Fatigue LOSS AND GAIN BY ELECTROPLATING

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• • • Data showing the reasons for the damage, and its extent, that is caused by electrodeposited metals when plated by the methods now in common use.

• • • Processes whereby advantages of rebuilding by electroplating can be retained without loss of fatigue strength.

• • • Suggested developments in electroplating processes, whereby electro-deposited coatings may possibly be made as effective as shot peening in increasing fatigue strength of plated machine parts.

THE ALWAYS TEMPTING IDEA of building up worn and undersized machine elements by electrodeposits is extremely hazardous when applied to highly stressed parts that are subject to repeated loads. The salvaging operation too often results in disastrous failure of the plated parts and severe damage to adjacent structures. When this rebuilding, as normally practiced, is applied to engines and other airplane parts there is, of course, the added danger of fatalities and injuries among passengers and operating personnel.

Numerous tests have shown that the fatigue strength of steel is greatly reduced when plated with hard metals such as copper, nickel, and chromium. Because of their better wear resistance and presumed structural strength, nickel and chromium, are usually selected for rebuilding operations.

Among the first to present quantitative values of the loss of fatigue strength as a result of electroplating was F. C. Lea (Ref. 1), whose fatigue test data are replotted in the S N diagram, Fig 1. Lea conducted fatigue tests by applying repeated push-pull loads to three groups of specimens made of: Commercial nickel; 14 percent carbon steel heat-treated to a tensile strength of 63,000 psi; and similar steel specimens plated with nickel. This S N diagram shows that the fatigue strength of the all nickel specimens is slightly greater than the steel specimens, and that the strength of the steel specimens is reduced by nearly one-half when a thin layer of nickel is electrodeposited on them.

Chromium plated rotating beam fatigue specimens of SAE 6130 steel were tested by H. K. Cummings, (Ref. 2) with the following results:

Steel Quenched and Tempered to 123,000 psi Tensile Strength	Endurance Limit, psi
Not plated	65,500
Plated 0.00015 in. thick	38,000
Plated 0.0045 in. thick	41,000

The results of tests reported by C. G. William and J. S. Brown (Ref. 3),

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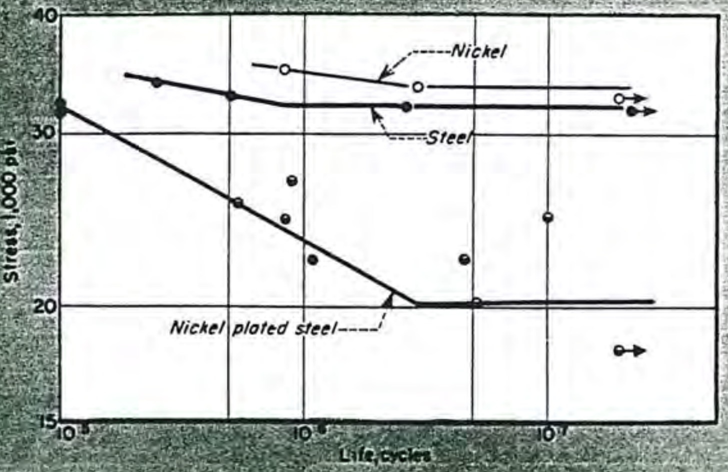

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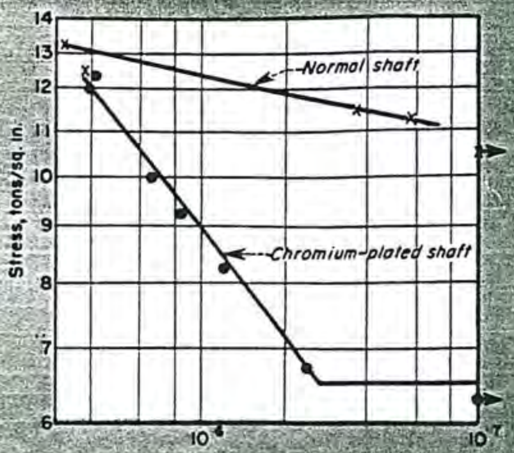
Fig. 1 — Loss of fatigue strength in steel when coated with electrodeposited nickel.



Engineering

Fig. 2 — Fatigue strength of non-plated steel crankshafts and of chromium plated crankshafts.

demonstrate that the loss of fatigue strength of chromium plated machine elements is substantially the same as in laboratory specimens. The replotted S N chart, Fig. 2, shows that chromium plating reduced the endurance limit of steel crankshafts to nearly half of their unplated strength.

The converging characteristics of the fatigue curves for plated and unplated specimens, shown in the S N charts Figs. 1 and 2, also show that the strength of both kinds of specimens tend to become equal at the short life high stress levels. This observation agrees with static tests reported by F. C. Lea (Ref. 1) and by R. D. H. Blaklie and H. J. Davies (Ref. 4), which show that electroplating does not alter the static strength of steel.

The most plausible theories that have been advanced to explain the deleterious effect of electrodeposited metals on the fatigue strength of steel are:

1. The deposited metal is residually stressed in tension, from which it necessarily follows that the base metal is residually stressed in compression to maintain equilibrium conditions. When a crack forms in a strongly adhering deposit, the residual tensile stress is locally transferred to the base metal in the manner indicated by Fig. 3, thereby reducing the fatigue strength of the base metal. A further loss results because the crack constitutes a notch, which is a stress raiser just like a notch of similar depth and sharpness in the surface of the base metal.

