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The Influence of Residual Stress in Nickel and Chromium Plates on Fatigue

Paper presents correlation of fatigue and residual stress results for 13 nickel-plate, 5 nickel-cadmium-plate, and 14 chromium-plate investigations

by H. J. Noble and E. C. Reed

ABSTRACT—Investigations of the effect of nickel and chromium plates on the endurance limit of medium-strength low-alloy steel show that this effect is equal within experimental error to the residual stress in the plate plus a constant, and can be expressed by a simple equation. Values of the constants have been derived.

Introduction

The effect of electrodeposits on the fatigue strength of plated parts has been of great interest for some time. Apparently inconsistent results, when residual stress and fatigue tests were repeated under supposedly similar conditions, led to a project to investigate the relationship between residual stresses and fatigue limits of various nickel and chromium electrodeposits on AMS 6322 steel (SAE 8740) hardened and tempered to Rockwell C 37-40. This paper presents correlation of fatigue and residual-stress results for 13 nickel-plate, 5 nickel-cadmium-plate, and 14 chromium-plate investigations.

Experimental Procedure

Endurance limits were determined on plated R. R. Moore rotating-beam specimens. A contractometer was used to determine as-plated stresses, and strip specimens were used to determine stresses as-plated and after baking. The contractometer and/or strip specimens were plated in the same bath and under the same conditions as the fatigue specimens for each investigation.

Specimens were plated with (1) self-regulating and (2) 45-percent/gal chromic-acid-type chromium, sulfamate-nickel, diffused-sulfamate-nickel-cadmium, Watts-type nickel, and diffused Watts-type nickel-cadmium electrodeposits, and with electroless nickel. Plating procedure included stopping off with wax all areas not to be plated, anodic-alkali cleaning of unwaxed areas, plus an acid-activation treatment, and then plating.

Stress Determination by Contractometer

As-plated stresses were determined using the Bren-

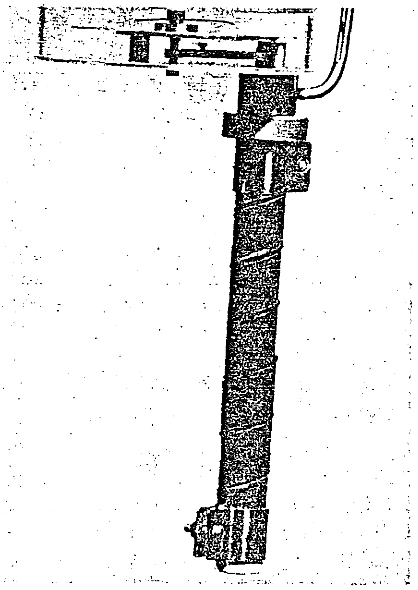

Fig. 1—Brenner–Senderoff spiral contractometer

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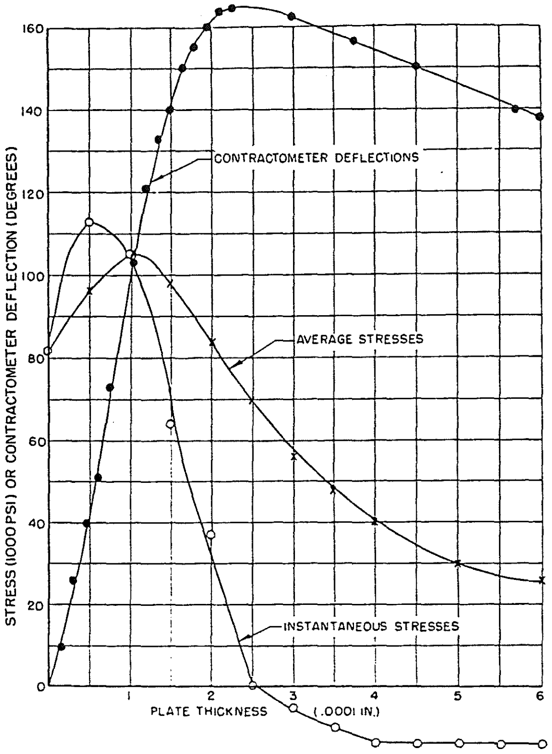

Fig. 2—Residual stresses and contractometer deflections for chromium plates of various thickness

ner–Senderoff spiral contractometer.[1] The contractometer employs a dial indicator which shows the degree of twist or untwist of a helix when only one side of the helix is plated. The helix is approximately 6 in. long by 3/4-in. OD, wound from flat stainless steel 3/4 in. wide × 1/100 in. thick. The construction of the contractometer limits its use to as-plated conditions (see Fig. 1).

