. 3 developed a maximum tensile strength of 300 ksi when tempered 20 minutes at 500°F. Steels No. 1 and 4 also showed their highest strengths when tempered at 500°F. They developed tensile strengths of approximately 285 ksi.

It was noted that Steel No. 4 did not develop as high a strength in this series as it did in the series shown previously in Figure 13 for the same hardening treatment. Tempering at the 500°F temperature of this series was expected to give a higher tensile strength than that developed by tempering at 550°F in the previous series. Although the tensile strength curve in Figure 14 was drawn through the tensile test value of the sample tempered at 500°F, it is considered possible that the tensile test result on that sample was low and that the curve should have been extrapolated to show a strength above 300 ksi. The

Table IX. Effect Of Tempering Temperature On Strength Properties Of Samples Rapidly Heated.

		Furnace At 1550°F						Furnace At 1750°F		
		Steel No. 1			Steel No. 3			Steel No. 4		
Hardening	Tempering	TS	F	El	TS	F	El	TS	F	El
Austenitize 1450°F	400°F 20 min	144	c	0	200	c/s	0	98	c	0
	500°F	284	c/s	0	300	s/c	0	282	s/c	0
	600°F	275	s	1.5	266	s	0.8	273	s	1.5
	700°F	249	s	2.3	248	s	1.8	243	s	2.5
	800°F	222	s	2.5	210	s	2.5	217	s	2.0

