U. S. Department of Commerce
National Bureau of Standards

Research Paper RP2011
Volume 43, August 1949

Part of the Journal of Research of the National Bureau of Standards

Effect of Chromium Plating on the Endurance Limit of Steels Used in Aircraft

By Hugh L. Logan

Chromium plating reduced the endurance limits of both normalized and hardened (quenched and tempered) SAE X4130 steels; the reduction was larger for the hardened steel. The endurance limits for steel of a given hardness decreased with increased plating bath temperatures. Baking of the plated steel, at temperatures up to 350° C, reduced the endurance limit; baking at 440° C increased the endurance limit of the plated steel. However (for hardened steel) baking did not restore the endurance limit to that of the unplated steel. Damaging effects of chromium on the endurance limits of plated steels are attributed to stresses in the chromium and/or steel, which are increased by low temperature baking but are relieved in part by baking at 400° to 440° C.

I. Introduction

During the period of 1930 to 1936 the Bureau of Aeronautics, Navy Department, submitted for examination a number of chromium-plated hollow-steel airplane propeller blades that had failed by fatigue in service. Preliminary fatigue tests in the laboratory confirmed conclusions, based on the examination of the propeller failures, that the endurance limit of the steel was materially reduced by chromium plating. In addition to the plating of propeller blades and other parts for protective purposes, manufacturers and maintenance shops were exploring the possibilities of reclaiming by chromium plating worn and undersize parts. These considerations prompted the Bureau of Aeronautics to support an extensive investigation conducted by the National Bureau of Standards on the effect of chromium plating on the endurance limits of steels used in aircraft.

Two steels designated SAE X4130 and 6130 were used in the investigation. However, most of the tests were made on X4130 steel, heat treated to a hardness of about Rockwell 40-C, with an ultimate tensile strength of approximately 180,000 lb/in.^{2}

The first phase of this study provided for the determination of the effects of chromium, as plated, on the endurance limit of the steels. The variables studied were: (1) plate thickness, (2) hardness of the steels plated, (3) current densities and temperatures of the plating baths, (4) surface grinding of the chromium after plating, and (5) interruptions of the plating process.

A second phase of the investigation was a systematic study of the effect of heating on the endurance limit of specimens of chromium-plated X4130 steel. If the decrease in the endurance limit of the plated steel is attributable to the large quantities of hydrogen evolved at the cathode during the process of chromium plating, then it appears that the endurance limit may be increased by the removal of hydrogen by heating. However, Swanger and France [1] [1] found that heating the specimens for 5 hours at 350° F (182° C) reduced the endurance limit of the plated steel to about 70 percent of that of the plated but unheated material. Wiegand and Scheinost [2] also reported that heating of chromium plated steel at 250° C decreased its endurance limit. Other workers have spot checked the effect on the endurance limit of heating chromium-plated steel. However, no systematic study of the effect of heating had been made.

A theory has been developed to explain, at least in part, the effects of chromium plating on the endurance limit of the steels studied.

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

Publication of this material, including data circulated during wartime in reports [3] that at that time were restricted but have since been declassified, has been approved by the Bureau of Aeronautics, sponsor of the investigation.

II. Materials

The materials, from which the specimens for this investigation were machined, consisted of three lots of SAE X4130 rod and one lot of 6130 rod. The compositions of these steels, as determined by chemical and spectrochemical analyses, are shown in table 1.

TABLE 1. *Composition of steels*

Element	SAE X4130 Steel			SAE 6130 Steel
	Lot A	Lot B	Lot C	
	Percent	*Percent*	*Percent*	*Percent*
Carbon	0.35	0.29	0.33	0.30
Manganese	.53	.47	.55	.61
Phosphorus	.01	.02	.03	.03
Sulfur	.02	.02	.01	.04
Silicon	.21	.25	.24	.25
Chromium	.95	.96	1.05	1.01
Molybdenum	.19	.24	0.20	(1)
Vanadium	(1)	(1)	(1)	0.22
Nickel	(1)	.15	.17	(1)

[1] Not determined.

Lot A of the X4130 steel was supplied by the Naval Aircraft Factory in two heat-treated conditions, normalized to Rockwell hardness number B–89, and quenched and tempered to Rockwell C–39. The 6130 steel was also supplied by the Naval Aircraft Factory but only in the quenched and tempered condition, Rockwell C–33. The other lots of X4130 rod were heat-treated at the National Bureau of Standards; they were quenched in oil from 1,575° to 1,600° F and subsequently tempered to approximately Rockwell C–40.

Typical microstructures of transverse sections of the steels are shown in figure 1. A longitudinal section of the normalized X4130 steel (not illustrated) showed definite indications of banding and segregation, which are not unusual for this type of steel.

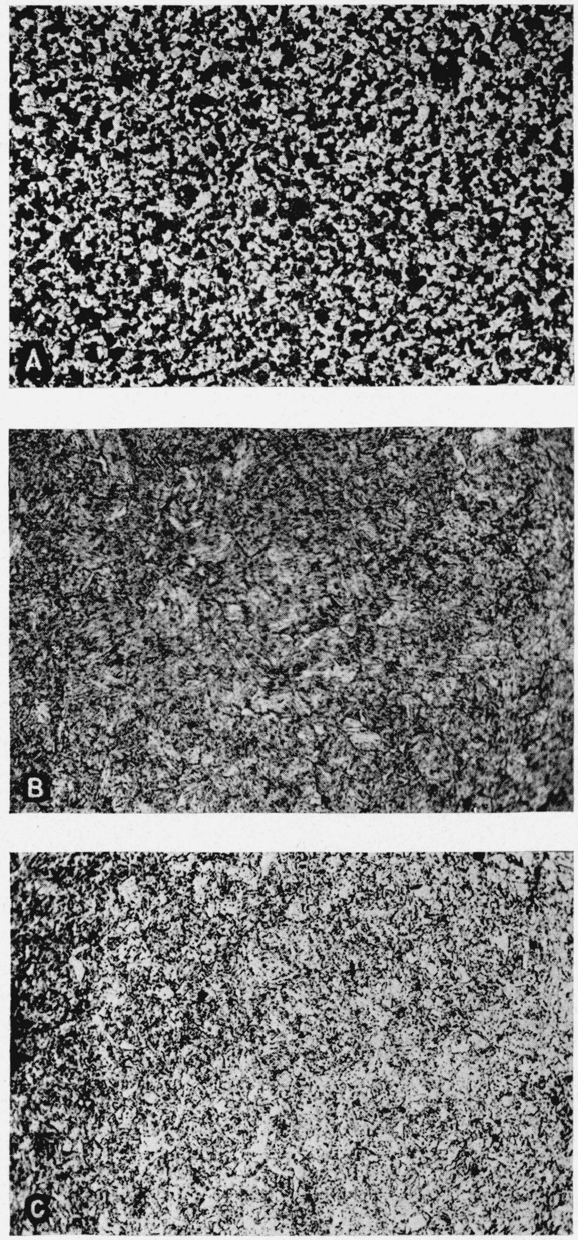

FIGURE 1. *Typical microstructures of transverse sections of steels investigated*