2. The fatigue strength of the base metal is reduced as a result of brittleness caused by occluded hydrogen from the plating bath.

Measurements of Residual Stress

Observations indicating the presence of residual stresses in electrodeposited metals were reported as early as 1860, but E. J. Mills (Ref. 5) was the first (1877) to record attempted measurements of their magnitudes. He found that when thermometer bulbs were coated with certain electrodeposited metals the mercury rose in the stem, showing that the deposited metal was residually stressed in tension. He also noted that the deposited layer fractured when it became too thick. Through the changes in the height of the mercury column, Mills calculated that nickel could develop a pressure of 43,000 psi; iron 40,500 psi; and silver 149,000 psi.

Residual stresses in plated nickel were measured by G. G. Stoney (Ref. 6), in 1909, by a method capable of greater accuracy than Mills's measurement. Thin steel rules 102 mm long, 12 mm wide and 0.32 mm thick were varnished on one side and electroplated with nickel on the opposite side. In response to the residual tensile stress in the nickel layers, the plated rules bent concave to the extent of 3 to 4 mm on the plated side.

Measurements of the nickel thickness and the radius of curvature of the plated specimens provided data from which the residual stress was calculated. These calculated stresses, together with other pertinent data, are given in Table I. Note that Stoney succeeded in altering the magnitude

Table I—Residual Stress in Nickel Plated Thin Steel Rules

Spec. No.	Deposit Thickness, in.	Tensile Stress, psi	Bath Temp, F	Current, amp
1	0.0002	43,000	50 to 60	0.05 to 0.11
2	0.0018	40,500	50 to 60	0.05 to 0.11
3	0.0007	40,000	50 to 60	0.05 to 0.11
4	0.001	40,500	50 to 60	0.05 to 0.11
5	0.0003	40,000	50 to 60	0.05 to 0.11
6	0.0065	38,500	50 to 60	0.05 to 0.11
7	0.0005	17,500	50 to 60	0.22
8	0.0012	22,000	175 to 195	0.11

of the residual tensile stress by variations in temperature of the bath and in the plating current, as is shown in specimens number 7 and 8 by the reduced residual stress.

Blaklie and Davies measured the residual stresses in electrodeposited nickel, copper, zinc, and lead following the method used by Stoney except that the formula for calculating the stress was slightly modified. Table II gives the results of their measurements.

Other nickel plated specimens were prepared by Blaklie and Davies for which the conditions of plating were altered from direct current alone to alternating current superimposed upon direct current. Table III gives the measured residual stress in two specimens plated by this method.

Residual stress measurements shown in Tables II and III were followed by reverse bending fatigue tests with the following results:

(1) Uncoated steel specimens that otherwise were identical with the specimens of Table II, for which the endurance limit was found to be ±15,500 psi, with no loss of fatigue strength.

(2) Steel specimens plated with nickel as specimen 1 of Table II for which the endurance limit was found to be ±10,500 psi, with 28 percent loss of fatigue strength.

(3) Steel specimens nickel plated by AC-DC as the specimens in Table III, for which the endurance limit was ±14,200 psi, with 7 percent loss of fatigue strength.

Reversed bending fatigue tests of steel coated with the other electrodeposited metals recorded in Table II showed that: Copper plating resulted in a loss of approximately 14 percent, lead deposits resulted in a small fatigue loss; and zinc plating was found to give a small increase in strength. The loss of fatigue strength of the copper plated specimens presumably resulted from the stress raisers that became effective when cracks developed in the firmly bonded but relatively weak copper deposits.

The damage from nickel deposited in the usual manner was reduced from 28 to approximately 7.5 percent when the steel specimen was given a coat of electroplated lead before the nickel was applied. The ductile layer of lead presumably permitted relaxation of the residual tensile stress in the nickel layer, and any remaining stress was presumably prevented from reaching the underlying steel when cracks developed in the nickel coat.

Cracks in Chromium Plate

Extreme difficulty has been experienced in measuring the residual stresses in electrodeposited chromium. Within the range of normal current density and bath temperature, the tensile stresses are so great that the chromium deposits are almost invariably fractured during the plating operation.

Residual stresses in chromium deposits were measured by W. Hume-Rothery and M. R. J. Wyllie (Ref. 7) by means similar to those used by Stoney and by Blaklie and Davies. The residual stress that was developed in the normal plating range was found to reach 60,000 psi tension.

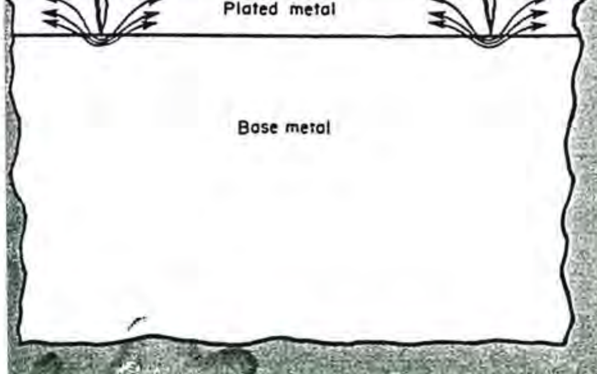
More recent measurements have been made by A. Brenner, P. Burkhead, and C. Jennings (Ref. 8) using an elaborate modification of the Stoney method. Helically wound steel ribbons were substituted for the flat strips previously used. Although large variations in stress were found, it is believed that the measured residual tensile stress of 80,000 psi is acceptable for sound electrodeposited chromium.