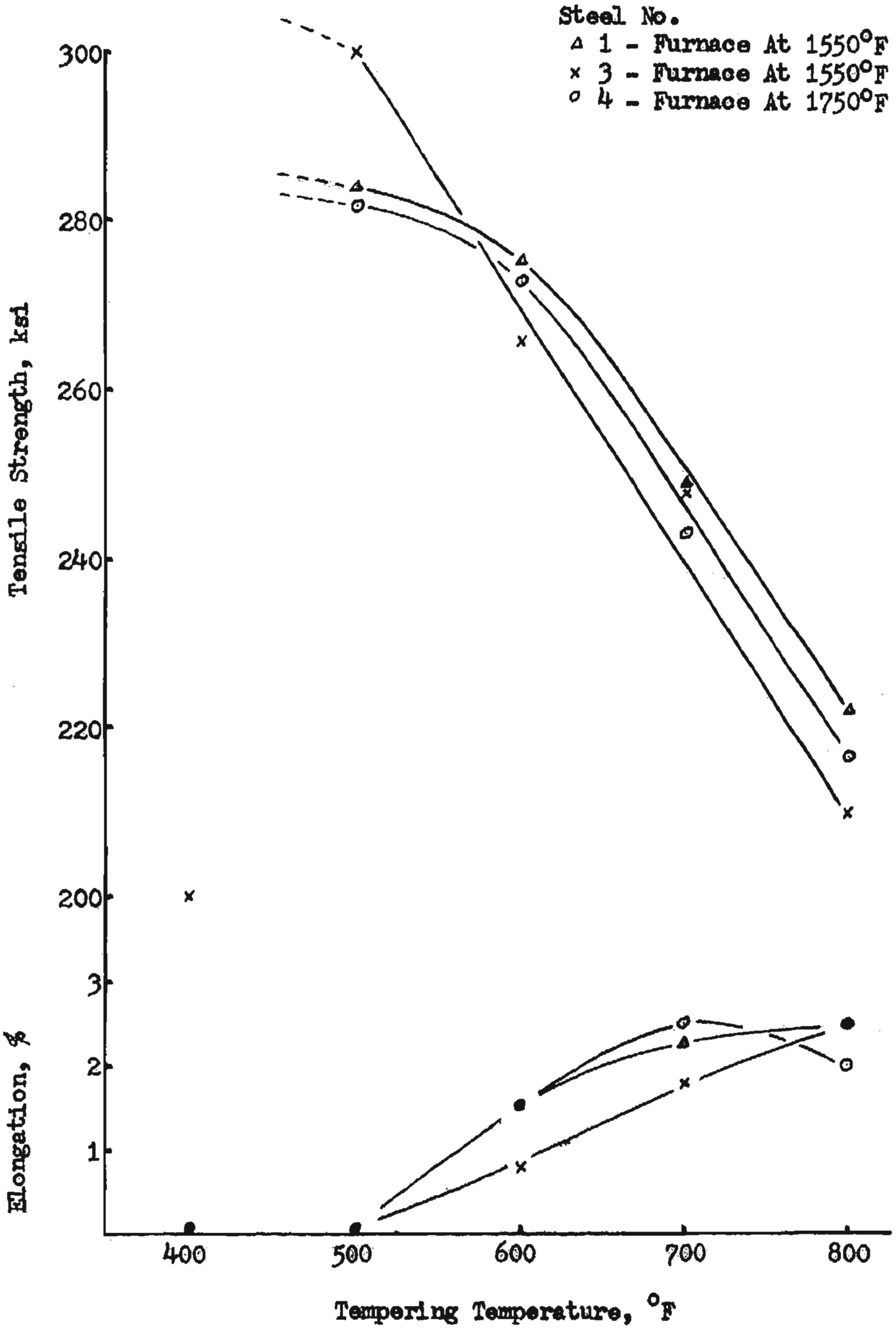

Figure 14. Effect Of Tempering Temperature On Strength Properties Of Steels No. 1, 3 And 4. All Samples Were Rapidly Heated To 1450°F To Austenitize And All Were Tempered 20 Minutes.

reason for this low strength could have been improper hardening, because the samples of Steel No. 4 in this series appeared to reach temperature sooner than in the previous series, also the low ductility in the sample tempered at 500°F may have been responsible for a bad tensile test. Not enough data was generated on Steel No. 1 in the other studies on hardening and tempering to indicate whether the strength at the 500°F tempering temperature was low. It may be noted that the 300 ksi tensile strength obtained in the sample of Steel No. 3 tempered at 500°F was the highest this particular steel gave in any of the hardening and tempering treatments studied.

Elongation was zero for the three steels at both the 400 and 500°F tempering temperatures. As temperature increased from 500 to 800°F, Steels No. 1 and 3 showed a fairly constant increase in elongation and reached a maximum of 2.5% at 800°F, while Steel No. 4 increased to a maximum of 2.5% at 700°F and then dropped off slightly at 800°F.

Table IX shows that the fracture surfaces were predominantly cleavage for the three steels at the 400°F tempering temperature. Tempering at 500°F produced fracture surfaces which were predominantly cleavage in Steel No. 1. At higher temperatures, the fracture surfaces were completely shear for each of the three steels. In each of the three steels, maximum tensile strength occurred in the temperature range where the mode of fracture was changing from cleavage to shear and apparently below the temperature range where any measurable elongation occurred.

Table X gives the strength properties of samples of Steels No. 3 and 4 heated to 1500°F in a furnace at 1750°F. These samples were tempered at 350 and 400°F for times of 1 and 4 hours.

Table X. Effect Of Tempering On Strength Properties Of Samples Rapidly Heated In Furnace At 1750°F.

		Steel No. 3			Steel No. 4		
Hardening	Tempering	TS	F	El	TS	F	El
Austenitize,							
1500°F 25 sec	350°F 1 hr	200	c	0	-	-	-
	4 hr	230	c	0	-	-	-
	400°F 1 hr	227	c/s	0	138	c	0
	4 hr	291	c/s	0	228	c/s	0

Direct comparison with the properties of the previous series was not possible since those samples were austenitized at 1450°F and, in the case of Steel No. 3, in a furnace at a lower temperature. However, longer tempering times in this last series gave some improvement in tensile strength at the 400°F temperature. This was most apparent with Steel No. 3 which obtained 291 ksi when tempered 4 hours at 400°F. The 350°F treatments did not produce enough ductility to permit a valid test of the samples of Steel No. 4, and they produced relatively low tensile strengths in Steel No. 3.

None of the samples of this series showed any elongation.

3. Pretreatments

Steels No. 3, 4 and 5 were given treatments prior to the hardening treatment. The purpose of these treatments was two-fold: (1) to show what effect condition of the steel before hardening had on its strength after hardening, and (2) to determine whether decarburization had occurred in slowly heated samples.

The pretreatment consisted of austenitizing the samples at 1450°F for times of 10, 20 and 30 minutes and air cooling. These treatments were intended to be the same as the austenitizing treatments used on samples hardened by slow heating. The samples were subsequently hardened with rapid heating to 1500°F in a furnace at 1550°F and tempered at 550°F for 20 minutes.

Table XI gives tensile strength and elongation data. Data from samples of Steels No. 3 and 4 can be compared directly to data from samples hardened by rapid heating to 1500°F and not pretreated (Table VI). A comparison of samples tempered for 20 minutes at 550°F

Table XI. Effect Of Pretreatment (Austenitize At 1450°F And Air Cool) On Strength Properties Of Samples Hardened In Furnace At 1550°F.