Tests were made on various chromium and nickel electrodeposits obtaining both average stress and instantaneous stress values using formulas derived by Brenner and Senderoff.[1] Contractometer deflections (twist) were plotted against plate thickness. The average stress for a particular thickness is obtained from the final deflection for that thickness. The instantaneous stress (surface stress at any given instant during the plating cycle) at a particular thickness is derived frrom the slope of the contractometer deflection–thickness curve at that thickness (see Fig. 2).

Stress Determination by Optical Interferometer[2]—Strip Method

Strip specimens, 3 × 3/4 ×1/10 in. were machined from AMS 6322 steel. One face of each specimen (3 × 3/4 in.) was polished to specular reflectance sufficient to produce an interference pattern when placed in contact with the optical flat and illuminated with mercury light (Fig. 3). The pattern was photographed. after which the specimen was plated on the side opposite the polished face. Curvature of the test

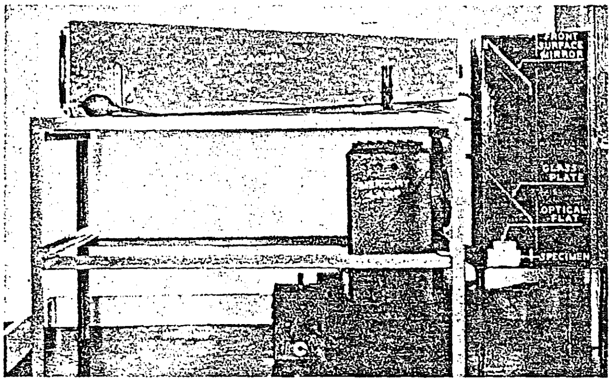

Fig. 3—Interferometer for producing and photographing interference patterns for residual-stress studies

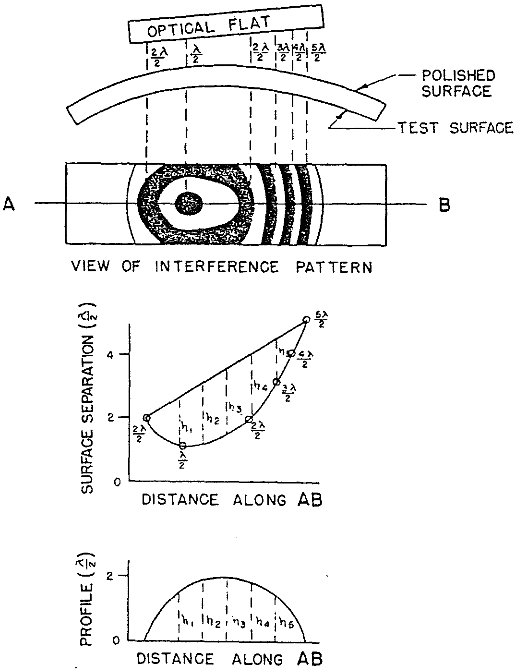

Fig. 4—Method of obtaining specimen curvature from interference pattern

piece due to plating was determined from photographs of interference patterns obtained before and after plating (Fig. 4). The effect of baking was determined by comparing photographs of interference patterns taken after plating with those taken after plating and baking. Average residual stresses were calculated from changes in longitudinal curvatures.[3] See Fig. 5 for typical average stress–thickness curves for chromium electrodeposits.

Fatigue-strength Determination

R. R. Moore rotating-beam fatigue specimens were rough machined, heat treated, finish ground and then polished mechanically in the longitudinal direction. Polishing was done with a wax wheel using No. 600

Al_2O_3 grit suspended in water. Specimens for each investigation were divided into groups of approximately 20 specimens each. One group was used for par bars and the other groups were plated and baked according to each test procedure.

Endurance limits, where 10^7 cycles is considered a run-out, were determined by the staircase method. Each specimen was run at a previously determined load increment, above or below the load of the preceding specimen, depending on whether that specimen ran out or failed. If the specimen ran out, the load was increased; if it failed, the load was decreased. From these failures and run-outs, an average value was obtained which is reported as the mean endurance limit.

