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RELIEF OF RESIDUAL STRESS IN STREAMLINE TIERODS

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ABSTRACT

About two-thirds of the residual stress in cold-worked SAE 1050 steel tierods was relieved by heating them 30 inutes at 600° F. Cold-worked austenitic stainless steel tierods could be heat at temperatures up to 1,000° F without lowering the important physical properties. With materials of straight 18–8 composition, however, the limiting heating temperature was found to be abouc 900° F, because at higher temperatures precipitation of chromium carbide occurred. It is possible that materials containing additions of titanium, columbium, or molybdenum could be heated at higher temperatures, since the carbides of these elements would be precipitated in preference to chromium carbide.

Microscopic examination and Vickers indentation tests indicated localized differences in the amount of cold-working. Such differences may explain the distribution of residual stress in cold-worked tierods.

CONTENTS

I. INTRODUCTION

A high percentage of the streamline tierod failures examined at the National Bureau of Standards have been attributed to torsional fatigue due to synchronous vibrations. One characteristic feature of such failures, in the streamline portion of the tierod, is that fracture invariably starts at or near the intersection of the minor axis with the surface. A typical fracture of this kind in an (18–8) corrosion-resistant steel tierod is shown in figure 1.

The reduction to streamline section is usually performed by rolling or drawing. In most tierods the high physical properties required are produced by cold-working during these operations. Such tierods naturally contain very high residual (internal) stresses. Residual stresses may be dangerous in highly stressed members, such as tierods, particularly when the distribution of stress is such that it acts in the same direction as the superimposed service stress.

In most tierods, the residual stress is so distributed that the highest tensile stress occurs at the intersection of the minor axis of the cross section with the streamline surface. This is the point at which the fractures start. High residual stresses, therefore, probably are important contributory causes of failure in these tierods.

In the attempt to reduce the number of failures of this type, an investigation was undertaken, at the request of the Bureau of Aeronautics, Navy Department, to determine whether or not the residual stress could be substantially relieved by a relatively low-temperature heat treatment without materially affecting the physical properties of the material.

II. MATERIALS

Streamline tierods of the materials listed in table 1 were included in the investigation.

TABLE 1.—*Materials used in investigation*

Material	Size [a]	Composition							
		C	Cr	Ni	Ti	Cb	Mo	Cu	Al
		%	%	%	%	%	%	%	%
A (SAE 1050 steel)	3/8–24	[b] .045 to .50							
B (SAE 1050 steel)	3/8–24	[b] .045 to .50							
C (18–8 stainless)	3/8–24	(b)	18.	8.					
D (18–8 stainless)	3/8–24	(b)	18.	8.					
E (18–8 stainless)	1/2–20	.12	19.1	9.0					
F (18–8 stainless)	10–32	(b)	18.	8.					
G (18–8+titanium)	10–32	(b)	18.	8.	0.4				
H (18–8+titanium)	1/2–20	.05	18.5	8.7	.37				
I (18–8+titanium)	5/8–18	(b)	18.	8.	.4				
J (18–8+columbium)	10–32	(b)	18.	8.		0.75			
K (18–8+columbium)	1/2–20	.09	17.8	9.7		.77			
L (18–8+columbium)	5/8–18	(b)	18.	8.		.75			
M (18–8+molybdenum)	5/8–18	.06 to .07	17.44	10.21			2.96		
N (18–2 stainless)	10–32	(b)	18.	2.					
O (18–2 stainless)	1/2–20	.10	17.3	2.17					
P (18–2 stainless)	5/8–18	(b)	18.	2.					
Q (16–1 stainless)	10–32	(b)	16.	1.					
R (16–1 stainless)	1/2–20	.11	15.5	1.65					
S (16–1 stainless)	5/8–18	(b)	16.	1.					
T (K-monel)	10–32	(c)		66.				29.	2.75
U (K-monel)	1/2–20	(c)		66.				29.	2.75
V (K-monel)	5/8–18	(c)		66.				29.	2.75

[a] Sizes given in Navy Department Specification 49T9a refer to threaded ends.
[b] Nominal composition.
[c] Typical analysis of a *K*-monel alloy.

III. MEASUREMENT OF RESIDUAL STRESS

The elliptical shape of the streamline tierods would not permit the use of the most precise method of residual stress determination originated by Howard [1] [1] and Heyn [2], developed and modified by Merica and Woodward [3] and Sachs [4], and used by Green [5] to estimate the residual stress in quenched steel cylinders and by Kempf and Van Horn [6] to investigate the relief of residual stress in aluminum alloys. The split-ring method used by Hatfield and Thirkell [7] or the slit-tube method of Crampton [8] were, of course, not applicable to solid, elliptically shaped tierods. However, the method used was somewhat similar to that of Crampton in that stress was partially relieved on one side of a plane of symmetry and the resultant distortion of the remaining material was measured.

In the calculation of the partial residual stresses, it was assumed that the stress distribution in the plane under consideration was linear.

[1] Figures in brackets indicate the literature references at the end of this paper.

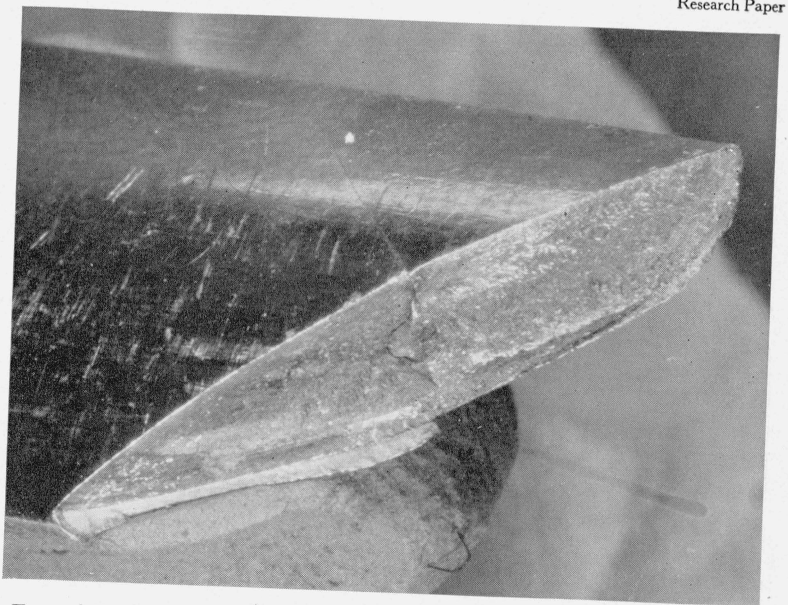

FIGURE 1.—*Torsional fatigue fracture in 18–8 stainless steel tierod;* ×5.