A, normalized X4130 steel, x100; B, Quenched and tempered X4130 steel, x500; C, quenched and tempered 6130 steel, x500. All etched 1 percent Nital.

III. Specimens and Test Methods

1. Preparation and Testing of Specimens

Specimens for the fatigue tests were of the usual "R. R. Moore type" [4] with nominal diameters of 0.30 in. in most cases; however, 0.25-in.-diameter specimens were used in some instances. Computation of the stresses in the outer fibers of the specimens, and hence the endurance limits, were based on the diameters of the specimens prior to plating. Diameters of all specimens machined at this Bureau were determined, before

TABLE 2. *Details of preparation of specimens used in the investigation*

SAE No.	Steel lot	Heat treatment	Rockwell hardness	Specimens prepared for plating by [1]	Specimens chromium plated by	Temperature of plating bath	Plating current density	Nominal thickness of plating
						° C.	amp/sq. ft.	in.
X4130	A		89–B	NAF	NAF	55	200	0.0001; 0.001; 0.004; 0.009 [2]
X4130	A		89–B	do	do	70	1,000	0.0001; 0.001; 0.004; 0.009 [2]
X4130	A		39–C	do	do	55	200	0.0001; 0.001; 0.004; 0.009 [2]
X4130	A		39–C	do	do	70	1,000	0.0001; 0.001; 0.004; 0.009 [2]
6130			33–C	do	do	55	200	0.0001; 0.001; 0.004; 0.009 [2]
6130			33–C	do	do	70	1,000	0.0001; 0.001; 0.004; 0.009 [2]
X4130	B	Oil quenched from 1,575 to 1,600° F. drawn at 900 to 925° F.	40–C	NBS	do	70	1,000	0.009
X4130	C		40–C	do	NBS	70	1,000	0.009.
X4130	C		40–C	do	do	55	350	0.001· 0.005; 0.010; 0.017.
X4130	C		40–C	do	do	85	700	0. 010.

[1] Includes heat treating, machining, and usually polishing.

[2] Two groups of specimens had been plated to a thickness of about 0.008 in. One of these groups was stated to have been plated to a thickness of 0.010 in. with about 0.001 in. of plate subsequently removed by grinding.

and after plating, with a dial gage comparator reading to 0.0001 in.

Prior to the final polishing, the specimens prepared at this Bureau were ground with a Norton "38" alundum wheel. Subsequently these grinding marks were removed with metallographic polishing papers by one of the following methods: (a) circumferential polishing of specimens in a lathe for fixed periods, determined by experiment to be sufficient to remove grinding marks or marks of coarser papers previously used (papers used were Behr-Manning emery 1, Aloxite 400, Behr-Manning emery 1/0 and 2/0); or (b) longitudinal polishing of specimens using Aloxite 400 paper followed by the Behr-Manning emery 1/0 polishing paper in the form of belts mounted on a rubber-backed wheel. In some instances commercially available coarse and medium emery-impregnated rubber wheels were used in place of the abrasive paper belts.

A few of the mechanically polished specimens were subsequently polished electrolytically as follows: Specimens were made the anodes in a bath containing 50 percent by volume of concentrated H_2SO_4 and 50 percent by volume of 75 percent H_3PO_4; a current density of 250 amp/ft ^{2} was maintained for 5 minutes; the temperature was 42° C. This reduced the diameters of the specimens by 0.0004 to 0.0006 in. Details regarding the preparation of the fatigue specimens are given in table 2.

Fatigue tests were made in R. R. Moore type rotating beam fatigue testing machines operating at 1,800 or 3,600 revolutions per minute with stresses generally applied in increments of 1,000 lb/in^2. Generally, eight to ten specimens were required to obtain the endurance limit in any one case. Specimens that had run 10,000,000 or more cycles without failure were considered to have been stressed at or below the endurance limit and were removed from the machines.

2. Electroplating of Specimens

Specimens were plated at the National Bureau of Standards by personnel of the Electrodeposition Section. The process prior to plating was as follows: Specimens were cleaned by scrubbing with fine pumice powder and rinsed thoroughly with water. The light oxide film that formed during the time required to assemble the specimens in the plating rack was removed by dipping for a few seconds in 20-percent hydrochloric acid solution. The specimens were again rinsed, placed in the chromium plating solution, and made anodic for 1 minute at the same current density used in plating. After the anodic treatment, full plating current was immediately applied.

The plating electrolyte contained 250 g/liter of CrO_3 and 2.5 g/liter of H_2SO_4. Specimens were plated at three different bath temperatures and current densities. A bath temperature of 55° C and a current density of 350 amp/ft^2 were selected as one condition, because they were within the range (45° to 60° C. and 70 to 450 amp/ft^2) generally used in industrial chromium plating. A temperature of 70° C and a current density of 1,000 amp/ft^2 were employed for the second condition in order to check certain results previously obtained in this investigation on