Residual stresses reported for chromium deposits range from zero upward to the quantities noted in the foregoing, but data are not available to indicate the effects of such stress variations on the fatigue strength of plated specimens.

The fatigue endurance limit of both normalized and hardened SAE X4130 steels were found by H. L. Logan (Ref. 9) to be reduced by chromium plating; the loss being greater for hardened steel. The endurance limits for steel of a given hardness decreased with increased plating bath temperature. Baking the plated specimens at temperatures up to 660 F, for the purpose of removing any effects of hydrogen, further reduced their fatigue strength. When the baking temperature was increased to 825 F, the fatigue strength was increased but not sufficiently to restore the endurance limit to that of the unplated hardened steel specimens.

Damaging effects of chromium on the fatigue strength of the plated steel are attributed to residual tensile stresses in the deposited chromium. These stresses are shown to be increased by low temperature baking, but when baked at 750 to 825 F they are partly relieved.

Fatigue endurance limits of unplated and chromium plated steel specimens of various analyses, hardnesses, plate thicknesses, and current densities are



ig. 3—When cracks form in tensile stressed plated metal esidual stress is locally transferred to the base metal.

Table II—Residual Stress in Electrodeposited Metals

Spec. No.	Metal Deposited	Stress, psi	Bath Temp, F	Amp per sq ft
1	Nickel	26,000 tensile	68	10
2	Copper	Nearly zero	95	30
3	Zinc	4,000 comp	65	10
4	Lead	Nearly zero	65	10

Table III—Specimens Plated With Alternating Current Superimposed Upon Direct Current

Spec. No.	Metal Deposited	Stress, psi	Bath Temp, F	Amp per sq ft	
				DC	AC on DC
5	Nickel	8,300	122	10	22
6	Nickel	4,900	122	10	35.7

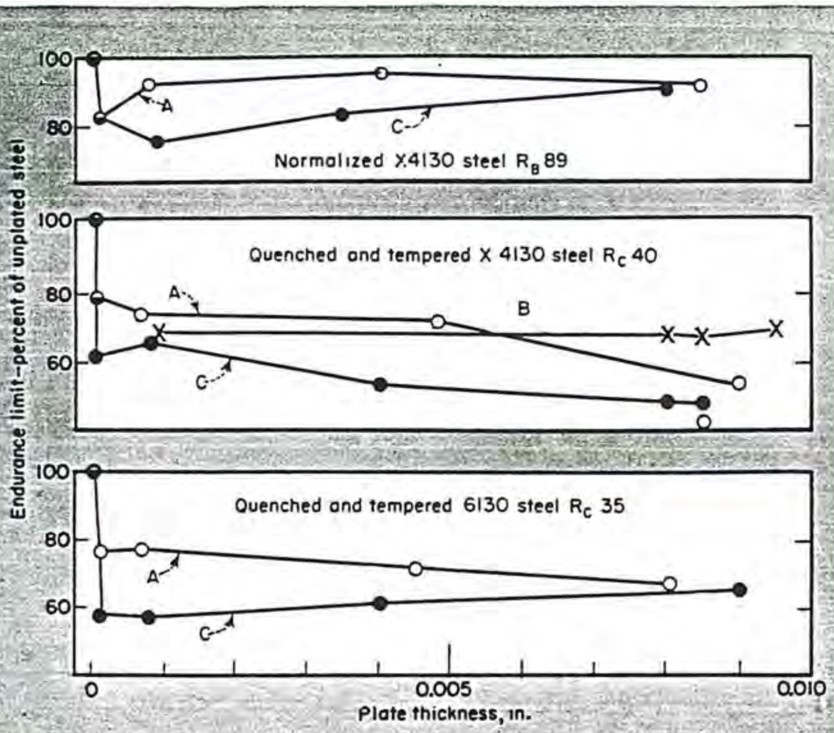


Fig. 4 — Fatigue strength loss from chromium plated on three steels under different temperatures and current densities. Legion: A = 130 F and 200 amp per sq ft; B = 130 F and 350 amp per sq ft; C = 160 F and 1000 amp per sq ft

graphically recorded in Fig. 4, which is from Logan's original publication.

The fatigue data shown in Fig. 1 were obtained as a part of an extensive investigation conducted by Lea (Ref. 1) to measure hydrogen penetration into metal cathodes and its effect upon the tensile and fatigue strengths of steel. He concluded that . . . "Hydrogen in the cathode does not diminish the resistance to impact of mild steel and its effect on repeated stress seems of itself unimportant. Nickel plating . . . lowers the range of repeated stress but this is not apparently due to occluded gases . . . it would appear that either initial (residual) stresses set up by the deposition or the discontinuities between the metals or, more likely, a crack which early forms in the deposited nickel is the cause of the lowering of the repeated stress range."

Surface Vulnerability and Applied Loads

It is well known that the state of residual stress in thin surface layers has a profound effect on the fatigue strength of repeatedly loaded machine elements and laboratory specimens. Surface residual compressive stresses induced by such processes as shot peening, superficial rolling, nitriding, and carburizing increase the fatigue strength of treated specimens. Conversely, surface residual tensile stresses resulting, under certain conditions, from such processes as grinding, straightening, induction and flame hardening decrease fatigue strength.

These effects have been shown to result from the fact that all surfaces, regardless of uniformity of section and perfection of finish, are weaker in fatigue than sound sub-surface metal (Ref. 10) and that fatigue failures can result only from tensile stresses (Ref. 11). It follows that the tensile stresses in the extra vulnerable surfaces from externally applied loads are reduced in magnitude by surface residual compressive stresses and the fatigue strength of the specimen is thereby increased. Surface residual tensile stresses augment applied tensile stresses and thereby decrease the fatigue strength of the specimen.