		Steel No. 3			Steel No. 4			Steel No. 5		
Hardening	Tempering	TS	F	El	TS	F	El	TS	F	El
Rapidly Heat To 1500°F 50 sec	550°F 20 min									
Pre-treatment -- Time At 1450°F:										
10 min		285	s	1.7	182	c/s	0*	272	s/c	0.5
20 min		276	s	0.8	269	s/c	0	262	s/c	0
30 min		265	s	0.8	257	s/c	0	266	s/c	0

* Sample was cracked.

showed that this pretreatment reduced both tensile strength and elongation and that the properties of Steel No. 4 were affected more than were those of Steel No. 3. Samples of Steel No. 5 could not be compared with samples which were not pretreated, but it is reasonable to expect a similar reduction in its properties as a result of pretreating.

Increasing the pretreatment time at 1450°F tended to decrease tensile strength and elongation in each of the three steels. Steel No. 3, for example, showed very little difference in tensile strength between the 10-minute pretreatment and no pretreatment, but as pretreatment time was increased to 20 and 30 minutes, the tensile strength decreased from 285 ksi to 276 and 265 ksi, respectively. Elongation decreased from 2% with no pretreatment to 1.7% with 10 minutes, and was 0.8% at both 20 and 30 minutes pretreatment.

To determine if decarburization was produced by the pretreatment, sections from samples of Steel No. 3 were mounted in bakelite and microhardness traverses were taken using the Knoop indenter and 100 gram load. The results on the pretreated samples were compared with results on a sample with no pretreatment hardened with the same rapid heating procedure and with results on a sample hardened by slowly heating and austenitizing for 20 minutes in a furnace at 1450°F. All of the samples had been tempered 20 minutes at 550°F.

No definite correlation between time at temperature (for pretreating or for hardening) and reduction of hardness at the surface of the sample was apparent. All of the samples showed an average hardness equivalent to Rockwell C57 - 58 on the center region about 0.005 inch from the surface. At a depth of 0.001 inch where the first reading of the traverse was made, the average hardness on the pretreated and slowly heated samples was approximately ½-point Rockwell C lower than on the center region. The hardness at the same depth on the rapidly heated sample with no pretreatment was approximately 1½ points Rockwell C lower than on the center region.

C. COMPARISON OF SIX STEELS

Since rapid heating in the hardening operation appeared to improve strength and ductility appreciably, it was decided to compare the six steels with each other using this heating procedure. However, as the data in Tables VI and VIII show, Steels No. 3 and 4 did not develop their best properties with exactly the same hardening treatment even though both gave their best properties when they were rapidly heated. Therefore, since the best hardening process was not known for each of the steels it was decided to adopt a single process for all. The hardening treatment selected for this work consisted of rapid heating to 1500°F in a furnace at 1550°F, quenching in warm oil and tempering at 550°F for 10 and for 20 minutes. Duplicate samples were treated with the results shown in the upper half of Table XII.

The first column in Table XII gives the approximate time elapsed between the end of the tempering and the tensile testing. It happened that the heat treating on these samples was completed late one day and half of them were tested approximately 15 hours later, early the next day. The other half were tested late the following day, about 50 hours after the heat treating. An examination of the results indicated that the properties of the samples tested 15 hours after heat treating were appreciably better than those tested 50 hours after heat treating. It did not seem reasonable to believe that the properties of this material would change so rapidly at room temperature.

Table XII. Strength Properties On Samples Of Six Steels Uniformly Hardened By Rapidly Heating To 1500°F In Furnace At 1550°F.

Elapsed Time Between Heat Treating And Tensile Testing	Tempering	Steel No. 1			Steel No. 2			Steel No. 3			Steel No. 4			Steel No. 5			Steel No. 6		
		TS	F	El	TS	F	El	TS	F	El	TS	F	El	TS	F	El	TS	F	El
15 Hours	550°F 10 min	305	s	1.7	220	c	0*	296	s	1.3	299	s/c	0.5	291	s	1.5	211	c	0*
	20 min	300	s	1.5	302	c/s	0.7	286	s	1.8	299	s	1.3	286	s	1.3	291	s	1.7
50 Hours	10 min	267	s/c	0*	144	c	0*	284	s	1.0	228	c	0*	266	c/s	0*	215	c	0*
	20 min	294	s/c	0.7	270	c/s	0	276	s	1.3	300	s/c	1.0	288	s	1.8	276	s/c	0.5
20 Hours	10 min							293	s	1.7	298	s	1.3						
	20 min							282	s	1.5	298	s	1.8						
40 Hours	10 min							286	s	1.3	303	s/c	2.3						
	20 min							282	s	1.0	298	s	1.5						
140 Hours	10 min							288	s	1.8	294	s/c	0.5						
	20 min							274	s	1.8	294	s	1.3						

* Tensile test data considered to be low and not used in determining averages shown in Figure 15.

Therefore, the samples whose properties are shown in the lower half of Table XII were treated. These samples showed that the properties were stable and that for some unknown reason a large percentage of the samples tested at 50 hours after heat treating gave unusually low tensile test data.