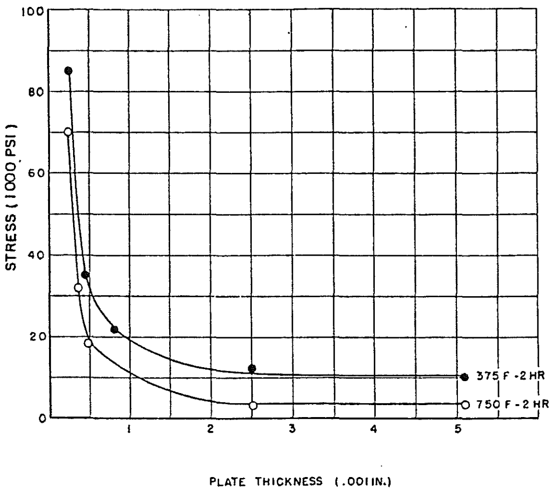

Fig. 5—Typical average residual stress–plate thickness curves for chromium electrodeposits

Results and Discussion

Nickel-plate Tests

On the basis of the 18 nickel-plate investigations listed in Table 1, the change in fatigue strength of a nickel-plated R. R. Moore type fatigue specimen, as compared to the unplated specimen, was approximately equal to the average residual stress in the plate. Average residual stresses of a particular nickel-plate and bake combination were approximately constant, irrespective of thickness. As-plated average stresses, as determined by both contractometer and interferometer had, in a previous investigation, been demonstrated to give results in close agreement with each other.[4] Good correlation of residual stress and fatigue can be obtained only when all specimens are plated under the same conditions, because normal variations in nickel-plating solutions may cause wide variations in stress.[4,5]

Chromium-plate Tests

No direct correlation was found to exist between residual stress and endurance limit in our chromium-plate investigations. Several tests gave but small differences in endurance lmit, whereas average residual

TABLE 1—RELATIONSHIP BETWEEN RESIDUAL STRESS AND FATIGUE PROPERTIES OF FIVE NICKEL AND NICKEL-CADMIUM PLATES ON AMS 6322 STEEL AFTER VARIOUS BAKES

Plate	Thickness (in.)	Bake ° F	Residual Stress* (psi) Average	Endurance Limit (psi) 10^7 Cycles Par Bar	Plated Bar Actual	Plated Bar Calculated
Sulfamate Nickel	.00030	None	−6,000	86,000	90,000	92,000
	.00018	375	3,000	78,000	74,000	75,000
	.00018	375	3,000	95,000	89,000	92,000
	.00040	375	2,000	93,000	92,000	91,000
	.00049	375	2,000	56,000†	57,000	54,000
	.00018	630	12,000	90,000	80,000	78,000
	.00040	900	19,000	93,000	70,000	74,000
Sulfamate Nickel Cadmium ‡	.00050	375	8,000	93,000	91,000	85,000
	.00049	630	11,000	90,000	77,000	79,000
	.00050	630	16,000	93,000	70,000	77,000
Watts Nickel	.00030	375	18,000	87,000	71,000	69,000
	.00030	375	28,000	87,000	61,000	59,000
	.00030	375	39,000	87,000	55,000	48,000
	.00040	375	21,000	93,000	71,000	72,000
	.00040	900	12,000	93,000	77,000	81,000
Watts Nickel Cadmium ‡	.00050	630	25,000	93,000	69,000	68,000
	.00050	630	31,000	93,000	56,000	62,000
Electroless Nickel	.00040	375	19,000	95,000	76,000	76,000

* Plus values = tension; minus value = compression.
† Hardened and tempered to Rockwell C 20.
‡ Nickel-cadmium plate is normally given a diffusion treatment of 630° F for 1 hr.