It is to be expected, therefore, that electrodeposited metals are harmful to fatigue strength in proportion to the magnitudes of the residual tensile stresses, and are beneficial in proportion to the magnitudes of the residual compressive stresses. Such proportionality is an over simplification because other factors, among which are adhesion, relative yield strength, ductility, and the manner in which the tests are conducted, alter the effective increase or decrease in the applied tensile stresses. The foregoing simple statement, however, will with reservations serve our immediate purpose.

The fatigue tests conducted by Blaklie and Davies, Tables II and III, show that the damage caused by electrodeposited nickel decreased from 28 to 7 percent when the residual tensile stress was reduced from 26,000 psi to 5,000 to 8,000 psi. They also show that when the residual stress in the plated layer was changed from tension to compression, as occurred in zinc deposits, the fatigue strength of the coated steel specimens was greater than the unplated specimens.

To obtain additional information on the effects of residual stresses in electrodeposited hard metals, the Research Laboratories Division of General Motors Corporation initiated a search for processes that would develop residual compressive stresses in plated nickel deposits.

It was believed that several objectives could be attained if means could be found whereby nickel could be consistently deposited in a state of residual compressive stress of controllable magnitude. It was expected that:

A. The loss of fatigue strength that normally occurs in nickel plated machine elements could be avoided, with the further probability that actual increase in fatigue strength would result.

B. Beneficial effect on fatigue of compressively stressed plated metal would provide new evidence that residual stresses have a direct effect on the fatigue strength of metals. Since the base metal would not be mechanically altered by the plating operation, any resulting changes in fatigue strength could not be confused with effects of work hardening.

C. The resistance to rusting of plated steel surfaces could be improved by depositing the plated metals in a state of compression. The plated layers would be more dense, decreased porosity would be expected, and spontaneous (stress corrosion) cracking would be avoided.

The cooperation of the Electro-Chemical Department of the Research Laboratories Division, General Motors Corporation, was solicited in an investigation to determine the validity of the foregoing assumptions.

It was anticipated that in any reasonable exploration of the many varibles numerous tests would be required and, therefore, a necessary preliminary was the development of means for measuring residual stresses in plated metals. It was important that the method should be simple, inexpensive and sufficiently accurate to disclose significant differences in residual stress magnitude resulting from minor variations in plating procedures.

The measuring techniques that were used and the results of numerous plating experiments have been reported in considerable detail by W. M. Phillips and F. L. Clifton (Ref. 12). Unfortunately, the residual stresses as originally calculated and published were incorrect but the stress values given herein have been corrected. Although the authors discuss the data from the viewpoint of decorative plating, the experiments are sufficiently complete to serve as guides for those interested in structural uses of electrodeposited nickel.

Residual Stress Varies Greatly

The data given in Table IV, which are taken from the Phillips and Clifton report show how variations in Watts' nickel bath affect the magnitudes of residual stresses in nickel when plated on steel. As a result of variations in bath composition, the residual stress is seen to range from a minimum of 5,900 psi tension to a maximum of 43,000 psi tension. Significant stress changes also occur with variations in bath temperature and with the thickness of the plated layers. Note the great increase in residual stress when the bath was contaminated with iron.

Also taken from the Phillips and Clifton report are the data given in Table V except that stresses have been re-calculated to eliminate errors in the original publication. This table shows the residual stresses in nickel deposits from various proprietary baths. For commercial reasons these baths are identified by code letters.

The original engineering objective was to find means whereby residual compressive stresses could be developed in hard metal deposits. This goal was attained by nickel deposited on steel from the proprietary baths, C, D, E, F, H, and J, Table V, and by nickel deposited on phosphor bronze from as many of these baths as were tested.

The residual stresses in nickel deposited on steel from the proprietary baths, Table V, range from 70,000 psi tension to 9,700 psi compression for a total variation of nearly 80,000 psi. As in the Watts bath, significant stress changes occurred with variations in bath temperatures. It is, perhaps, important to note that with baths A and B the residual stress increases as the bath temperature is reduced, while