Since some of the tensile strengths in Table XII were considered to be low it was decided to disregard the obviously low data in comparing the various steels. The hardnesses of the samples were known and were used to determine the "obviously low" data. A correlation between hardness and tensile strength for steel is available. (13) This correlation is claimed to be accurate to within 10%. For this reason, those samples whose tensile strengths were appreciably lower than 10% of the value given in the above hardness-tensile strength correlation were discarded. On this basis the seven samples indicated in Table XII by an asterisk after their elongation were not used in determining the average tensile properties of the six steels shown in Figure 15.

Figure 15 shows the averages of the tensile properties of the six steels. Steel No. 1 showed the highest tensile strength of 305 ksi for the 10 minute tempering time. Its strength dropped somewhat to slightly below 300 ksi after tempering for 20 minutes. Steel No. 4 gave the second highest tensile strength of almost 300 ksi for both tempering times. The other steels had strengths in the range of 280 to 290 ksi. Since the data for Steels No. 2 and 6 for the 10 minute tempering time was discarded according to the selection process described above, no tensile strength is shown for these steels at the shorter tempering time.

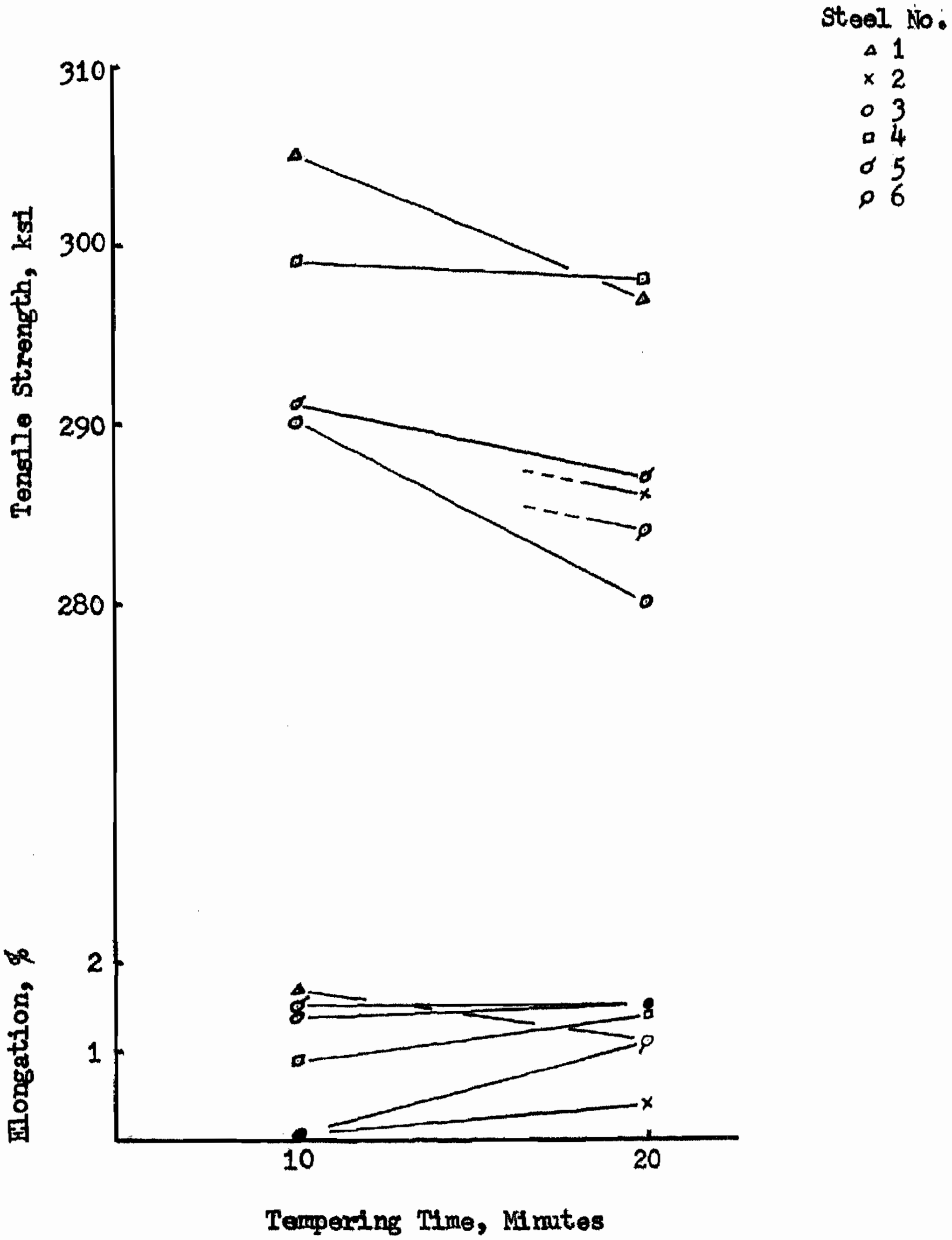

Figure 15. Average Tensile Strength And Elongation Of Six Steels Hardened By Rapid Heating To 1500°F In A Furnace At 1550°F. All Samples Were Tempered At 550°F.