843576—49——2

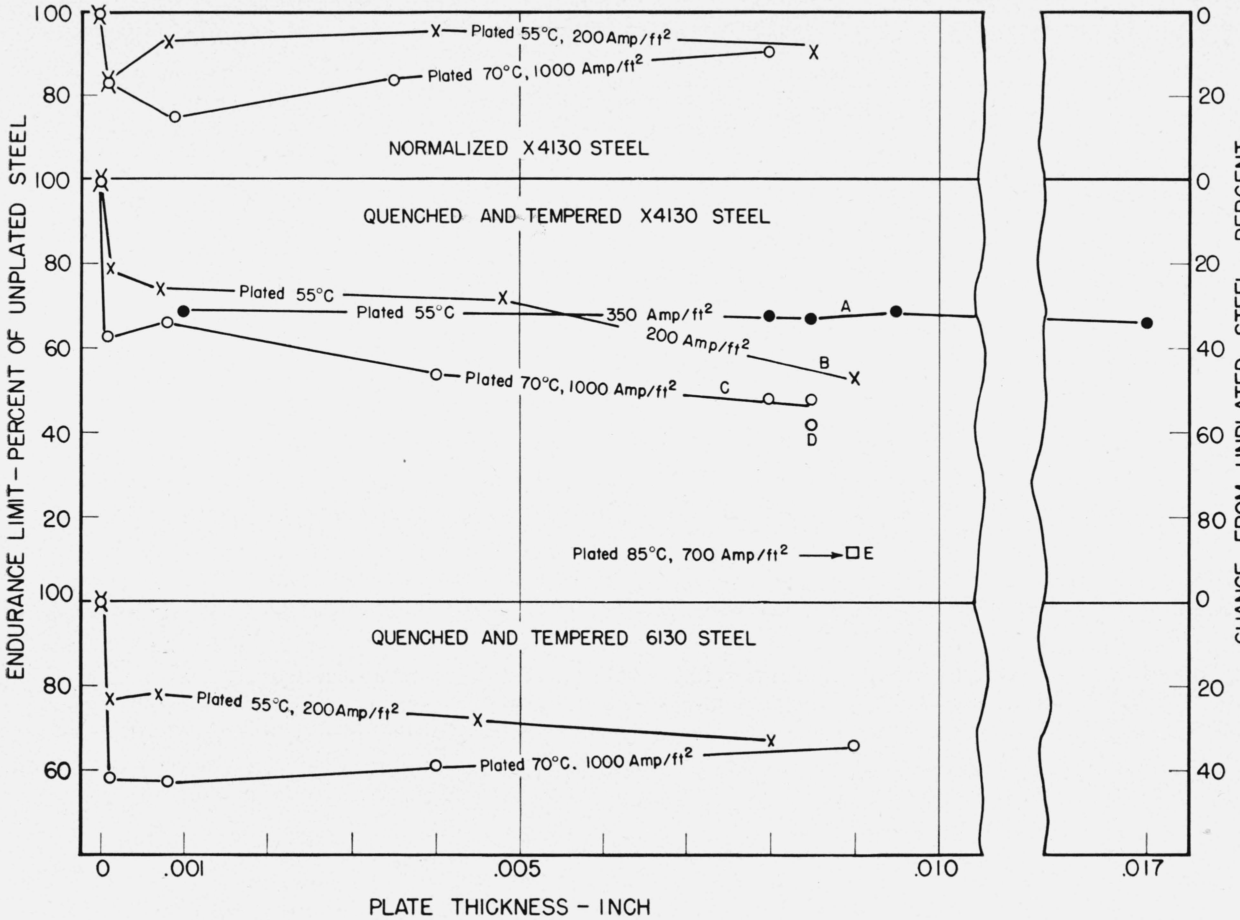

FIGURE 2. *Relationship between the endurance limits and plate thicknesses of X4130 and 6130 steels.*

Data obtained on specimens plated at NBS are shown by curve A and points D and E. All other data were obtained on specimens plated at the NAF.

specimens similarly plated at the Naval Aircraft Factory. A bath temperature of 85° C and a current density of 700 amp/ft² were selected for the third condition, since chromium deposited in this way is supposed to be subject to less contraction when heated than is chromium plated under the other conditions, and it appeared advisable to determine the extent to which this factor might affect the endurance limit of the steel.

In order to determine the effect of interrupted plating on the endurance limit, two sets of specimens were plated to the same final thickness; one set was plated continuously and the other by an interrupted operation. Plating was resumed following the interruption only after the employment of the proper commercial technique for plating chromium on chromium; this involved a short reversal of the current and the gradual increasing of the current from a low value to the plating current.

No information was provided by the Naval Aircraft Factory as to the surface preparation, after the final machining and prior to plating, of fatigue specimens prepared at that agency. The composition of the plating bath used by the Naval Aircraft Factory in plating of fatigue specimens was the same as that used at this Bureau and described above; specimens were stated to have been plated in a bath maintained at 55° C at a current density of 200 amp/ft² and at 70° C and 1,000 amp/ft².

3. Heat Treatment of Chromium-Plated Specimens

Some specimens were heated in oil at about 100° C, in boiling ethylene glycol at 193° C, or in N-butal phthalate at 297° C. Other specimens were heated to temperatures up to 200° C in an electrically heated laboratory oven, with forced air circulation, thermostatically controlled to ±2° C. Temperatures of 300°, 350°, 400°, and

440° C, controlled to ±3° C, were obtained with an electrically heated tempering furnace with forced air circulation.

IV. Results and Discussion

1. Effect of Chromium Plating on the Endurance Limits of SAE X4130 and SAE 6130 Steels

(a) Normalized X4130 Steel

The results of fatigue tests on the normalized X4130 steel (heat A) are given in table 3 and shown graphically in figure 2. The decrease in the endurance limit of the normalized steel caused by chromium plating was generally small; the minimum endurance limit of any group of plated specimens was 75 percent of the endurance limit of the unplated steel. This value was obtained on specimens plated to a thickness of 0.001 in. at a current density of 1,000 amp/ft^2. Most sets of specimens had endurance limits ranging from 83 to 95.5 percent of that of the unplated steel. Specimens plated in the bath at 55° C and a current density of 200 amp/ft^2 had endurance limits equal to or greater than those plated at 70° C and 1,000 amp/ft^2.