Table IV—Residual Stresses in Nickel Deposited on Steel Base From Watts Bath

Test No.	Bath composition (pH adjusted H_2SO_4 and $NiCO_3$)	pH	Temp, F	Current density, amp/sq ft	Thickness, in.	Calculated stress, psi
1	$NiSO_4$,32 oz/gal	2.8	135	30	0.002	9,500
2	" "	5.3	135	30	"	19,000
3	" " $NiCl_2$,4 oz/gal	2.8	135	30	"	10,700
4	" " " "	5.3	135	30	"	13,000
5	" " " " H_3BO_3,4 oz/gal	2.8	135	30	"	8,800
6	" " " " " "	5.3	135	30	"	13,500
7	Same as No. 5 plus H_2O_2,0.475 oz/gal	2.8	135	48	"	12,700
8	" " " 0.950 "	"	"	"	"	9,500
9	" " " 1.425 "	"	"	"	"	5,900
10	$NiSO_4$,32 oz/gal; H_3BO_3,4 oz/gal	"	"	"	"	9,800
11	" " " " $NiCl_2$,0.5 oz/gal	"	"	"	"	9,500
12	" " " " " 1.0 "	"	"	"	"	9,000
13	" " " " " 2.0 "	"	"	"	"	6,300
14	" " " " " 4.0 "	"	"	"	"	7,300
15	" " " " " 8.0 "	"	"	"	"	11,400
16	" " " " " 16.0 "	"	"	"	"	18,300
17	" " " " " 24.0 "	"	"	"	"	20,000
18	Same as No. 7	2.5	150	"	"	9,400
19	" "	"	130	"	"	9,400
20	" "	"	112	"	"	13,400
21	" "	4.0	150	"	"	10,600
22	" "	"	130	"	"	9,800
23	" "	"	112	"	"	10,000
24	" "	5.4	150	30	"	14,500
25	" "	"	130	"	"	13,300
26	" "	"	112	"	"	19,500
27	" "	2.8	135	"	"	9,400
28	" "	"	"	48	"	9,300
29	" "	5.3	"	30	0.000250	27,000
30	" "	"	"	30	0.00052	26,400
31	" "	"	"	"	0.000785	25,800
32	" "	"	"	"	0.00108	24,000
33	" "	"	"	"	0.00194	13,400
34	" "	"	"	"	0.00278	12,300
35	" " plus Fe, 0.275 oz/gal	2.5	"	"	0.002	43,000
36	" " " 0.550 oz/gal	2.5	"	"	"	37,000

No agitation, except solution agitation in Test No. 28.

Calculated stresses in deposit from Test No. 7; 10,400 psi when applied on bronze, 11,100 when applied on brass.

All deposits had good ductility except those obtained in Tests Nos. 35 and 36.

Table V—Residual Stress in Nickel Deposits from Proprietary Baths

Note: Deposit thickness = 0.002 in.; Rec. make-up = Recommended make-up

Test No.	Type of Bath	Composition	pH	Temp, F	Current density, amp/sq ft	Agitation	Change of deflection, in.	Calcul. stress, psi		Ductility
								Steel base	Bronze base	
1	A	Rec. make-up less additions	3.75	150	48	Solution	0.0043	14,000		Good
2	"	Plus addition No. 1	3.75	150	48	"	0.0060	19,500		"
3	"	Plus additions Nos. 1 and 2	3.75	150	48	"	0.0054	17,500		"
4	"	Plus additions Nos. 1, 2, 3	3.75	150	48	"	0.0182	59,000		"
5	"	Plus additions Nos. 1, 2, 3, 4	3.75	150	48	"	0.0230	70,000	61,000	Bad
6	"	Rec. make-up	3.75	150	48	"	0.0160	52,000	50,000	"
7	"	" "	3.75	140	48	"	0.0159	52,000	51,200	"
8	"	" "	3.75	130	48	"	0.0177	57,000	54,800	"
9	B	" "	2.6	160	48	"	0.0055	18,000		Fair
10	"	" "	2.6	140	48	"	0.0073	23,700		"
11	C	" "	3.0	140	48	None	0.00058	1,890	− 3,000	Good
12	"	" "	3.0	130	48	"	0.00008	0	− 2,200	"
13	"	" "	3.0	120	48	"	−0.0014	− 4,500	− 7,400	"
14	D	" "	3.5	125	48	"	−0.00079	− 2,600	− 2,800	Bad
15	E	" "	4.0	135	48	Solution	−0.0030	− 9,700	−12,000	Fair
16	F	" "	3.5	135	48	"	−0.0030	− 9,700	−10,000	"
17	G	" "	4.0	130	48	None	0.0057	18,500		Bad
18	"	" "	4.0	130	30	"	0.0059	19,100		"
19	H	" "	3.1	140	48	"	−0.0012	− 3,900		Fair
20	I	" "	3.0	135	25	"	0.0082	26,600		Good
21	"	" "	3.0	135	48	"	0,00426	13,800		"
22	"	" "	3.0	135	96	"	0.0043	13,900		"
23	J	" "	2.8	135	48	"	−0.00115	− 3,730	− 6,000	"

Calculated stress in deposit on brass from Test No. 5 was 51,000 psi.

Table VI—Procedure for Compressive Plating

CLEANING

1. **Degrease**
2. **Cathodic clean 3 minutes**
3. **Hand scrub with pumice**
4. **Cathodic clean 30 seconds**
5. **Water rinse**
6. **Anodic treat in concentrated H_2SO_4 at 6 volts for 1 minute**
7. **Water rinse**

PLATING

1. **Plate at 40 amp per sq ft for required time to deposit desired thickness. 1200 amp min per sq ft equals 0.001 in. of nickel. Rotate specimen to obtain uniform plate thickness.**

2. **SOLUTION A. A bright nickel solution having the following composition:**

Single nickel salts, $NiSO_4 \cdot 6H_2O$	**40 oz/gal**
Nickel chloride, $NiCl_2 \cdot 6H_2O$	**8 oz/gal**
Boric acid, H_3BO_3	**5 oz/gal**
Brightener A	**0.125% by volume**
Non-pitter	**0.08 oz/gal**
Brightener B	**0.8 oz/gal**

pH 3.5 to 4.8, temp 115 to 140 F

2. **SOLUTION B. A newer bright nickel solution that is easier to control. It will probably give results similar to that of Solution A.**

Note: With Solution B, residual compressive stress of 5,400 psi has been measured.

with bath C the opposite is true. With baths G and I, the residual stress decreases as current density is increased.

The Phillips and Clifton report shows that nickel deposited in a state of low tensile stress or in residual compression did not crack in the salt spray test as did specimens in which the residual tensile stress was relatively great. The tests were not, however, sufficiently numerous or varied to determine whether corrosion resistance increases with the magnitude of the residual compressive stress as was expected. This probability remains to be explored.