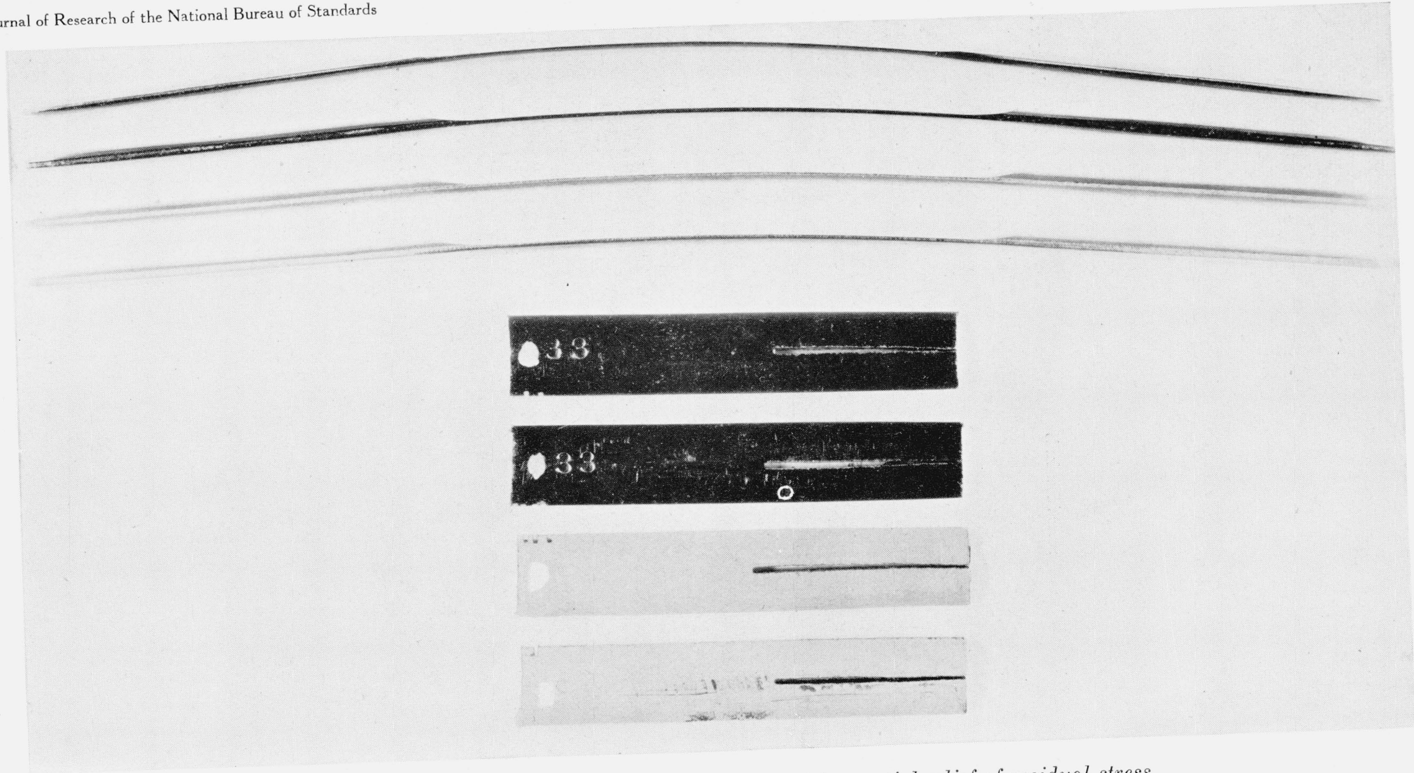

FIGURE 2.—*Distortion in tierod specimens caused by partial relief of residual stress.*

First. second, fifth, and sixth specimens from top are 18–8 stainless steel, others are SAE 1050 steel. ×0.8.

This assumption involved some error, as the actual stress distribution probably was not linear. For this reason the calculated average partial stress in the plane of the minor axis probably is too high, and the calculated partial stress at the end of the minor axis probably is too low. The sum of these partial stresses, however, is believed to be a fair index of the actual residual stress at the end of the minor axis.

The residual stress distribution in the tierods in the "as received" condition was determined by measurements on the major and minor axes of the streamline cross section. Distribution of longitudinal stresses with reference to the minor axis of the cross section was determined by measuring the change in width after partially splitting the tierod longitudinally by a saw cut. The cut ends of cold-worked tierod specimens approached each other, tending to close the saw cut. (See fig. 2.) This indicates initial tension along the longitudinal plane of the minor axis and compression at the ends of the major axis. The partial residual stress along the longitudinal plane of the minor axis (one-half width of saw cut from center of the major axis) was calculated, as follows:

The deflection caused by partially splitting a section by a saw cut was measured by the change in width due to cutting. The radius of curvature and calculated by the formula

$$R=\frac{L^2}{2d},$$

where R=radius of curvature in inches,
L=length of saw cut inches,
d=deflection (one-half the change in width).

The partial residual stress was then calculated by the formula

$$S_1=\frac{EC_1}{R},$$

where S_1=partial residual stress near the center of the major axis in pounds per square inch,
E=modulus of elasticity (3×10^7 lb/sq in.),
C_1=distance from saw cut to neutral axis of segment (0.42 times width of segment).

Stress distribution with respect to the major axis of the cross section was determined by measuring the deflection after machining specimens on one side to approximately half their original thickness. Partial relief of residual stress due to machining caused the specimens to become convex on the machined side (fig. 2). This indicates that the residual stress was compressive at the major axis and was tensile at the end of the minor axis. The partial residual stress at the end of the minor axis was measured as follows:

The amount of deflection at the end of the minor axis was measured with a micrometer depth gage having a length (chord) of 4 inches. The radius of curvature was calculated by the formula

$$R=\frac{L^2}{2d},$$

where L=one-half gage length in inches,
d=deflection in inches.

The partial residual stress was then calculated by the formula

$$S_2 = \frac{EC_2}{R},$$

where S_2=partial residual stress at the end of the minor axis in pounds per square inch,

C_2=distance from end of minor axis to neutral axis (0.58 thickness of specimen after machining, in inches).

A nominal value of the residual stress at the ends of the minor axis, therefore, would be the sum of the two partial residual stresses—the partial stress about an axis parallel to the minor axis (S_1) and the partial stress at the end of the minor axis (S_2) about an axis parallel with the major axis. In most tierods both stresses were tensile and in some of them the total residual stress was very high. The deformation caused by partial relief of high residual stresses in some of the tierod specimens is shown in figure 2.

Examples of the measurements of partial residual stress made for SAE 1050 steel tierod specimens (materials *A* and *B*) in the as-received condition are given in tables 2 and 3. Table 4 gives the approximate residual stress (the sum of the two partial residual stresses) at the end of the minor axis, obtained by similar measurements on all materials included in the investigation.

It is estimated that the experimental error involved in the measurement used in calculating the residual stress is less than 5 percent. In this connection, it will be noted in table 2 that actual measurements taken at various lengths of cut on specimens of *A* and *B* materials gave (except for the first readings on each) values for radius of curvature well within the calculated error.