TABLE 2—RELATIONSHIP BETWEEN RESIDUAL STRESS AND FATIGUE PROPERTIES OF TWO CHROMIUM PLATES ON AMS 6322 STEEL AFTER VARIOUS BAKES

			Residual Stress (psi)*		Endurance Limit (psi)		
Plate	Thickness (in.)	Bake °F	"A" Average	Calculated .002 in., Average	Par Bar	"B" Plated Bar Actual	"B" Plated Bar Calculated
Chromium A†	.00027	None	49,000	7,000	90,000	73,000	70,000
	.00030	None	20,000	3,000	90,000	73,000	74,000
	.00157	None	2,000	2,000	90,000	77,000	75,000
	.00027	750	7,000	1,000	90,000	85,000	84,000
	.00030	750	−7,000	−1,000	90,000	85,000	86,000
	.00157	750	0	0	90,000	85,000	85,000
Chromium B†	.00025	None	54,000	7,000	90,000	71,000	70,000
	.0003	None	55,000	8,000	90,000	71,000	69,000
	.0003	375	60,000	9,000	82,000	60,000	60,000
	.0012	375	13,000	8,000	82,000	58,000	61,000
	.005	550	9,000	9,000	61,000‡	37,000	39,000
	.0003	750	18,000	3,000	82,000	85,000	74,000
	.0012	750	0	0	82,000	78,000	77,000
	.005	750	0	0	61,000‡	59,000	56,000

* Plus values = tension; minus values = compression.
† A = self-regulating type (proprietary); B = 45 oz/gal chromic-acid type
‡ Hardened and tempered to Rockwell C 20.

stresses differed markedly (see columns marked A and B, Table 2).

Average residual tension stresses in chromium-plated specimens have been shown previously to increase slightly after baking at 375° F from values obtained from the no-bake condition. These stresses were decreased almost to zero after baking at 750° F. Endurance limits appear to be affected by the change in stresses due to heating since fatigue strengths were lower for as-plated and 375° F baked specimens than for 750° F baked specimens.

Tensile stress approaching 100,000 psi may occur at approximately .00015-.0002-in. thickness of plate. Stresses fall off rapidly with increasing thickness and level off beyond .002 in. at values below 15,000 psi (Fig. 2 and 5). It was noted also that, for thicknesses of .002 in. or more, the chromium plate was markedly cracked. Normal variations due to contaminants in chromium-plating solutions do not cause wide variations in stress. Stress measurements in very thin plates may appear to be inconsistent due to the rapid change in stress with plate thickness.

The effects of temperature and plate thickness on residual stress in chromium plate are illustrated in Fig. 6.

Results on the effects of various bakes on fatigue life are substantiated by Bureau of Standards tests.[6] Those tests show that heating chromium-plated parts in the 350-550° F range lowers fatigue strength below that in the as-plated condition in most cases, and that baking at 750° F almost completely restores fatigue strength to that of the unplated condition.

In order to develop a theory for the correlation of residual stress in chromium plate with the endurance limit of chromium-plated fatigue specimens, we must consider the fact that results showed that chromium-plated specimens with two different thicknesses of plate had different average residual stresses but similar endurance limits. For example, chromium as-plated from a self-regulating-type bath had average residual tension stresses of 58,000 psi for .00026-in.-thick plate and 3,000 psi for .00155-in.-thick plate: yet, the plated R.R. Moore fatigue specimens gave endurance limits within 4,000 psi of each other. In other words, there appeared to be similar "effective stresses" for the two thicknesses of chromium. To explain "effective stresses", the following is suggested. At .002-in. thickness of chromium plate, average residual stresses tend to level off (see Figs. 2 and 5). At this thickness, the plate has very many fine

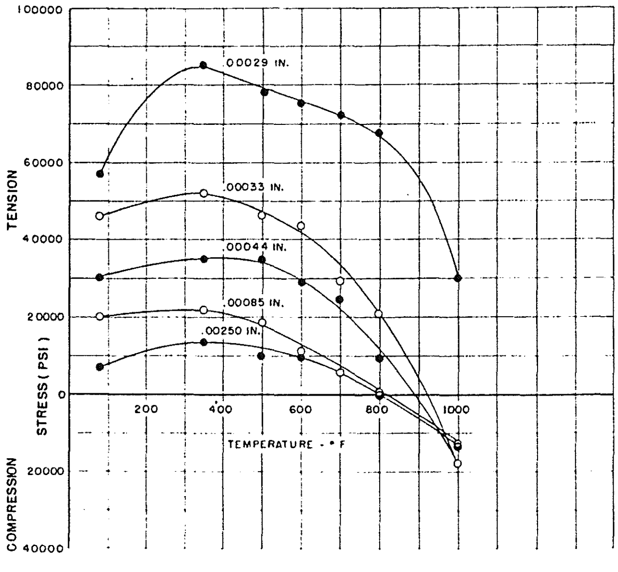

Fig. 6—Effect of thickness on stresses in chromium after heating 2 hours at indicated temperatures