It was not possible immediately to conduct fatigue tests at the Research Laboratories Division, General Motors Corporation, to determine the effects of residual compressive stresses in nickel deposits on steel specimens. It was learned, however, that a U. S. Government Laboratory was conducting a series of tests to measure the extent of fatigue damage resulting from nickel plating and the effect of shot peening specimens after plating and the base metal before plating.

Shot peening after plating had previously (Ref. 13) been found effective in restoring fatigue strength to steel specimens plated with tensile stressed hard as well as soft nickel.

Controlled Stress in Nickel Deposits

The Research Laboratories Division, General Motors Corporation, offered to nickel plate two groups of fatigue specimens for tests by the government laboratory. The plating would be so controlled that the nickel deposits on one group would be residually stressed in tension and on the second group would be residually stressed in compression. This offer was accepted and specimens ready for plating were supplied.

The procedure that was selected for plating the first group of specimens developed residual tensile stress of 25,000 psi, and the process used for the second group developed 6,000 psi residual compressive stress. The plated specimens were returned to the government laboratory where they were fatigue tested in comparison with noncoated, fully polished specimens of the same base steel. The results of these tests are shown in the replotted S N diagram, Fig. 5. The endurance limit of the polished base steel was found to be 45,000 psi, which dropped to 29,000 psi when plated with the 25,000 psi tension stressed nickel.

In contrast to this loss of 35 percent, the specimens plated with nickel stressed to 6,000 psi compression actually indicated a gain in strength. The indicated gain, however, is well within the range of experimental error and, until more data are available, it should be assumed that these compressively stressed nickel plated specimens are approximately equal to the polished base steel.

Although these controlled stress tests or similar tests should be repeated to establish more definitely the variations in the fatigue strength of the three kinds of specimens, the differences shown between tensile and compressive residual stress are sufficiently great to justify the conclusion that fatigue strength of nickel plated specimens is directly affected by the state of residual stress in deposited nickel.

The procedures given in Table VI were used for cleaning and nickel plating the fatigue specimens having residual compressive stress of 6,000 pounds per square inch.

It is important to remember that the fatigue comparisons shown in Fig. 5 were made with specimens in which the base steel was fully polished. It has been shown (Ref. 10) that polishing induces residual compressive stresses sufficiently great (possibly 15,000 to 20,000 psi) to increase the fatigue limit of rotating beam steel specimens 10 to 15 percent.

It would therefore not be expected that the fatigue strength of polished steel specimens plated with nickel would be appreciably increased by plating until the retained residual (See Ref. 10 for definition of "retained residual stress") compressive stress in the nickel coat exceeds the retained residual compressive stress induced by the polishing. It is not probable that this condition prevailed in the specimens plated with nickel stressed 6,000 psi in compression unless the yield strength of the nickel coat exceeded the yield strength of the base steel.

Since under reversed loading, much of the residual compressive stress may be lost by compressive yielding, it is desirable to coat the surface of the base metal with a deposit having a high elastic limit, as well as good adhesion and high residual compressive stress. A coat that possesses these qualities need not have much ductility.

Effectiveness of the residual compressive stress in plated metal is lost unless the bond to the base metal is strong enough to support the stress at the junction of the two metals.

In the experiment conducted by the Research Laboratories Division, General Motors Corporation, the maximum residual compressive stress obtained was 9,700 psi. Since this result was, presumably, an accidental characteristic of one of the proprietary baths, it is probable that residual compressive stress of greater magnitude can be induced by nickel baths developed for that specific purpose. With strongly bonded nickel having residual compressive stress of 15,000 to 20,000 psi, and high yield strength, it should be possible to improve greatly the fatigue strength of machine elements by nickel plating.

The desirability of high yield strength and high hardness suggest that, if chromium can be plated in a state of high residual compression together with high bond strength, it will be superior to nickel for rebuilding and fatigue strengthening purposes. Although no efforts to obtain compressively stressed chromium are known, this field may have been neglected because research along this line the fatigue strength of machine ele- has not seemed important.

In rebuilding highly stressed machine parts by electroplating, the sign and the magnitude of the residual stress in the deposited metal should be determined. For this purpose a measuring technique similar to that developed by the Research Laboratories Division, General Motors Corporation, is recommended. At least one measuring specimen should be plated in the same tank with each machine part and the conditions of plating as nearly identical as possible.