TABLE 2.—*Partial residual stress near center of major axis of SAE 1050 steel (materials A and B) tierods in the as-received condition*

[Measurements made on specimens split by a saw cut]

Material		Original width	Width after splitting	Change in width (2*d*)	Length of cut (*l*)	Width of segment	Radius of curvature	Partial residual stress, tension (S_1)
		in.	*in.*	*in.*	*in.*	*in.*	*in.*	*lb/sq in.*
SAE 1050 steel	*A1*	0.551	0.532	0.019	1.28	0.26	86.2	38,300
	A2	.550	.523	.027	1.38	.26	70.5	46,800
	A3	.550	.523	.027	1.37	.26	69.5	47,500
	A4 [a]	.551	.547	.004	0.50	.26	62.5	48,600 average.
			.545	.006	.64	.26	68.3	
			.540	.011	.87	.26	68.8	
			.535	.016	1.05	.26	68.9	
			.527	.024	1.28	.26	68.3	
			.517	.034	1.55	.26	70.6	
SAE 1050 steel	*B1*	.547	.524	.023	1.48	.25	95.2	33,100
	B2	.547	.525	.022	1.45	.25	95.5	32,900
	B3	.546	.524	.022	1.43	.25	92.9	33,900
	B4 [a]	.547	.544	.003	0.51	.25	86.7	34,700 average.
			.542	.005	.68	.25	92.5	
			.536	.011	1.00	.25	91.0	
			.530	.017	1.24	.25	90.5	
			.525	.022	1.42	.25	91.7	
			.517	.030	1.65	.25	90.7	

[a] Measurements were made at various lengths of cut on specimens *A4* and *B4* to test the accuracy of method of calculation.

TABLE 3.—*Partial residual stress at end of minor axis of tierods in as-received condition, materials A and B*

[Measurements made on specimens machined to half of original thickness]

Material		Original thickness	Thickness after machining	Deflection in 4-in. gage length	Radius of curvature	Partial residual stress, tension (S_2)
		in.	*in.*	*in.*	*in.*	*lb/sq in.*
SAE 1050 steel	*A*	0.138	0.071	0.086	23.2	53,300
	B	.139	.070	.088	22.7	53,600

TABLE 4.—*Residual stress at end of minor axis of tierods in as-received condition*

Material		Partial residual stress, S_1	Partial residual stress, S_2	Residual stress $S=S_1/+S_2$	Ratio S_1/S
SAE 1050 Steel	*A*	+45,300	+53,300	+98,600	0.46
	B	+33,600	+53,600	+87,200	.39
18–8	*C*	+49,100	+79,100	+128,200	.38
	D	+55,100	+65,000	+120,100	.46
	E	+78,000	+75,000	+153,000	.51
	F	+47,400	+32,600	+80,000	.59
18–8 Ti	*G*	+36,400	+33,200	+69,600	.52
	H	+45,200	+58,600	+103,800	.44
	I	+40,600	+71,200	+111,800	.36
18–8 Cb	*J*	+42,200	+42,300	+84,500	.50
	K	+49,900	+71,300	+121,200	.41
	L	+33,900	+71,000	+104,900	.32
18–8 Mo	*M*	+55,000	+57,500	+112,500	.49
18–2	*N*	−19,400	*0	−19,400	---
	O	−4,500	*0	−4,500	---
	P	−4,900	*0	−4,900	---
16–1	*Q*	−19,400	*0	−19,400	---
	R	−8,700	*0	−8,700	---
	S	−7,400	*0	−7,400	---
K-monel	*T*	−3,600	*0	−3,600	---
	U	+7,400	+10,100	+17,500	.42
	V	+10,800	+12,900	+23,700	.46

\+ sign indicates tension.
− sign indicates compression.
* no appreciable deflection.

With all of the materials except 18–2, 16–1, and *K*-monel, severe cold-working during fabrication was relied upon to produce the high physical properties required in tierods. It is understood that these materials also received some cold-working during fabrication but were heat-treated afterward to obtain the required physical properties. It is evident from the measurements made on these specimens that the residual stress distribution resulting from heat treatment is just the opposite of that obtained from cold-working. Thus, in all the 18–2 and 16–1 tierods and in the smallest size *K*-monel tierods, the longitudinal stress along a plane containing the minor axis of the cross section was found to be compressive instead of tensile. In the two larger *K*-monel tierods, the stress was tensile but was very small compared with the values obtained with materials not heat-treated after fabrication. No attempt was made to relieve the relatively small amount of residual stress in these tierods by further heat treatment.

IV. RELIEF OF RESIDUAL STRESS BY LOW-TEMPERATURE HEAT TREATMENT

It was assumed that, in heating, the two partial residual stresses would be relieved in the same proportion. Either of the partial values and the mean value of the nominal residual stresses would, then, remain in the same ratio throughout the heat treatment. In the tests outlined below, the partial residual stress was determined by splitting the ends of specimens with a saw cut. The residual stress was then calculated by dividing by the ratio of partial to nominal residual stress displayed by each material in the as-received condition. This ratio is given in the last column of table 4.

Specimens of SAE 1050 steel tierod materials *A* and *B* were heated for periods of 30 minutes and 2 hours at temperatures between 200 and 900° F. Residual stress measurements for material *A* are given in table 5. These, together with tensile strength, permanent set, and elongation in 2 inches, obtained on specimens heated 30 minutes at the same temperatures, are shown diagrammatically in figure 3. Relief of residual stress was noticeable even at low temperatures. The stress fell off abruptly above 200° F, and at 600° F about two-thirds of the stress had been relieved. Heating for a longer period (2 hours) relieved the stress more effectively, especially at the higher temperatures. It is probable, however, that a longer heating period would also affect the tensile properties at lower temperatures.

Heating the SAE 1050 steel tierod specimens for 30 minutes caused a marked increase in tensile strength and permanent set values at temperatures up to 400° F and a rapid decrease above 500° F (fig. 3). Owing to the initial increase, these properties did not fall below the original values until the temperature exceeded 600° F, at which temperature most of the residual stress had been relieved.

TABLE 5.—*Effect of temperature and period of heating on relief of residual stress in size 3/8–24 SAE 1050 steel tierod specimens*

[Material *A*]

Heating temperature, °F	Residual stress after various heating periods, lb/in.² (tension)			
	30 minutes		2 hours	
	Partial (S_1)	Residual (S)	Partial (S_1)	Residual (S)
As-received	45, 300	98, 700	([a])	([a])
200	43, 500	94, 900	([a])	([a])
300	34, 200	74, 500	([a])	([a])
400	27, 000	58, 800	28, 400	61, 900
500	21, 900	47, 700	([a])	([a])
600	17, 800	38, 800	6, 200	13, 500
700	6, 600	14, 400	0	0
800	3, 000	6, 500	0	0
900	0	0	0	0

[a] No measurements made.

Examples of residual stress measurements made on 18–8 corrosion-resistant tierod specimens are given in table 6. Curves illustrating the effect of heat treatment on various sizes of tierods of this material are shown in figure 4. Curves of the same general character were obtained for like sizes of 18–8 materials containing alloy additions of titanium, columbium, and molybdenum. In general, heating at temperatures up to 700° F appeared to have little effect on relief of stress. Stress relief was most rapid at temperatures between 800 and 1,000° F. At 1,000° F most of the residual stress had been relieved.

It was noted that tierods of different sizes varied considerably in regard to uniformity of residual stress in the as-received condition.