cracks, which probably accounts for the leveling-off stress. Therefore, plate thickness of .002 in. is selected as the base-line for comparing average residual stresses. Residual stresses in any thickness of plate have high-tension instantaneous stresses in the first few tens of thousandths of plate and then these stresses drop rapidly (Fig. 2). In a plated specimen the stresses in the plate and in the specimen are in equilibrium. As cracks progress through the chromium plate during fatigue testing, plate tension stresses are reduced and new equilibrium conditions are reached between the plate and the specimen. This indicates that the final "effective" residual stresses affecting the fatigue life of the specimen are composed of reduced stress (calculated stress) plus the stress in the cracked chromium, which is an empirical constant derived from the chromium-plate fatigue-test data. The reduced stress (calculated stress) is determined as follows:

$$s = \frac{P}{A} = \frac{P}{wt} \quad \text{and} \quad S = \frac{P}{A} = \frac{P}{wT}$$

$$\text{or} \quad P = swt = SwT$$

$$\text{or} \quad S = \frac{st}{T}$$

where s = measured average stress (psi)
P = force in cross section of plate (lb)
w = unit width of plate (in.)
t = plate thickness (in.)
S = reduced stress (calculated stress—psi)
T = plate thickness (in.) for reduced stress —.002 in. for chromium plate with t less than .002 in. With $t = .002$ in. then $T = t$.

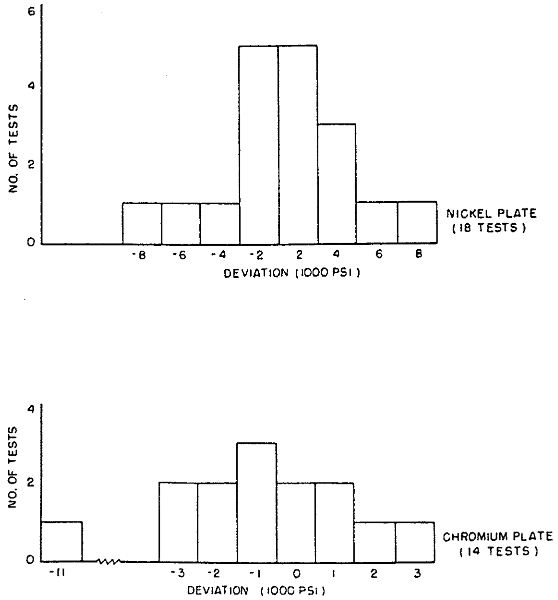

Fig. 7—Deviation of calculated endurance limits from actual endurance limits for plated AMS 6322 steel R. R. Moore fatigue specimens

In other words, an average stress of 50,000 psi in a .001-in.-thick plate would become a calculated stress of 25,000 psi in a .002-in.-thick plate.

As mentioned in the introduction, this work was done on AMS 6322 steel (SAE 8740), heat treated to a range of Rockwell C 37-40. Little work has been done on other hardness ranges so that it is not known how well the conclusions will apply. However, limited testing in the same hardness range of one of the 12-percent chromium steels indicates that the relationship holds for this material also.

Conclusions

On the basis of testing listed in this paper, residual stresses in electrodeposits of chromium and nickel affect the fatigue properties of plated AMS 6322 steel specimens by the following relationship:

$$F_p = F_u - (S + K)$$

where F_p = endurance limit of plated specimen (psi)
F_u = endurance limit of unplated specimen (psi)
S = reduced stress (calculated stress—psi)
K = constant which varies with plate and bake (psi)

Since stress varies considerably with thickness in chromium plates, but very little with nickel plates, S is calculated from the relationship:

$$S = \frac{ts}{T}$$

where t = actual thickness of electrodeposit (in.)
s = measured average stress (psi)
T = .002 in. for chromium with t less than T. With $t = .002$ in. than $T = t$. $T = t$ for nickel

The constant K is zero for nickel electrodeposits, 13,000 psi for chromium electrodeposits in the "as-plated" condition or after a low bake, and 5,000 psi after baking at 750° F.

On the basis of the above conclusions, deviations of calculated endurance limits from actual endurance limits are plotted as bar graphs (Fig. 7). Data, though limited, show normal distributions, with variations from true values within the accuracy of stress measurements and endurance-limit determinations.

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