Steel No. 1 showed the highest ductility with 1.7% elongation after tempering for 10 minutes. Its elongation fell to about 1% after 20 minutes tempering. The other five steels showed an increase in elongation with increased tempering time. Steels No. 2 and 6 had 1% or less elongation while Steels No. 3, 4 and 5 had between 1% and 1.5%.

V. DISCUSSION OF RESULTS

A. GENERAL

Tensile testing of hardened high carbon steels, which have been tempered at temperatures below about 700°F to obtain high strength, presents a somewhat different problem from the testing of steels at lower strength levels. High carbon steels at high strength levels exhibit relatively low ductility and, probably for this reason, tend to be sensitive to both surface condition and internal discontinuities. Surface notches and decarburization or internal microcracks and inclusions can affect the tensile test data obtained on high strength steels. The extent to which it is affected, however, is difficult to know without employing sophisticated flaw detection equipment and closely controlling surface conditions. Such sample preparation and inspection was not attempted in this project.

During the experimental work, most instances of a tensile sample failing at low strength relative to others of a given series occurred when the particular sample broke in or adjacent to the grips of the tensile testing machine. This is not to say, however, that all samples which broke in or next to the grips exhibited low tensile values. Tensile strength achieved in the test, rather, seemed related to the mode of failure as indicated by the fracture surfaces -- cleavage or shear -- which in turn was related to the ductility. Highest tensile strength most often occurred in samples showing some degree of elongation, though not necessarily the highest relative to other samples, and usually in samples showing more shear than cleavage on the fracture surface. The data of Table XII obtained with the six steels show this trend. In Figure 16, the tensile strengths of the samples from