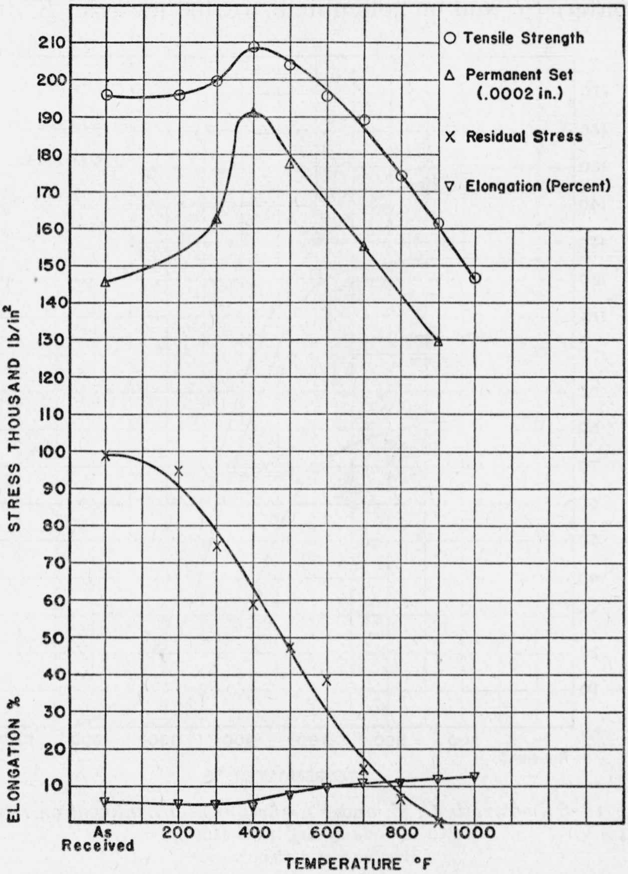

FIGURE 3.—*SAE 1050 steel (material A), effect of heat treatment on physical properties and relief of residual stress.*

Heating period, 30 minutes.

In tierods of intermediate size (½–20) the initial stress was much more uniform than in the larger (⅝–18) or smaller (10–32) sizes.

Much of the "scatter" obtained in residual stress measurements made with specimens heated at low temperatures was probably due to variations of initial stress among different specimens of the same material. With size ½–20 specimens the "scatter" was largely eliminated at higher temperatures. The curves showing the heating characteristics of the larger or smaller tie-rods were smoothed out, to some extent, by plotting the highest values obtained at any given temperature for the three heating periods used. This, in effect, increased the number of specimens in the low-temperature range.

Increasing the time of heating increased the amount of stress-relief at higher temperatures (800° to 1,000° F) but apparently had little effect at temperatures below 700° F (fig. 5).

The effects of heat treatment on the physical properties of specimens of 18–8 material *C* and on columbium-treated material *K* were found

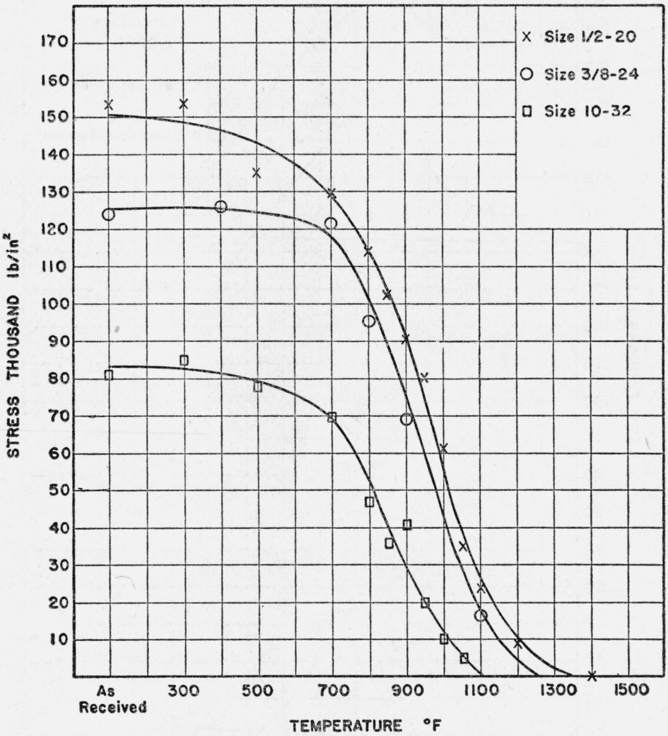

FIGURE 4.—*18–8 (materials C, E, and F), effect of heat treatment on relief of stress in tierods of different sizes.*

Heating period, 30 minutes.

to be quite similar (fig. 6 and 7). Both materials showed a slow and comparatively small increase in strength with heating temperature to a maximum at 800° to 900° F. Above these temperatures the rate of decrease was slow, so that the tensile strength, yield strength, and permanent set were maintained over a considerable range of temperature at values in excess of the original.

With the titanium-treated material *H*, the increase in strength with heating was much greater and occurred over a smaller range of temperature (fig. 8). At temperatures above 900° F the rate of decrease was rapid, but the strength at 1,000° F was still in excess of the original.

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TABLE 6.—*Effect of temperature and period of heating on relief of residual stress in size ½–20 18–8 stainless steel tierod specimens* [a]

[Material E]

Heating temperature	Residual stress after various heating periods, (lb/sq in. (tension)											
	30 minutes		1 hour		2 hours		5 hours		10 hours		24 hours	
	Partial (S_1)	Residual (S)	Partial (S_1)	Residual (S)	Partial (S_1)	Residual (S)	Partial (S_1)	Residual (S)	Partial (S_1)	Residual (S)	Partial (S_1)	Residual (S)
°*F*												
As-received	78,000	153,000	78,000	153,000	78,000	153,000	78,000	153,000	78,000	153,000	78,000	153,000
300	78,900	155,000	69,200	136,000	64,200	126,000						
500	68,600	135,000	66,300	130,000	64,200	126,000						
700	65,100	128,000	62,300	122,000	64,300	126,000	59,300	116,000	57,300	112,000	57,200	112,000
800	58,200	114,000	54,200	106,000	55,100	108,000	49,000	96,100	50,400	99,000	46,600	91,000
850	52,100	102,000	47,400	93,000	45,500	89,000	37,300	73,200	31,100	61,000	30,600	60,000
900	45,900	90,000	39,800	78,000	36,100	71,000	26,900	52,800	17,800	35,000	10,800	21,000
950	40,500	79,000	33,100	65,000	24,100	47,000						
1,000	31,100	61,000	24,100	47,000	15,300	30,000						
1,050	17,700	35,000	17,800	35,000	8,900	17,000						
1,100	12,300	24,000	9,200	18,000	5,500	11,000						
1,200	4,700	9,000	0	0	0	0						
1,400	0	0	0	0	0	0						

[a] Where values are omitted no measurements were made.