(b) Quenched and Tempered SAE X4130 Steel

The results of fatigue tests on quenched and tempered SAE X4130 steel (lots A, B, and C), hardness approximately 40 Rockwell C, bare, and plated to various thicknesses under various plating conditions are given in table 3. Most of the data are also shown graphically in figure 2. The endurance limits of the quenched and tempered steel specimens were reduced much more by chromium plating than were those of the normalized specimens (hardness, Rockwell 89–B). The maximum endurance limits of specimens plated to a thickness of 0.008 to 0.010 inch at a bath temperature of 55° C and tested as plated were 68 to 69 percent of that of the unplated steel. Endurance limits of the specimens in general decreased with increased bath temperatures. Specimens plated at 70° C to the same thickness as those plated at 55° C and discussed above had endurance limits 40 to 48 percent of that of the unplated steel, and

TABLE 3. *Endurance limits of unplated and chromium-plated steels*

Steel	Nominal plating thickness— 0 inch	0.0001 inch		0.001 inch		0.004 inch		0.009 inch		Ground to 0.009 inch		0.017 inch	
	lb/in.^{2}	*lb/in.*^{2}	%[1]	*lb/in.*^{2}	%[1]	*lb/in.*^{2}	%[1]	*lb/in.*^{2}	%[1]	*lb/in.*^{2}	%[1]	*lb/in.*^{2}	%[1]
PLATED AT 70° C—CURRENT DENSITY 1,000 AMP/FT^2													
Normalized X4130. Hardness, Rockwell 89–B	44,000	36,500	83	33,000	75	37,000	84	40,000	91	38,000	86	----	------
Q & T 6130. Hardness, Rockwell 33–C	83,000	48,000	58	47,000	57	51,000	61	55,000	66	55,000	66	----	------
Q & T X4130. Hardness, Rockwell 39–C	93,000	59,000	63	61,000	66	50,000	54	45,000	48	58,000	62	----	------
PLATED AT 55° C—CURRENT DENSITY 200 AMP/FT^2													
Normalized X4130. Hardness, Rockwell 89–B	44,000	37,000	84	41,000	93	42,000	95.5	40,000	91	45,000	102	----	----
Q & T 6130. Hardness, Rockwell 33–C	83,000	64,000	77	65,000	78	60,000	72	56,000	67	61,000	74	----	----
Q & T X4130. Hardness, Rockwell 39–C to 40–C	93,000	73,000	79	69,000	74	67,000	62	49,000	53	65,000	70	----	----
PLATED AT 55° C—CURRENT DENSITY 350 AMP/FT^2													
Q & T X4130. Hardness, Rockwell 39–C to 40–C	93,000	----	----	66,000	71	----	----	64,000	69	----	----	61,000	66
PLATED AT 85° C—CURRENT DENSITY 700 AMP/FT^2													
Q & T X4130. Hardness, Rockwell 39–C to 40–C	93,000	----	----	----	----	----	----	10,000	11	----	----	----	----

[1] Percentage of unplated steel.

those plated at 85° C only 11 percent of that of the unplated steel.

Endurance limits of specimens of the quenched and tempered steel, plated at the Naval Aircraft Factory (table 2), generally decreased with increased plate thickness (fig. 2, curves B and C). There was no significant change in endurance limit with increased plate thickness for specimens plated at 55° C at the NBS (fig. 2, curve A). Plating at this Bureau in the bath at 55° C was at a current density of 350 amp/ft^2 as compared to a current density of 200 amp/ft^2 at that temperature at the Naval Aircraft Factory. Specimens plated by the Naval Aircraft Factory to a thickness of approximately 0.009 in. at 70° C, current density 1,000 amp/ft^2, had a 14-percent higher endurance limit than specimens plated under the same conditions at this Bureau. Curve *C*, fig. 2 represents Naval Aircraft Factory specimens, and point *D*, National Bureau of Standards specimens.

There was no significant difference in the endurance limits of two sets of specimens, both plated to the same final thickness under similar conditions, of which one was plated continuously and the other by an interrupted operation.

(c) Quenched and Tempered SAE 6130 Steel

The results of fatigue tests on the quenched and tempered SAE 6130 steel (hardness Rockwell 33–C), bare and plated to various thicknesses at current densities of 1,000 and 200 amp/ft^2, are given in table 3 and are shown graphically in figure 2.

Endurance limits of specimens plated at 70° C increased as the plating thickness was increased above 0.001 in.; on the other hand, the endurance limits of specimens plated at 55° C decreased with increased plate thickness above that value. The endurance limits of specimens with 0.009-in. thick plating were approximately the same for both sets of plating conditions and amounted to 66 to 67 percent of that of the unplated steel. Specimens plated to thicknesses of 0.0001 and 0.001 in. had endurance limits of 77 to 78 and 57 to 58 percent of that of the unplated steel for bath temperatures of 55° and 70° C, respectively.

The data obtained on the ground and unground specimens having approximately the same final plate thickness (0.009 in.), in general, indicated that the ground specimens had endurance limits equal to or greater than those of the "as plated" specimens (table 3).

2. Effect of Heating on the Endurance Limit of Chromium-Plated X4130 Steel

The results of fatigue tests on specimens of lots B and C of the SAE X4130 steel, chromium plated to thicknesses of 0.001 to 0.017 in. and subsequently baked at temperatures ranging from 100° C to 440° C, are given in tables 4, 5, and 6; some of the data are shown graphically in figures 3 and 4. The endurance limits of these specimens reached a minimum value for temperatures between 193°

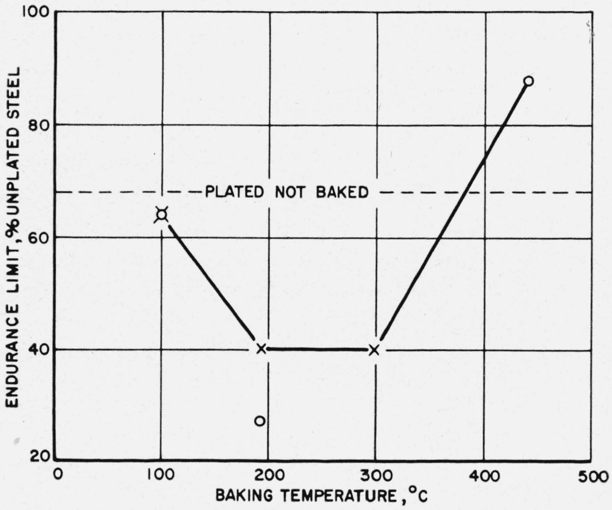

FIGURE 3. *Influence of baking temperatures on the endurance limits of quenched and tempered X4130 steel specimens chromium plated at 55° C and a current density of 350 amp/ft^2 to a thickness approximately 0.008 in.*

○, Baked in air; X, baked in an organic liquid.