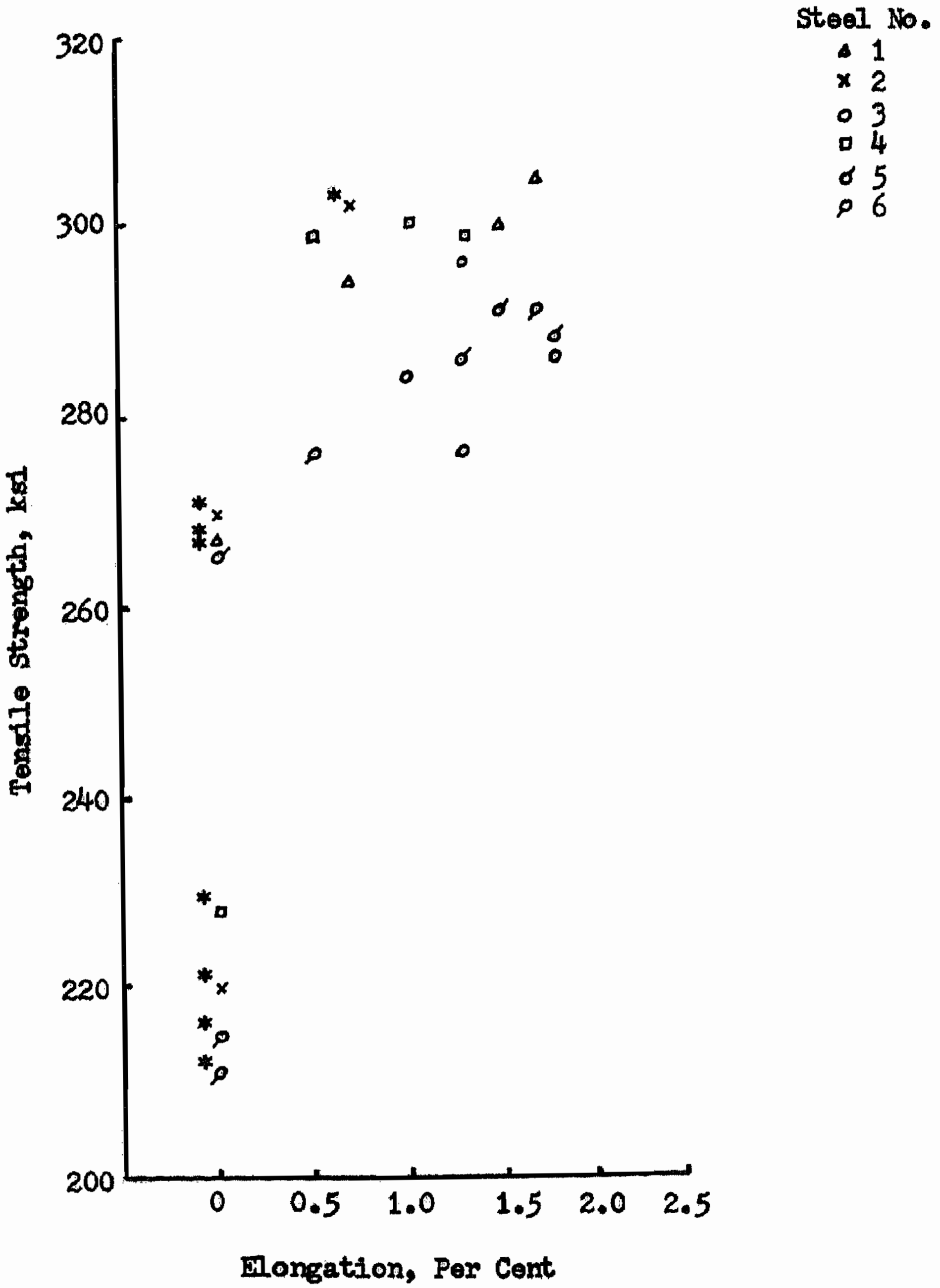

Figure 16. Tensile Strength-Elongation Relationship Of Six Steels. The Asterisk Designates Samples Which Failed By A Cleavage Or Predominantly Cleavage Mode.

Table XII are plotted against their elongations. The samples with lowest tensile strengths failed predominantly by a cleavage mode and showed no elongation. The samples with highest tensile strengths failed predominantly by shear and showed a measurable elongation.

All samples that failed by a cleavage or predominantly cleavage mode are designated by an asterisk to the left of the point plotted in Figure 16. All the samples with no measurable elongation had cleavage or predominantly cleavage type fractures. All the others failed by shear except the sample of Steel No. 2 with 302 ksi tensile strength and 0.7% elongation. All samples showing more than 1% elongation had fracture surfaces which showed a completely shear type failure.

It seems reasonable to assume that failure at the jaws of the tensile testing machine was not responsible, in itself, for lowered tensile test results. In those steels which were notch sensitive, the jaws might have provided surface indentations which initiated failure. However, failure probably could have been initiated almost as easily at a surface defect or internal flaw in any other area of the sample. For this reason tensile tests were not judged "good" or "bad" only on the basis of the location of fracture in the sample. The tensile strength - elongation relationship of Figure 16 shows, for example, three samples of Steel No. 4 that broke at 300 ksi with elongations ranging from 0.5% to 1.3%. All three failed by a shear or predominantly shear mode, yet two failed in the gripped region and one, with 1.3% elongation, failed at a position outside of the grips.

Uniform elongation was measured on the section of the tensile sample outside of the fracture zone in this study. This procedure should give lower elongation than a standard procedure that would include local deformation adjacent to the fracture. However, this non-standard method was considered to give a better indication of the relative ductility of the steels with rather low ductility. Two reasons can be given for thinking this. Local deformation at the fracture in some samples prevented fitting the two pieces together well and would have made it impossible to measure their final length. Secondly, the type tensile test sample used in this work would have presented a serious problem with failures outside the gauge length because no reduced section was used.

In addition to the relationship between tensile strength and elongation shown in Figure 16, the observations on the nature of the fracture surfaces also indicated a need for ductility in order to obtain high tensile test results with the testing procedure being used. Data on the steels hardened by slow heating and tempered at various temperatures from 450 to 700°F (Table V) show that at the lower tempering temperatures the steels displayed cleavage type fractures and low tensile test results. At the higher tempering temperatures the samples had shear type fracture surfaces, gave higher elongation and showed more reproducible or consistent tensile strength data (see data on Steel No. 3 in Table V). The highest tensile strengths were measured with samples tempered at intermediate temperatures where the steels were acquiring sufficient ductility to permit good tensile testing. At the intermediate tempering temperature where highest tensile strength was measured, the fracture surfaces indicated a mixed failure mechanism with shear tending to be more prominent. These samples with highest tensile strength did not give consistent elongation data. It appeared that the appearance of the fracture surfaces could be correlated better with high tensile strength values than could the elongation data.