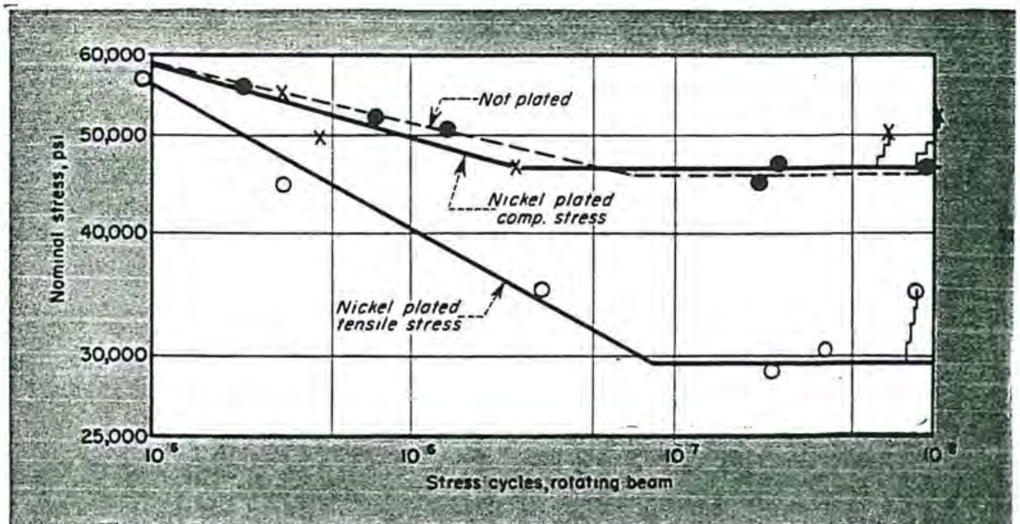


Fig. 5 — Fatigue strength of steel plated with controlled stress in nickel deposit.

Mechanical Prestressing Effective

Although electrodeposited coatings that are residually stressed in compression are more desirable for structural purposes, including protection against corrosion, it is possible to avoid much of the loss of fatigue strength resulting from coatings that are residually stressed in tension. Since fatigue failures occur only from tensile stresses, the extension of cracks formed in the plated metal into the base metal can be prevented by inducing residual compressive stress in the surface of the base before plating. Prestressing of the base metal can be accomplished by shot peening, superficial rolling, and other mechanical and thermal treatments.

The results of prestressing rotating beam fatigue specimens by shot peening prior to chromium plating are shown in the S N diagram, Fig. 6. This diagram has been replotted from data obtained from the same government laboratory that reported the tests shown in Fig. 5. The four plotted curves show:

(a) Curve labeled "Not Plated" is the same as the similarly labeled curve in Fig. 5 and represents rotating beam fatigue strength of fully polished base steel.

(b) Curve labeled "Chrome Plated" shows the fatigue strength of fully polished base metal after plating with chromium.

(c) Curve labeled "Shot Peened" shows the fatigue strength of the unplated base steel after shot peening.

(d) Curve labeled "Peened and Chrome-Plated" shows the effect of induced residual compressive stress in the base steel that was shot peened before the chromium was deposited.

These curves show that the fatigue strength of specimens plated after peening is greater than that of the fully polished base steel but not as great as that of the peened but uncoated base metal. Prestressing is seen to have increased the fatigue strength of chromium plated steel 35 percent.

The same government laboratory also reported a similar series of tests in which nickel (not plated by the Research Laboratories Division, General Motors Corporation) was used in place of chromium. The data are replotted in Fig. 7 in which similarly labeled curves represent the same conditions as are described for Fig. 6. Note however that the "Shot Peened" curve of Fig. 6 is not shown in Fig. 7, but a new curve is added:

(e) Curve labeled "Nickel Plated

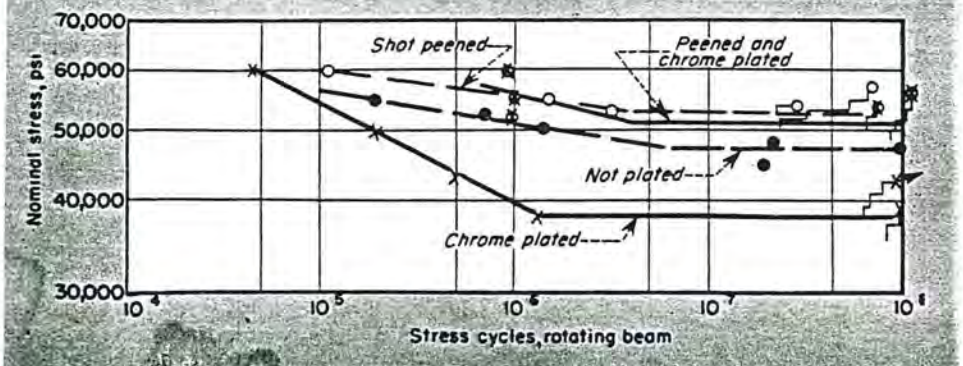


Fig. 6 — Comparison of fatigue strengths of uncoated, chromium plated, shot peened, and peened and chromium plated steel rotating beam specimens.

and Peened" shows the effect of shot peening the specimens after instead of before they were plated.

It is seen that prestressing by shot peening has more than doubled the fatigue strength of the nickel plated specimens. The loss of strength (60 percent) of the unpeened plated specimens as compared to the polished base steel, however, is the greatest known to the author. The magnitude of the residual tensile stress in the plated nickel was not given but, presumably, it was much greater than the 25,000 psi of the equivalent curve of Fig. 5, which shows a loss of 37 percent.

Perhaps it is the effects of high residual tensile stress that prevented as great a strength recovery (41,000 psi) of the peened and plated specimens, Fig. 7, as that (56,000 psi) which occurred in the Fig. 6 equivalent specimens.

Shot peening of the specimens of Fig. 7 was performed by the Research Laboratories Division, General Motors Corporation, using $\frac{1}{8}$ in. polished steel bearing balls at a velocity to give an intensity of .006-.008A2 as measured by the Almen standards. Smooth steel balls were used to avoid, as far as possible, damaging the peened surfaces by cuts and bruises, which often occurs when using commercial grades of chilled iron shot containing rough and fractured particles. Surface irregularities caused by shot peening reduce the fatigue strength of specimens to the same extent as similar stress raisers from other causes.