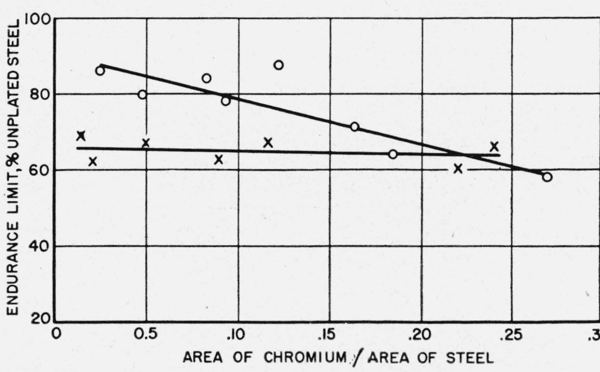

FIGURE 4. *Relationship between endurance limit and ratio of cross-sectional chromium-plated area to steel area for quenched and tempered SAE X4130 steel specimens 0.250 and 0.300 in. in diameter.*

X, As plated; ○, plated and baked 1 hour at 440° C.

TABLE 4. *Endurance properties of SAE X4130 steel specimens (hardness, approximately 40 C scale) chromium plated and subsequently heated*

Nominal thickness of plating	Heat treatment			Endurance limit	
	Temperature	Medium	Time	lb/in.²	Percentage of unplated steel
LOT C STEEL, PLATING BATH TEMPERATURE 55° C, CURRENT DENSITY 350 AMP/FT ²					
in.	° *C*		*hr*		
0.0085	------	None	------	64,000	67
.009	100	Oil	1	56,000	64
.010	100	do	12	<48,000	<55
.0095	193	Ethylene glycol	1	35,000	40
.0105	193	do	6	33,000	37.5
.0100	193	do	100	33,000	37.5
.0105	193	Air	1	24,000	27
.0085	200	do	6	32,000	34
.0087	296	Butal phthalate	1	35,000	40
.009	440	Air	1	83,000	87.5
LOT B STEEL, PLATING BATH TEMPERATURE 70° C, CURRENT DENSITY 1,000 AMP/FT ²					
.008	------	None	------	45,000	51
.008	95.5	Oil	24	39,000	44
.008	95.5	Air	24	35,000	40
.008	200	do	6	32,000	36
.008	300	do	4	46,000	52
.008	350	do	1	51,000	58
.008	400	do	1	55,000	63
.008	440	do	1	59,000	67
LOT C STEEL, PLATING BATH TEMPERATURE 70° C, CURRENT DENSITY 1,000 AMP/FT ²					
.009	------	None	------	40,000	42
.008	200	Air	6	25,000	26
.008	300	do	4	28,000	28.5
.008	440	do	1	47,000	49.5
LOT C STEEL, PLATING BATH TEMPERATURE 85° C, CURRENT DENSITY 700 AMP/FT ²					
.010	------	None	------	10,000	11
.010	193	Ethylene glycol	6	13,000	14.5
.010	440	Air	1	42,000	46.5

and 300° C; at higher baking temperatures the endurance limits increased, and at temperatures of 400° and 440° C exceeded those of the unbaked plated specimens. The endurance limit of one set of specimens heated in air for 1 hour at 193° C was 27 percent of that of the unplated steel (table 4). The endurance limit of specimens heated in ethylene glycol at 193° C was somewhat higher than that of specimens heated in air and was independent of the time specimens were held at the baking temperature. Specimens plated to a thickness of 0.002 in. and heated for 1 hour at 440° C had an endurance limit as high as 87½ percent of that of the unplated steel compared to 68 to 69 percent for unbaked plated specimens. However, the endurance limits of the plated specimens heated 1 hour at 440° C decreased as the ratio of the cross-sectional area of chromium plating to steel

TABLE 5. *Effect of specimen diameter and plating thickness on the endurance limit of quenched and tempered SAE X4130 steel, hardness Rockwell, 40-C, lot C, chromium plated at a current density of 350 amp/ft ², bath temperature 55° C*

Specimen diameter	Nominal plate Thickness	Ratio of cross-sectional chromium plate to steel area	Baking treatment		Endurance limit	Percentage of endurance limit of unplated steel
			Time	Temperature		
in.	*in.*		*hr*	° *C.*	*lb/in²*	*Percent*
0.25 to 0.30	------	0	----	------	95,000	100
.30	0.017	0.24	----	------	63,000	66
.30	.0085	.116	----	------	64,000	67
.30	.001	.014	----	------	66,000	69
.25	.0105	.22	----	------	57,000	60
.25	.005	.090	----	------	59,000	62
.25	.001	.021	----	------	59,000	62
.30	.0085	.116	2	200	31,000	33
.30	.0085	.116	6	200	31,000	33
.30	.018	.265	1	440	<55,000	<58
.25	.002	.122	1	440	83,000	87.5
.25	.011	.184	1	440	61,000	64
.25	.010	.164	1	440	67,000	71
.25	.009	.157	2	440	80,000	84
.25	.012	.201	4	440	70,000	74
.25	.005	.082	1	440	80,000	84
.25	.0015	.024	1	440	82,000	86

TABLE 6. *Effect of type of surface preparation of the basis steel prior to plating, on the endurance properties of SAE X4130 steel (lot C) chromium plated to a thickness of 0.008 to 0.009 in. at a current density of 1,000 amp/ft².*

Bath temperature 70° C

Type of surface treatment ¹	Heat treatment		Endurance limit	Percentage of endurance limit of unplated mechanically polished steel
	Time	Temperature		
	hr	° *C*	*lb/in.²*	
Mechanical ²	------	------	95,000	100
Electrochemical ²	------	------	87,000	92
Mechanical	------	------	40,000	42
Electrochemical	------	------	24,000	25
Mechanical	6	200	25,000	26.5
Electrochemical	6	200	24,000	25
Mechanical	1	440	47,000	49.5
Electrochemical	1	440	45,000	47.5

¹ All specimens were mechanically polished in a longitudinal direction with "400A" Aloxite paper. Subsequently, specimens labeled "Electrochemical" were made anodes in $H_2SO_4+H_3PO_4$ solution and were reduced about 0.0005 in. in diameter by electrochemical means.

² Not plated.

increased, reaching values less than for the unbaked steel for very thick plating.