The data for samples hardened by rapid heating showed the same tendency to associate highest tensile strength with a mixed mode of failure (Table IX). Furthermore, the data tend to indicate that a tempering temperature in the vicinity of 500°F was necessary to give these steels sufficient ductility to permit meaningful tensile testing. At lower tempering temperatures the actual strength of these steels may have been very high, but it was not possible to load the samples to their full capacity with the testing procedure used in this study.

It is believed that the steels studied in this investigation contained too much carbon to show very high strengths and appreciable ductility. The high-carbon martensite tends to be the internally twinned type in which carbide precipitation is very effective in preventing deformation. Perhaps a hardened, lower carbon steel would contain less twinned martensite and could be tempered at lower temperatures without losing so much of its ductility, because carbide precipitation is not thought to be so effective in preventing deformation in the lower carbon martensites with dislocation substructures.(3)

It is possible that the improvement in properties of these steels with rapid heating in the hardening operation was associated with their high carbon content and that the improvement can be viewed as further evidence that their carbon content was too high to allow them to achieve the ductility necessary to permit measurement of a very high tensile strength. Austenite of more than 0.5% carbon tends to give martensite with a substructure predominantly of the twinned type. (3) In the slow heating procedure, the steels were held at the austenitizing temperature for at least a short time which could have been long enough to allow the carbon to diffuse throughout and produce, if not homogeneous, at least mostly high-carbon austenite. The high-carbon austenite would then give a predominantly twinned type martensite in which carbide precipitation is very effective in preventing deformation when the tempering temperature is low. High strength is normally obtained at lower tempering temperatures and this was probably the case with these steels. However, at those tempering temperatures where the actual strength was very high the ductility was apparently too low to allow accurate determination of the tensile strength. At higher tempering temperatures (500°F or higher) where ductility improved sufficiently to allow a more nearly accurate test of tensile strength, the tensile strength had apparently dropped to 300 ksi or lower.

The hardening operation employing rapid heating allowed the steel to spend only a few seconds in the austenite range, and it is possible that the austenite at the start of the quench was nonhomogeneous with a large portion of the carbon concentrated near the former cementite sites and with a large percentage of the material being lower than 0.5% carbon content. If this were the case, this austenite could have transformed into a martensite that was predominantly dislocation substructured. Tempering this martensite at low temperatures would have produced a more ductile material and may have been responsible for the rapidly heated samples showing a better combination of strength and ductility.

It would appear possible that a careful examination of the samples using transmission electron microscopy might be capable of verifying or disproving the above ideas. No such study was attempted in this work.

Another observation that might support the idea that the carbon content was too high to achieve both very high strength and good ductility in these steels was the detection of a slightly softer surface on the samples hardened by rapid heating. Since a small amount of decarburization was found on the steels in the as-received condition, the low surface hardness could be due to this lower carbon content. As mentioned above, lower carbon martensite tends to be more ductile after low temperature tempering and the softer surface on the rapidly heated samples may have made them less sensitive to surface defects allowing stress to approach the actual strength of the sample more closely during tensile testing. Thus, the higher measured tensile strengths of the rapidly heated samples might be at least partially due to a slightly decarburized surface.

The surface on the slowly heated samples may have picked up carbon by diffusion from the interior which gave the surface slightly higher hardness than that on the rapidly heated samples. The higher carbon surface could have caused these samples to be more notch sensitive and could have been a contributing factor in the obtaining of lower tensile test data on the slowly heated samples.

If the carbon content of these steels was indeed too high to give the best combination of high strength and ductility, a better combination of these properties should be realized in lower carbon steels. It is difficult to know how much the carbon should be reduced, but plain carbon steels in the 0.4 to 0.6% carbon range should be studied, if this work is continued.

A comparison of the compositions of the six steels given in Table I shows that Steels No. 3 and 5 were lowest in carbon content.

This lower carbon content did not appear to make them more ductile. Steel No. 4 was highest in carbon content and displayed the most ductility. Steel No. 2 was highest in sulfur (0.40%) and phosphorus (0.20%) which might have been responsible for its low elongation; yet, Steel No. 6 also showed low elongation and a strong tendency toward fracture by cleavage and it had sulfur and phosphorus contents approximately equal to those of the other steels. Except for the high tin content (0.20%) in Steel No. 1 and the possibly high molybdenum in Steels No. 1 and 3, the concentrations of the other elements were about the same in each of the six steels. These limited data do not indicate any effect of composition on properties.

B. HARDENING TREATMENTS

The steels showed different strength properties relative to each other with different hardening treatments. Rapid heating in the hardening operation gave higher tensile strengths than did slow heating and a soaking time at the austenitizing temperature. With slow heating to the austenitizing temperature, the treatment which appeared to give highest tensile strength on the basis of data developed on Steels No. 3, 4 and 5 was to austenitize at 1450°F for 20 minutes and to quench in warm oil. This treatment produced tensile strengths in the vicinity of 260 ksi and elongations slightly over 3% after tempering 4 hours at 600°F (Table IV). The same hardening treatment produced a tensile strength of approximately 270 ksi in Steel No. 3 with tempering both at 450°F for long times and at 550°F for a short time (Table V). Elongation tended to be less than 1.5% at those lower tempering temperatures.