With all three materials, heating lowered the elongation values in the temperature range of maximum tensile strength. With the titanium-treated material especially, the elongation at intermediate temperatures was comparatively low. However, as most of the fractures occurred at or near the edge of the grips, the elongation measurements must be regarded as representing minimum values. Moreover, in the temperature range of most interest to this investigation (above 900° F), all three materials showed increased elongation. At 1,000° F, the elongation values were in all cases equal to or greater than the original.

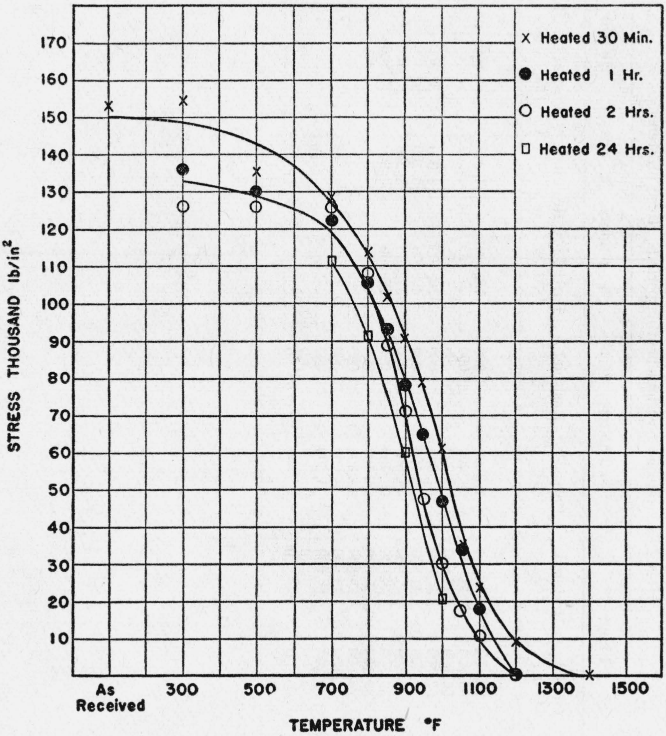

FIGURE 5.—*18–8 (material E), effect of temperature and period of heating on relief of residual stress.*

The values of "yield strength" (offset=0.2 percent) shown in the figures were determined from the stress-strain curves. It is defined as that stress at which the stress-strain curve is intersected by a line which intercepts the axis of the abscissas at 0.2-percent strain and is parallel to the slope of the stress-strain curve at the origin.

The permanent set was determined by measuring the difference in strain at a small initial load after loading and unloading to successively higher loads until sets of about 0.02 percent were noted. These data were referred to zero stress by plotting to a large scale and drawing a smooth curve through the observed points.

Vickers indentation tests were made on specimens of materials *E* and *M* after heating 30 minutes at temperatures ranging from 300° to 1,800° F. The Brinell numbers of these specimens are shown diagrammatically in figures 9 and 10. These curves display variations

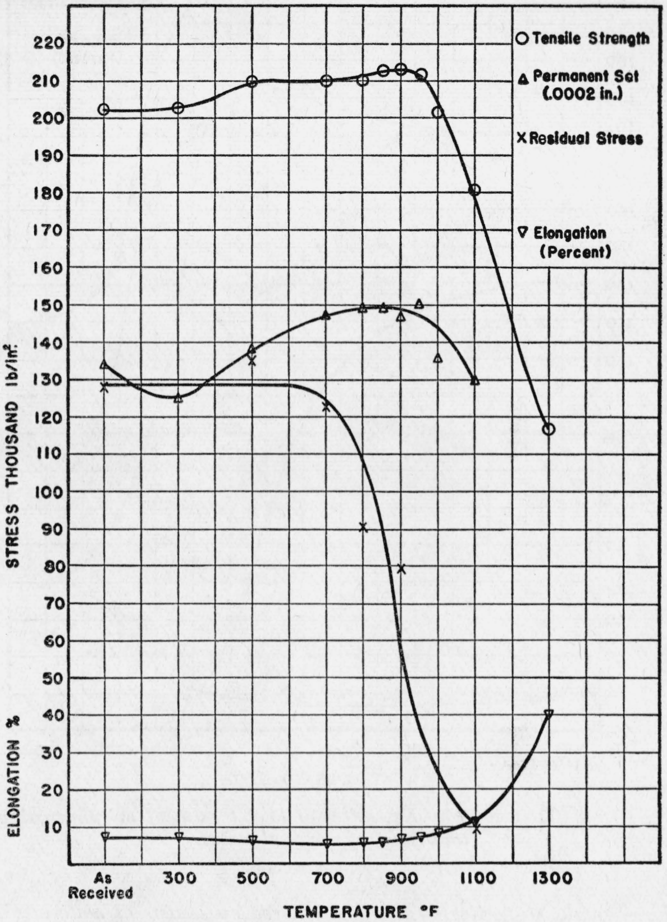

FIGURE 6.—*18–8 (material C), effect of heat treatment on physical properties and relief of residual stress.*

Heating period, 30 minutes.

of identation numbers with temperature similar to those exhibited by the tensile-strength curves obtained for similar materials.

The tensile properties of material *M* in the as-received condition are given in table 7. This table also contains the tensile properties of specimens of size ⅝–18 tierods of 18–2, 16–1, and *K*–monel (materials *P*, *S*, and *V*) in the as-received condition.

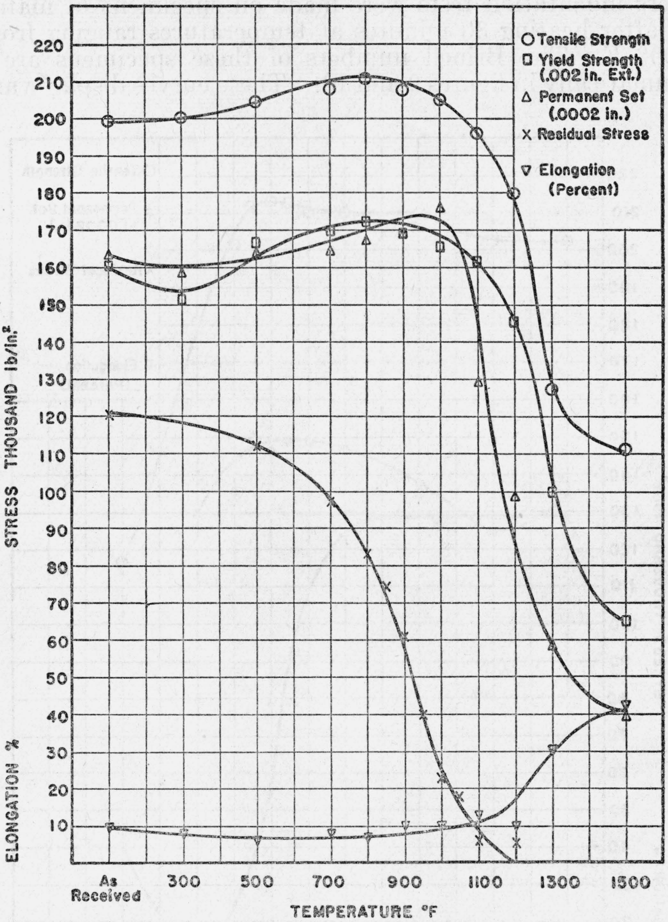

FIGURE 7.—*18–8–*Cb *(material K), effect of heat treatment on physical properties and relief of residual stress.*

Heating period, 30 minutes.