The endurance limit of specimens polished electrolytically prior to plating and tested without subsequent heating was lower than that of mechanically polished specimens (table 6). However, the endurance limits of the plated and heated specimens were independent of the original surface preparation prior to plating.

3. Discussion of Causes of Effects of Chromium Plating on Endurance Limits of Steels

Three possible explanations for the fact that the endurance limits of the steels were reduced by the chromium plate have been proposed: The embrittlement due to hydrogen; cracks in the chromium plate at which stress concentrations occur; and the presence of residual stresses in the chromium or steel or both as the result of the plating. It is of course recognized that these factors may be interrelated and possibly be manifestations of one another.

It is well known that the plating efficiency for depositing chromium is low, approximately 15 to 20 percent of the current being used to deposit chromium. Large quantities of hydrogen are produced at the cathode, and the chromium plate has been shown to contain as much as 128 volumes of hydrogen per volume of chromium [5, 6]. Theories explaining the manner in which the cathodic hydrogen is held in the chromium [7] have been proposed but are not pertinent to the discussion at this point. Zapffe [8] has explained brittleness observed in bend tests on wire plated with chromium as due to hydrogen. Brenner, Burkhead, and Jennings [9] showed that approximately 95 percent of the hydrogen is removed by heating chromium at 450° C. These facts suggest that the improvement in endurance limit of specimens heated at 440° C is due to the expulsion of hydrogen. However, specimens heated at 200° C had in some cases only 50 percent of the endurance limit of unheated specimens, whereas data given by Brenner and coworkers showed that approximately half of the hydrogen was removed from the chromium by heating at 200° C. It is difficult, therefore, to see how the results of the fatigue tests reported here can be attributed directly to hydrogen embrittlement.

At a magnification of 250 diameters, the surfaces of the electroplated chromium samples studied had a pebble-grained appearance. The specimens plated at 55° and 70° C also exhibited surface cracks having the appearance of grain boundaries (figs. 5 and 6). The cracks were less numerous in the specimens plated at 70° C than for those plated at the lower temperature. No cracks were found on specimens plated at 85° C. Metallographic examinations of longitudinal sections of the chromium-plated specimens at distances of 0.01 in. or more from the fatigue fracture failed to reveal cracks penetrating through the chromium, or to reveal cracks extending any appreciable distance into the chromium from the outer surface. There were, however, numerous inclusions and voids in the chromium.

Mehr, Oberg, and Teres [10] reported that, in general, the number of cracks in a given area increased as the chromium plate was heated. Other observers [3] had noted that heating of the chromium plate at a temperature as low as 100° C tended to widen the cracks. The author found this crack-widening tendency to be more pronounced as the temperature of heating was increased (fig. 7).

Bennett [11] has shown that notches reduce the endurance limit of normalized X4130 steel approximately 20 percent and that fine cracks reduce the endurance limit by more than 50 percent. The presence of cracks in the chromium plated at 55° and 70° C might explain the reduction in the endurance limits of steel specimens plated at these temperatures. However, no cracks were found in chromium plated at 85° C, and specimens plated at this temperature had the lowest endurance limit of any specimens tested. Furthermore, preliminary results of an investigation, now in progress, indicate that fatigue damage in chromium-plated steel specimens starts below the surface of the chromium and does not appear to be associated with the surface cracks developed during the plating of the chromium. It must be concluded, therefore, that cracks in the chromium do not have the same effect on the endurance limit of specimens as cracks in the basis steel.

It is well-established that residual stresses in a metal markedly influence its endurance limit. The increased endurance limits, obtained by the shot peening [12] of steel parts, are believed to be the result of residual compressive stresses in the surface of the metal. Conversely, residual ten-

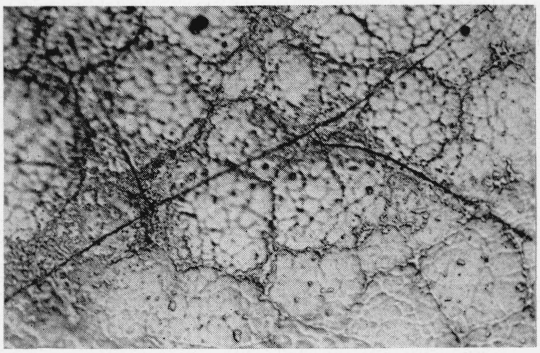

FIGURE 5. *Surface of chromium plated on steel at 70° C (current density 1,000 amp/ft ²).*

Areas bounded by sharply defined cracks are larger than those in chromium plated at 55° C (see fig. 6). Unetched, x500.

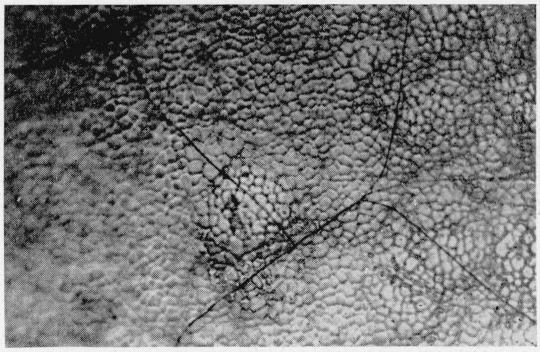

FIGURE 6. *Surface of chromium plated on steel at 55° C (current density 200 amp/ft ²).*

Unetched, x500.