In many applications, it will be found desirable to prestress by superficial rolling rather than by shot peening. Rolling can develop residual compressive stress of exceptional magnitude and surface roughening can be thus avoided. In an O.S.R.D. report (Ref. 14), tools suitable for superficial rolling of various shaped surfaces have been illustrated and briefly described.

Laboratory Tests Often Misleading

Whether prestressing is induced by suitable plating processes or by mechanical operations before or after plating, the effectiveness of the residual stress in increasing fatigue strength cannot be measured by arbitrary repeated loading schedules. Preferred laboratory fatigue specimens apply reversed loads of equal magnitude whether the tests are in bending, torsion, or push-pull. Specimens subjected to reversed stresses lose substantial parts and sometimes all of the compressive residual stress by compressive yielding (Ref. 10) of the surface or tensile yielding of the core. The result is loss of fatigue strength in as great or greater proportion than the loss of residual compressive stress.

Few machine parts operating in normal service are subjected to reversed loading. Among the parts on which the load is reversed, plus and minus loads of equal magnitude are rarely found. The true effectiveness of prestressing treatments applied to machine parts can only be found by actual service use of the treated part or, less accurately, by a laboratory test in which the machine part is subjected to a loading schedule similar to that which occurs in normal service.

A reasonably reliable laboratory test loading schedule requires that the normal service loads have previously been determined by suitable strain measuring instruments. For critical applications beware of "simulated service" loading schedules. Such tests when not supported by actual measurements and service experience will often serve only to deceive the experimenter. Unproved simulated tests should be regarded as counterfeit tests. A large percentage of laboratory tests fall into this category.

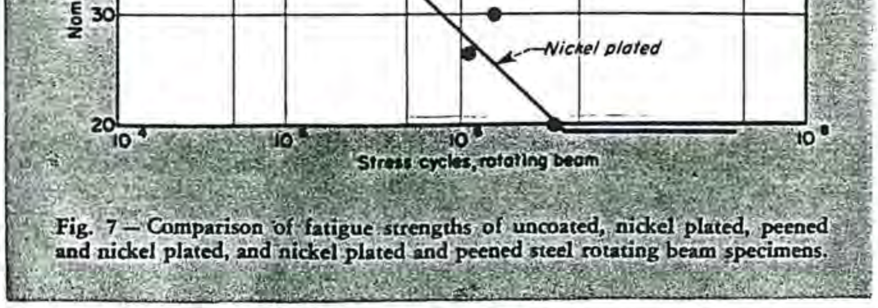


Fig. 7 — Comparison of fatigue strengths of uncoated, nickel plated, peened and nickel plated, and nickel plated and peened steel rotating beam specimens.

REFERENCES

1. F. C. Lea, Penetration of Hydrogen into Metal Cathodes and its Effect Upon Tensile Properties of Metals and Their Resistance to Repeated Stresses; with a Note on the Effects of Non-Electrolytic Baths and Nickel Plating on these Properties. *Proc. Royal Soc.* (London), V No. 123A, 1929, pp. 171-185.

2. H. K. Cummings, Case Hardening and Chromium Plating Data. Unpublished Report to Bureau of Aeronautics, U. S. Navy Dept. Soc. Prevention of Fatigue of Metals, Battelle Memorial Inst., John Wiley & Sons, p. 171.

3. C. G. Williams and J. S. Brown, Fatigue Strength of Crankshafts. *Engineering*, V No. 154, No. 3992 and 3993, pp. 58-59 and 78-79.

4. R. D. H. Blaklie and H. J. Davies, Effect of Surface Conditions and Electrodeposited Metals on the Resistance of Materials to Repeated Stresses. *Proc. Inst. Mech. Eng.*, 1930, Part One, pp. 731-750. *Summary Engineering*, V No. 150, 1930, pp. 670-673.

5. E. J. Mills, Electrostriction, *Proc. Royal Soc.*, A V26, 1877, p. 504.

6. G. G. Stoney, The Tension of Metallic Films Deposited by Electrolysis, *Proc. Royal Soc.*, A Vol. 82, 1909, pp. 172-175.

7. Wm. Hume-Rothery and M.R.J. Wyllie, The Structure of Electrodeposited Chromium. *Proc. Royal Soc.*, V No. 181, July 1943, pp. 331-344.

8. A. Brenner, P. Burkhead and C. Jennings, Physical Properties of Electrodeposited Chromium. *National Bureau of Standards*, V. 40, pp. 31-59.

9. Hugh L. Logan, Effect of Chromium Plating on the Endurance Limit of Steels Used in Aircraft. *National Bureau of Standards*, Research Paper RP2011, Vol. 42, Aug. 1949.

10. J. O. Almen, Fatigue Weakness of Surfaces, *Product Engineering*, V 21, No. 11, 1950, pp. 117-139.

11. J. O. Almen, Fatigue Failures are Tensile Failures, *Product Engineering*, V 22, No. 3, 1951, pp. 101-124.

12. W. M. Phillips and F. L. Clifton, Stress in Electrodeposited Nickel. *Proceedings 34th Annual Convention*, Electroplaters Society, June 1947, pp. 97-110.

13. R. L. Mattson and J. O. Almen, Effect of Shot Blasting on the Physical Properties of Steel, Final Report, Part III O.S.R.D., No. 6647. Published by National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, pp. 160-161.

14. R. L. Mattson and J. O. Almen, Effect of Shot Blasting on the Physical Properties of Steel, Final Report, Part III O.S.R.D., No. 6647. Published by National Defense Committee of the Office of Scientific Research and Development, War Metallurgy Division, pp. 25-34.