Although rapid heating produced higher tensile strengths than did slow heating, the various steels gave different tensile strengths when hardened by exactly the same rapid heating treatment. Steel No. 4 achieved highest tensile strength with heating to 1450°F in a furnace at 1750°F. Steel No. 3, on the other hand, achieved highest tensile strength with heating to 1450°F in a furnace at 1550°F. Hardening Steels No. 3 and 4 by their best treatment and tempering at 550°F for 10 minutes developed 288 ksi tensile strength and 2% elongation in No. 3 and 321 ksi tensile strength and 1% elongation in No. 4 (Tables VI and VIII). Tempering Steel No. 4 for 60 minutes lowered tensile strength to 291 ksi and increased elongation to 2%.

Steels No. 2 and 6 seemed to show lower ductility than the other steels at high strength levels and they were not studied thoroughly enough to know what heat treatment would develop their highest strength properties.

C. COMPARISON OF STEELS

The experimental work covered a rather broad area since it was intended to investigate the properties of the six steels and to determine if any were capable of developing appreciable ductility at tensile strengths of 300 ksi or higher. In order to do this it was necessary to limit the number of samples studied but still explore a wide variety of treatments. Each of the six steels was not given every treatment studied and the number of duplicate samples used to determine properties was very limited. A large number of duplicate samples would probably be necessary to evaluate properly the properties of this high strength, low ductility material. In spite of this deficiency in the data, some discussion of the properties of these steels is possible. While actual values of tensile strength and elongation are mentioned, it should be remembered that these are usually values obtained on single samples and the reproducibility of tensile test results was probably not high on these samples, especially at the higher strengths and lower ductilities.

The data generated on the six steels indicated that they could be divided into two groups on the basis of their tensile properties. Steels No. 1, 3, 4 and 5 showed a tendency toward ductile behavior while Steels No. 2 and 6 showed a tendency toward brittle behavior when heat treated to high strength levels. This separation into two groups is apparent when the tensile data for the steels after hardening by slow heating are compared (Table III). With this hardening procedure and low tempering temperatures, none of the steels gave sufficient elongation to make it stand out, but after tempering at 600°F the ductile group (Steels No. 1, 3, 4 and 5) displayed shear type failures while the other group had cleavage fracture surfaces. The measured tensile strength was somewhat higher for the ductile group after tempering at 600°F and more noticeably higher when the tempering temperature was lowered to 500°F (Figure 5).

The steels developed more ductility with the better hardening treatment which used rapid heating. In this condition the two groups of steels separated themselves on the basis of the elongation data (Table XII and Figure 15). The elongation of Steels No. 2 and 6 was appreciably lower than that of Steels No. 1, 3, 4 and 5.

Steels No. 1, 2, 3 and 4 developed tensile strengths of 300 ksi or higher when hardened by the rapid heating procedure and tempered at

$550^\circ F$ (Tables VI, VII, VIII and XII). Steel No. 4 developed a tensile strength of 321 ksi, the highest tensile strength measured during the course of this work. At the 300 ksi strength level, Steel No. 4 appeared more ductile than the others, showing as much as 2.3% elongation. Steel No. 2 gave low elongation data and tended to give a cleavage type failure. Steel No. 6 behaved very much like Steel No. 2 and it is reasonable to believe that these two steels did not give higher tensile test results because they lacked sufficient ductility to permit good tensile testing (Table XII). While Steel No. 5 did not reach 300 ksi, it gave measureable elongation and appeared to belong in the ductile group rather than with Steels No. 2 and 6.

VI. CONCLUSIONS

1. All of the steels studied were too high in carbon content to show high tensile strength with appreciable ductility.

2. Tempering below a temperature of about 500°F does not sufficiently soften the steels to allow a valid test of their tensile strengths.

3. A shear or predominantly shear type failure, as indicated by the fracture surfaces of a tensile test sample, was a better indication of a good tensile test than was the elongation measured on a sample tempered in the low temperature range.

4. The austenitizing procedure in the hardening operation appeared to affect the as-quenched condition of the steel and to determine the maximum tensile properties that could be obtained by subsequent tempering.

5. When these steels were tempered to get a fracture during tensile testing that was partially cleavage, but predominantly shear, the steel had the highest tensile properties that could be obtained by tempering the particular as-quenched condition under study.

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