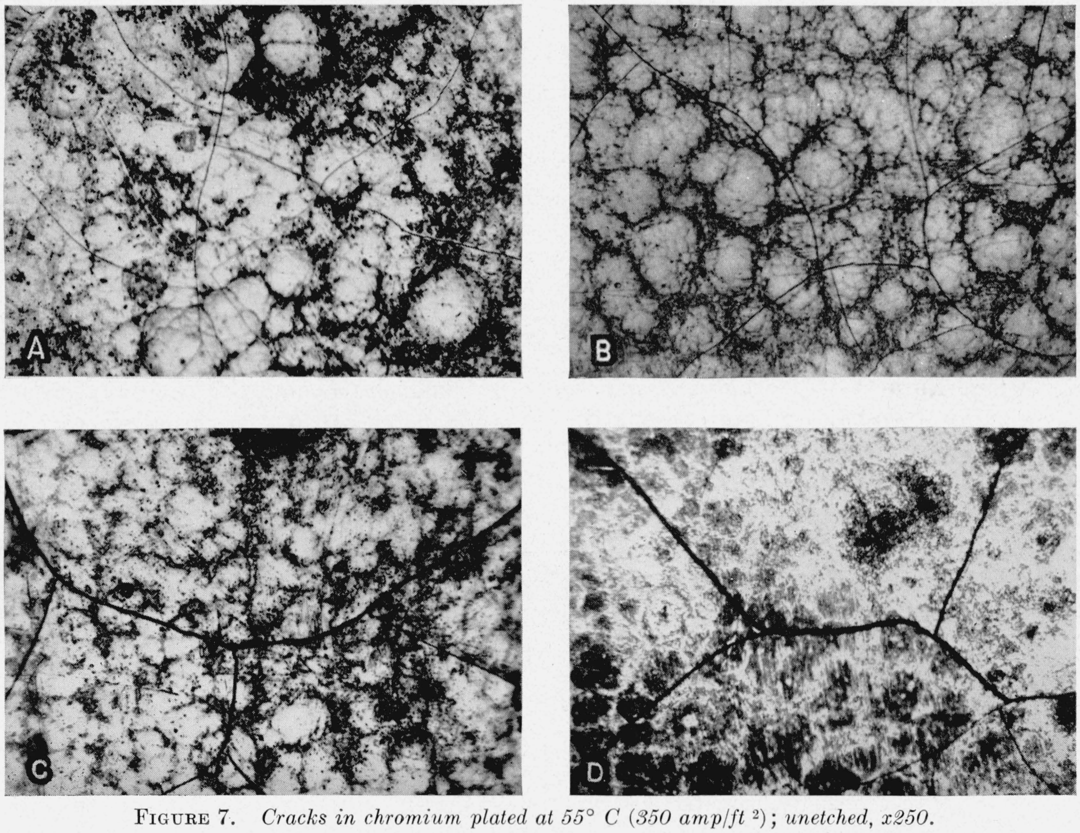

FIGURE 7. *Cracks in chromium plated at 55° C (350 amp/ft ²); unetched, x250.*

A, As plated; B, heated 1 hr at 193° C; C, heated 1 hr at 296° C; D. heated 1 hr at 440° C.

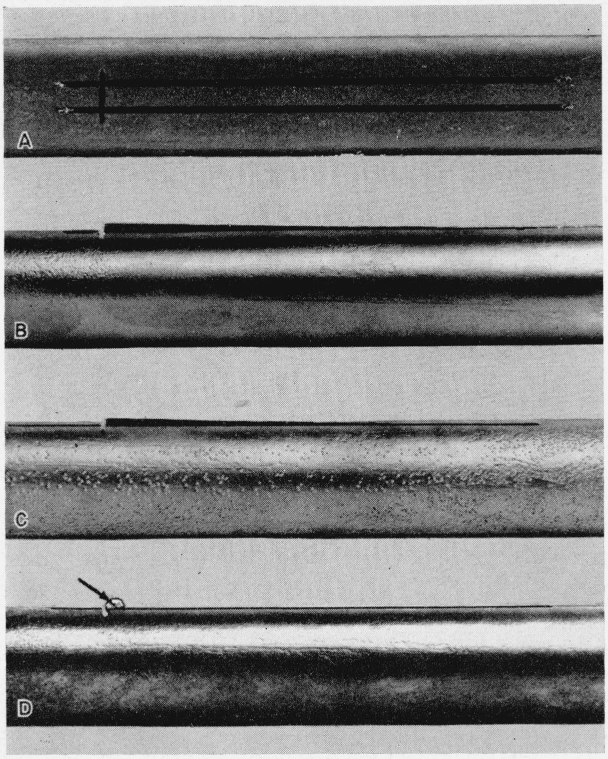

FIGURE 8. *Chromium-plated steel tubes.*

A, Top view of tube showing "tongue;" B, C, and D, side views of tubes showing deflections of "tongue." B, tube plated, heated at 200° C and "tongue" subsequently cut; C, tube plated, "tongue" cut and tube subsequently heated at 200° C; D, tube plated, heated at 440° C and "tongue" cut. A 3/16-in. ball bearing (indicated by arrow) is resting on the depressed "tongue" surface.

sile stresses in the surface layers of the specimens are considered to lower the endurance limit of the material. Hume-Rothery [13] reported tensile stresses as high as 50,000 lb/in.^{2} in electrolytically deposited chromium. Brenner, Burkhead, and Jennings [9] reported that the residual tensile stresses in chromium plated to a thickness of 8×10^{-4} in. increased from approximately 15,000 lb/in.^{2} for a bath temperature of 50° C to over 60,000 lb/in.^{2} for chromium plated from a bath at 85° C. The endurance limit of specimens plated at 55° C was higher than that of specimens plated at 70° C and very much higher than that of specimens plated at 85° C. This is to be expected if the internal stress in the chromium plate increased with the temperature of the plating bath in accordance with Brenner's findings.

The formation of cracks in chromium plating is usually attributed to the rupture of the deposit as the result of high residual tensile stresses [9]. The presence of cracks in the chromium, therefore, indicated at least partial relief of residual stresses. Specimens having the largest number of cracks per unit area, discussed above, would be expected to have the lowest residual stresses, and the residual stresses would be greater as the cracks per unit area decreased (and as the plating temperature increased).

Hidnert [14] showed that an electrodeposited chromium specimen, on the first heating to 500° C, decreased in length and that during the cooling to room temperature it continued to decrease in length. The net decrease in length amounted to 1.1 percent. Hidnert's results showed an inflection in the heating curve at about 300° C. Preliminary results of a current investigation by the author indicate that there is an inflection in the temperature-electrical resistivity curve at about this same temperature. Hidnert did not give any data for specimens heated to 200° C and cooled to room temperature. In the present investigation, the densities of tubes of chromium were determined for each of the following conditions: "as deposited," after heating at 193° C (in boiling ethylene glycol) and after a second heating in helium at 440° C. The densities were 6.95 g/cm^3 as plated, 7.01 g/cm^3 after heating at 193° C, and 7.09 g/cm^3 after heating at 440° C. Brenner [9] indicated that changes in the volume of chromium on heating were isotropic. Hence, heating at 200° C would tend to reduce the volume of the plated chromium. If the chromium was restrained from contracting, as for example by being plated on steel, residual tensile stresses would be set up in the chromium that might be expected to lower the endurance limit. That such stresses do exist in chromium plated on steel is shown in figure 8, B and C. Thin-walled steel tubes were annealed, pickled to remove scale, and chromium plated. Tube B, figure 8, was heated at 200° C for 6 hours, and a "tongue" was subsequently cut in the tube. The deflection shown indicated that there had been residual tensile stresses in the chromium. The tongue was cut in tube C after plating and was deflected only a small amount. Heating at 200° C, however, caused the chromium to contract in volume and produced the deflection shown.