TABLE 7.—*Tensile properties of size ⅝–18 tierod specimens of materials M, P, S, and V in the as-received condition.*

Material	Ultimate tensile strength	Yield strength (offset=0.2 percent)	Permanent set (0.02 percent)	Elongation (2 in.)	Location of fracture
	lb/in.²	*lb/in.²*	*lb/in.²*	*Percent*	
M (18-8 Mo)	196, 100	139, 000	145, 000		Outside elongation marks.
	189, 100	140, 000	145, 000	7.0	Free length.
P (18-2)	216, 100	168, 500	169, 000	15.0	Do.
	211, 600	168, 000	166, 000	17.0	Do.
S (16-1)	195, 000	152, 500	169, 000	14.5	Do.
	192, 900	153, 000	159, 000	13.0	Do.
V (*K*-monel)	189, 100	175, 000	158, 000	10.0	Do.
	189, 500	175, 000	177, 000	11.0	Do.

Specimens of materials *E*, *H*, *K*, and M were tested, full size, in the Izod machine after heating 30 minutes at temperatures ranging from 300° to 1,400° F. All specimens of *E*, *K*, and *M* materials merely bent over without breaking. Complete breaks were obtained

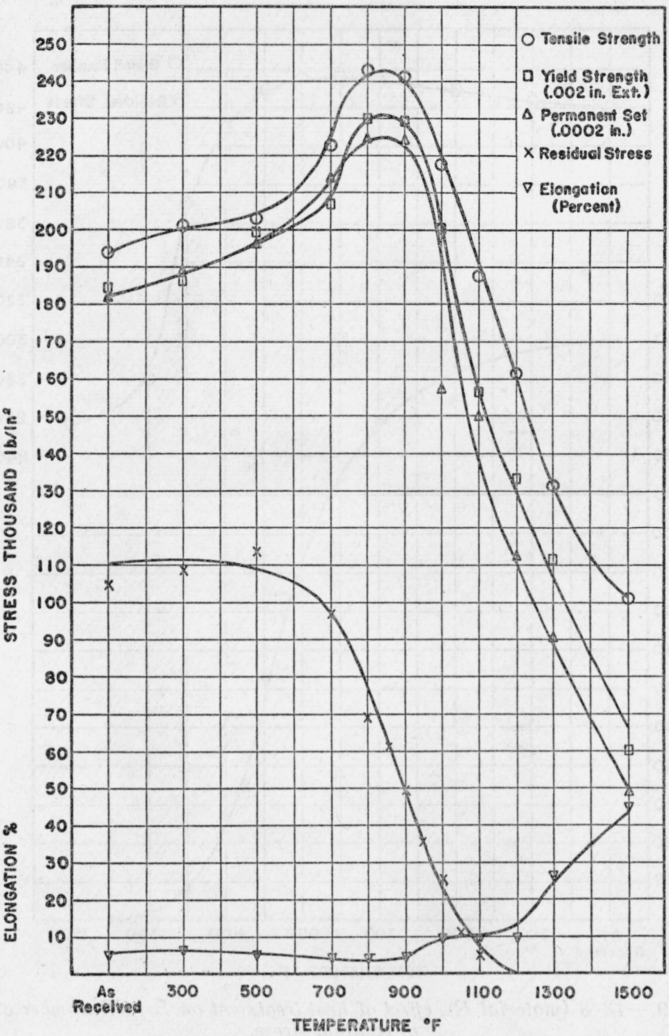

FIGURE 8.—*18–8–*Ti (*material H*), *effect of heat treatment on physical properties and relief of residual stress.*

Heating period, 30 minutes.

only on specimens of *H* material heated at 800°, 900°, and 1,000° F. Even in these cases the specimens bent considerably before fracture. The tup dragged along the specimen, and the values of energy consumption, therefore, had no significance. The tests indicated, however, that heating for 30 minutes at temperatures up to 1,400° F. did not produce extreme brittleness in any of these materials.

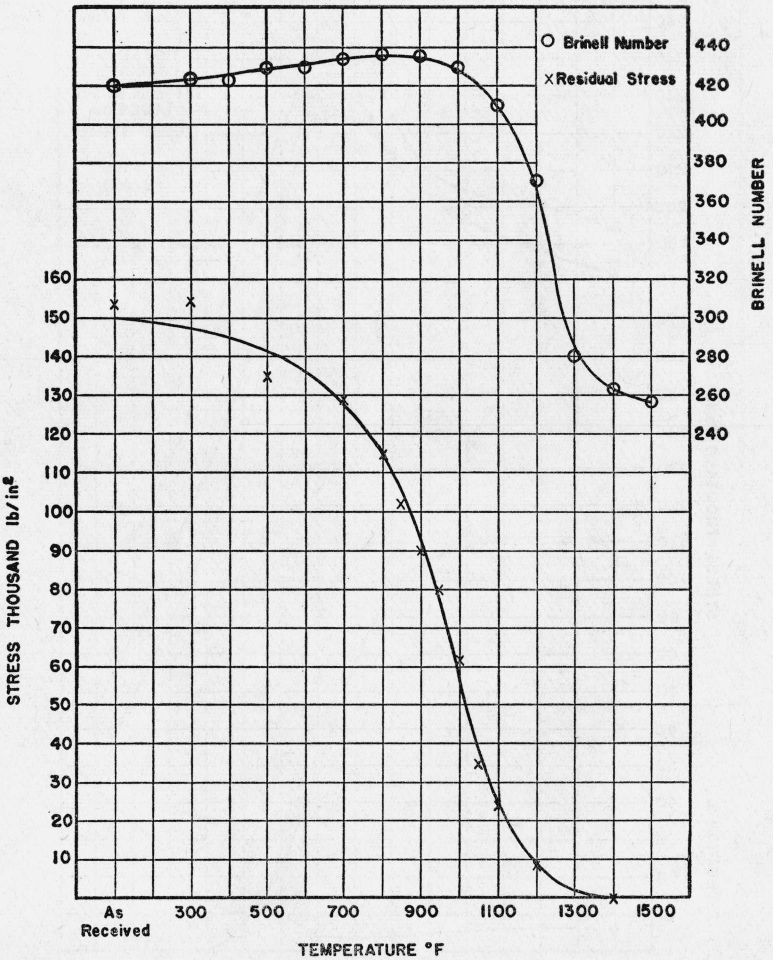

FIGURE 9.—*18–8 (material E), effect of heat treatment on Brinell number and relief of residual stress.*

Heating period, 30 minutes.

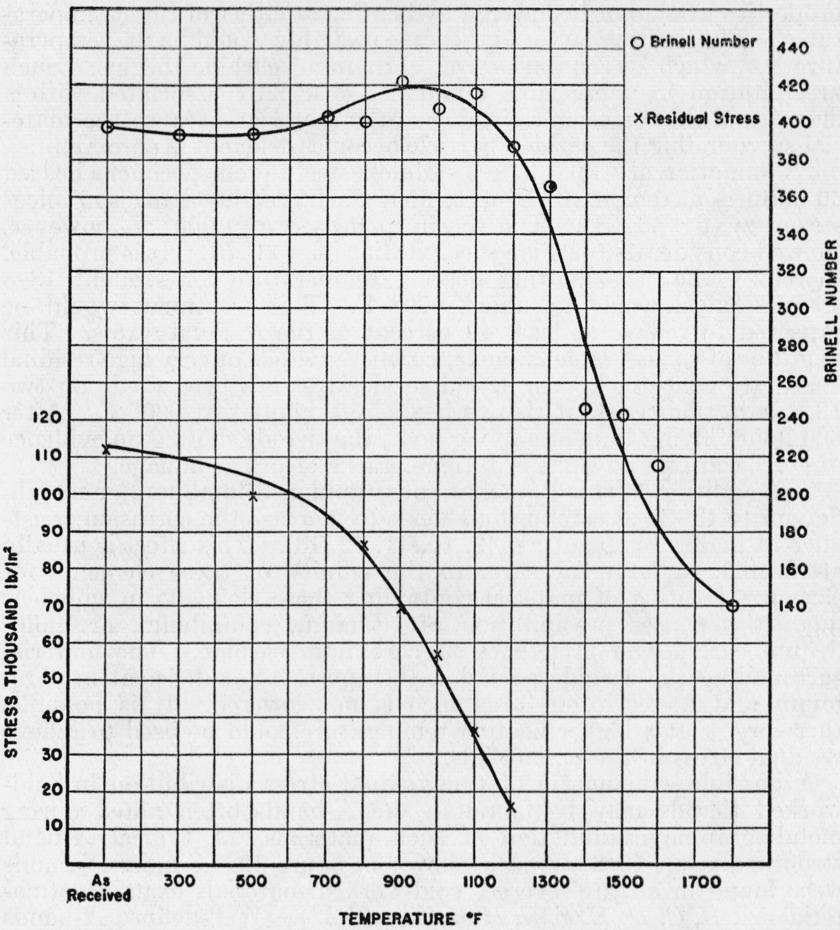

FIGURE 10.—*18–8–*Mo (*material M*), *effect of heat treatment on Brinell number and relief of stress.*

Heating period, 30 minutes.

V. DISCUSSION OF RESULTS

The test results indicate that a large part of the residual stress in SAE 1050 steel tierods can be relieved easily by low-temperature heat treatment. Heating the specimens for 30 minutes at 600° F, for instance, relieved about two-thirds of the stress in the ⅜–24 size tierod without lowering the important mechanical properties of the material. Since this type of tierod depends for protection upon a cadmium coating applied after fabrication, heat treatment would have no adverse effect on its corrosion resistance.

With the stainless steel tierods the effective range of heat-treating temperature appears to be very narrow. For a 30-minute heating period, substantial relief of stress would require a heating temperature of 900° to 1,000° F. The tensile tests indicate that the mechanical properties would not be lowered by heating at either of these temperatures. The limiting factor in this case probably would be the temperature at which precipitation of chromium carbide begins. Such precipitation in appreciable quantities is usually associated with a decrease in the corrosion resistance of the material, because the material surrounding the carbide particle becomes deficient in chromium.

Examination of straight 18–8 stainless steel tierod specimens heated 30 minutes at temperatures up to 900° F. showed no changes in micostructure (fig. 11, *A*). The specimen heated at 1,000° F, however, showed considerable carbide precipitation (fig. 11, *B*). It is probable, therefore, that the limiting heating temperature for straight 18–8 stainless steel would be about 900° F. This treatment would be expected to relieve at least 40 percent of the residual stress. This might be of considerable importance where tierods of very high residual stress are concerned. An actual service test has been made on two 18–8 corrosion-resistant tierods heated 30 minutes at 900° F. After 800 hours' flying time in a flying boat, the tierods showed no evidence of corrosion and no signs of fatigue cracks or other damage.

The addition of small amounts of titanium, columbium, or molybdenum to the 18–8 composition tends to increase the corrosion resistance at higher temperatures [9, 10, 11, 12, 13]. This effect is usually attributed, in large measure, to the affinity of these elements for carbon. Heating of material containing these elements in sufficient quantities causes precipitation of titanium, columbium, or molbdenum carbides in preference to chromium carbide. The material surrounding the carbide particles, therefore, is not deficient in chromium and its corrosion resistance is not lowered. It is possible, therefore, that a higher heating temperature could be used to relieve residual stress in these materials.

A possible explanation of the residual stress distribution in cold-worked tierods may be found in the *X*-bands often noted during metallographic examination of such materials. A typical *X*-band structure in an 18–8 tierod is shown in figure 12. Similar *X*-bands were found in all the severely cold-worked materials examined (materials *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*, *J*, *K*, and *M*). Well-defined *X*-bands were also found in *K*-monel tierods (materials *U* and *V*), but none were detected in 18–2 or 16–1 tierods, materials *O*, *P*, *R*, and *S*. It is believed that these bands are zones in which the metal has been more severely cold-worked during fabrication than in zones outside the bands. Evidence based on the microstructure of some of the materials and on Vickers indentation tests supports this view.

The typical microstructure on transverse sections within and outside the *X*-bands in a specimen of an 18–8 stainless steel tierod is shown in figure 13. Comparison of the size of grains in these micrographs shows that they are smaller and more uniformly deformed within the *X*-band than in areas outside. Vickers indentation tests made on a transverse section of a tierod of *M* material (18–8 Mo) showed that the metal within the bands was distinctly harder than that outside. The average value of readings obtained within the bands was 423 (Vn-30). Outside the bands the average value was 388.

According to Heyn's original theory of the origin of residual stresses in metals, the more severely cold-worked metal within the *X*-bands

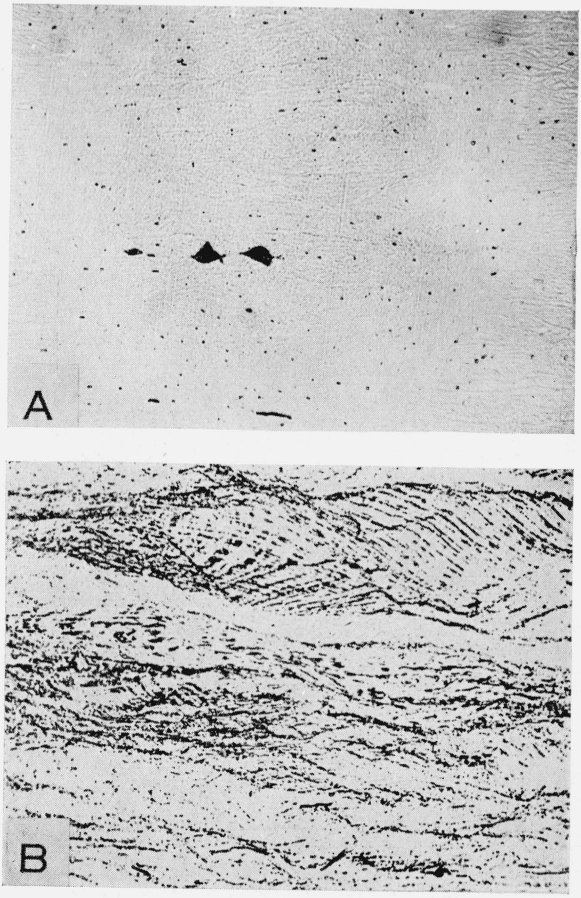

Figure 11.—*18–8 (material E), microstructure of specimens heated 30 minutes at: A, 900° F.; B, 1,000° F. ×500.*