Heating of chromium at a temperature of 440° C produced, as indicated by the density data, more than twice the contraction obtained by heating at 193° C. It is suggested that if a chromium-plated steel specimen is heated to 440° C, the concurrent expansion of the steel and contraction of the chromium stresses the chromium above its ultimate tensile strength at that temperature, consequently relieving the internal stresses at least in part. This is illustrated on figure 8, tube D, which was heated to 440° C for 1 hour, after plating, but prior to cutting of the tongue. In the figure, a 3/16-in. ball is resting on the free end of the tongue, which is depressed below the surface of the tube. The tongue deflected so that the chromium was on its convex surface. This indicated that the chromium had been permanently elongated during the heat treatment due to expansion of the steel; there had been either plastic flow or fractures in the chromium or both.

On the basis of the foregoing discussion, it is postulated that the residual tensile stresses in electrodeposited chromium are a major factor in adversely affecting the endurance limits of steel upon which the chromium is plated. Heating at temperatures of 100° to 300° C tends to contract the chromium; the underlying steel resists this contraction, thus producing increased tensile stresses in the chromium and further reducing the endurance limit. Contraction of the chromium during heating at 400° and 440° C, coupled with the expansion of the steel at these temperatures, stressed the chromium beyond its ultimate tensile strength, produced permanent deformation, and hence relieved the stresses in the chromium to some extent with resulting increases in endurance limits of the plated specimens so treated.

V. Summary

1. Chromium plating of SAE X4130 and 6130 steels reduced the endurance limits of these materials, as determined in the rotating-beam type of test.

2. The endurance limits of these steels plated under a given set of conditions generally decreased with increased hardness of the steel. For a steel of a given hardness (Rockwell 40–C), the reductions in endurance limit increased with increased plating bath temperatures.

3. The endurance limits of specimens plated, and subsequently surface ground, were equal to or greater than those of unground specimens having the same final plating thickness. Interruption of the plating process did not affect the endurance limit of the plated specimens, provided that proper precautions for plating chromium on chromium were taken before the plating was resumed.

4. The endurance limits of specimens heated after plating and tested at room temperature reached a minimum value for a baking temperature between 190° and 300° C. Endurance limits of specimens heated for 1 hour at 440° C were significantly higher than those of the "as plated" steel.

5. Reduction of the endurance limits of steel by chromium plating is believed to be due, in part at least, to residual tensile stresses in the chromium. Heating of chromium increased its density and hence decreased its volume. It is postulated that heating at low temperatures increased the residual tensile stresses in the chromium; at sufficiently high temperatures, the concurrent contraction of the chromium and expansion of the steel stressed the chromium above its ultimate tensile strength, thus relieving some of the residual tensile stresses in the chromium and increasing the endurance limit of the plated specimens.

The author gratefully acknowledges the valued advice, aid, and assistance of the following in various phases of this investigation: Naval Aircraft Factory, Philadelphia; N. E. Promisel, Chief Metallurgist, Bureau of Aeronautics, Navy Department, Washington; William Blum and Vernon Lamb of the Bureau's Electrodeposition Section, Harold Hessing, Houston Babb, Thomas P. Royston, Jr., Irene C. Minor, and Lura F. Roehl of the Metallurgy Division of the Bureau. Harold E. Francis, Guy R. McConnell, Richard C. Rohan, and Molly Thompson, formerly of the Metallurgy Division, also assisted in the investigation.

VI. References

[1] W. H. Swanger and R. D. France, National Bureau of Standards. Unpublished.

[2] H. Wiegand and R. Scheinost, Endurance strength of hard chromium plated parts, Z. Ver. deut. Ing. **83**, 655 (1939).

[3] Chromium plating, Bibliography and Correlated Abstract, by M. Kolodney, for War Metallurgy Committee, Information Release No. 4, p. 49 (July 1943).

[4] Metals Handbook (Am. Soc. Metals) p. 120, 1948 ed.

[5] S. P. Makariewe and N. D. Birükoff, The influence of dissolved hydrogen on the hardness of electrolytic chromium, Z. Elektrochem. **41,** 623 (1935).

[6] E. V. Potter and H. C. Lukens, Hydrogen content of electrolytic chromium and its removal, Metals Tech. **15** (January 1948) T. P. 2312.

[7] C. A. Snavely, A theory for the mechanism of chromium plating; a theory for the physical characteristic of chromium plate; Preprint 92–35, Electrochem. Soc. (1947).

[8] C. A. Zapffe and M. E. Haslem, Measurement of embrittlement during chromium and cadmium electroplating and the nature of recovery of plated articles, Trans. Am. Soc. Metals **39,** 241 (1947).

[9] A. Brenner, P. Burkhead, and C. Jennings, Physical properties of electrodeposited chromium, J. Research NBS **40,** 31 (1948) RP1854.

[10] L. Mehr, T. T. Oberg, and J. Teres, Fatigue limit of chromium plated steel, Monthly Rev. Am. Electroplaters Soc. **34,** 1345 (1947).

[11] J. A. Bennett, A study of the damaging effect of fatigue stressing on SAE X4130 steel, J. Research NBS **37,** 123 (1946) RP1733.

[12] J. O. Almen, Shot blasting to increase fatigue resistance, SAE Trans. **51,** 248 (1943).

[13] W. Hume-Rothery and M. R. J. Wyllie, The structure of electrodeposited chromium, Proc. Roy. Soc. (London) [A] **181,** 331 (1943).

[14] P. Hidnert, Thermal expansion of electrolytic chromium, J. Research NBS **26,** 81 (1941) RP1361.

WASHINGTON, March 30, 1949.