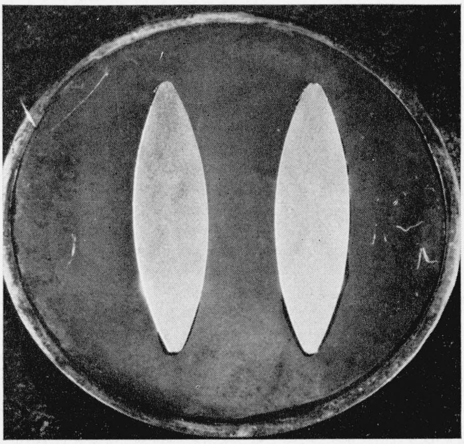

FIGURE 12.—*X-bands in transverse sections of 18–8 tierods.*

Electrolytic etch in 10-percent oxalic acid. ×2.

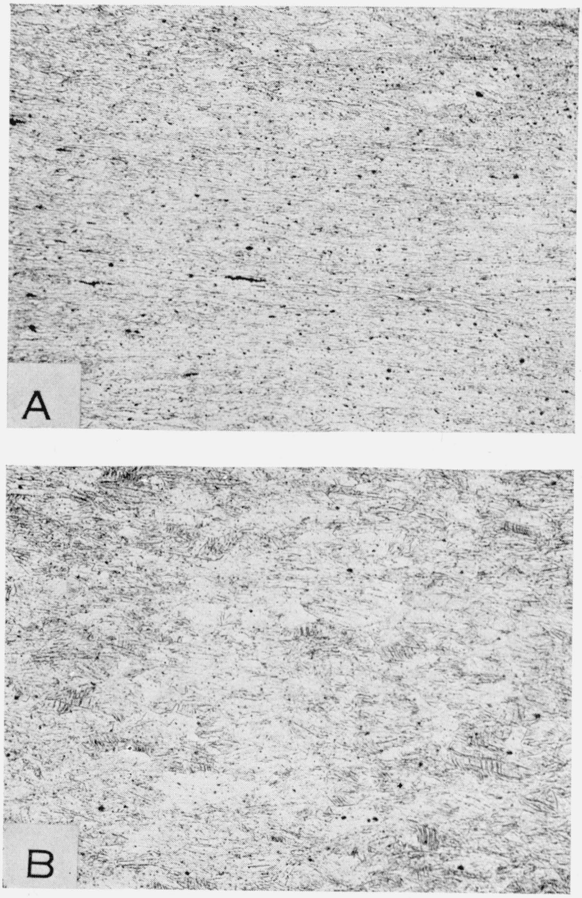

FIGURE 13.—*A, microstructure within X-band; B, microstructure outside X-band.*

Electrolytic etch in 10-percent oxalic acid. ×100.

would tend to be of greater length than the surrounding areas if both were unrestrained. Actually, however, under mutual restraint, the two areas assume an intermediate length, residual compressive stresses being set up in the more severely cold-worked areas while areas less severely cold-worked are in tension.

Although *K*-monel tierods also showed *X*-bands, the Vickers indentation number of metal within the bands was not appreciably higher than that outside. It is probable that the heat treatment received by this material after fabrication caused the hardness to become more uniform, even though the material was not completely recrystallized to remove all evidence of cold work. In this connection, it was noted that complete recrystallization during annealing of any of the materials caused disappearance of the *X*-bands.

VI. SUMMARY

Streamline tierods of various compositions were investigated with regard to relief of residual stress by low-temperature heat treatment.

It was found that about two-thirds of the residual stress in tierods of SAE 1050 steel could be relieved by heating them 30 minutes at 600° F. This treatment did not materially lower the mechanical properties of the material.

Tierods of 18–8 stainless steel or the same with additions of titanium, columbium, or molybdenum could be heated at temperatures up to 1,000° F without seriously lowering the mechanical properties of the materials. At this temperature most of the residual stress would be relieved.

Heating tierods of straight 18–8 composition for 30 minutes at 1,000° F, however, caused precipitation of chromium carbides. The limiting temperature for this material, therefore, probably would be about 900° F. Heating tierods 30 minutes at this temperature would relieve about 40 percent of the residual stress. It is possible that tierods containing additions of titanium, columbium, or molybdenum could be heated at higher temperatures, since in these materials the carbides of these elements would be precipitated in preference to chromium carbide.

Tierods of 18–2, 16–1, and *K*-monel, which had been heat-treated during fabrication, were found to contain very low residual stress in the as-received condition. Further heat treatment for relief of stress would not be necessary.

Microscopic examination and Vickers indentation tests indicated that the metal within the *X*-bands often noted in cold-worked tierods had been more severly cold-worked than that outside the bands. It is probable that the distribution of residual stresses was influenced by these localized differences in amount of cold working.

The authors acknowledge their indebtedness to D. J. McAdam, Jr., who developed the formulas used in estimating residual stress; to C. S. Aitchison and R. W. Mebs, who made the tensile tests; and to H. L. Logan, who performed some of the work on *X*-bands.

VII. REFERENCES

[1] J. E. Howard, Trans. Am. Inst. Metals **7,** 101 (1913).
[2] E. Heyn, J. Inst. Metals **12,** 3 (1914).
[3] P. D. Merica and R. W. Woodward, Tech. Pap. BS **9,** T82 (1917).
[4] G. Sachs, Z. Metallkunde **19,** 352 (1927).
[5] O. V. Green, Trans. Am. Soc. Steel Treating **18,** 369 (1930).
[6] L. W. Kempf and R. R. Van Horn, Am. Inst. Min. Met. Engrs. Tech. Pub. 1334–E. 350, Metals Tech. **8,** (June 1941).
[7] W. H. Hatfield and G. L. Thirkell, J. Inst. Metals **22,** 67 (1919).
[8] D. K. Crampton, Trans. Am. Inst. Min. Met. Engrs. **89,** 233 (1930).
[9] P. Payson, Trans. Am. Inst. Min. Met. Engrs. **100,** 306 (1932).
[10] E. C. Bain, R. H. Aborn, and J. J. Rutherford, Trans. Am. Soc. Steel Treating **21,** 481 (1935).
[11] V. N. Krivobok and associates, Trans. Am. Soc. Steel Treating **21,** 22 (1933).
[12] F. M. Becket and R. Frank, Trans. Am. Inst. Min. Met. Engrs. **113,** 143 (1934).
[13] R. Frank, Trans. Am. Soc. Metals **27,** 505 (1939).

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