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 higher 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 65,000 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:

<table>
<thead>
<tr>
<th>Steel Quenched and Tempered to Endurance Limit, psi</th>
<th>Not plated</th>
<th>Plated 0.00015 in. thick</th>
<th>Plated 0.0045 in. thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>125,000 psi Tensile Strength Limit, psi</td>
<td>65,500</td>
<td>38,000</td>
<td>41,000</td>
</tr>
</tbody>
</table>

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

The fatigue endurance limits of unplated and chromium plated steel specimens of various analyses, hardnesses, plate thicknesses, and current densities are
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 Electrochemical 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 variables numerous tests would be required and, therefore, a necessary preliminary work the development of means for measuring residual stresses in plated metals. It was important that the

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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
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 VI—Procedure for Compressive Plating

<table>
<thead>
<tr>
<th>CLEANING</th>
<th>PLATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrease</td>
<td>1. Plate at 40 amp per sq ft for required time to deposit desired thickness. 100 amp min per sq ft equals 0.001 in. of nickel. Rotate specimen to obtain uniform plate thickness.</td>
</tr>
<tr>
<td>Cathodic clean 3 minutes</td>
<td>2. SOLUTION A. A bright nickel solution having the following composition: Single nickel salts, NiSO₄ · 6H₂O 40 oz/gal</td>
</tr>
<tr>
<td>Hand scrub with pumice</td>
<td>Nickel chloride, NiCl₂ · 6H₂O 8 oz/gal</td>
</tr>
<tr>
<td>Cathodic clean 30 seconds</td>
<td>Boric acid, H₃BO₃ 5 oz/gal</td>
</tr>
<tr>
<td>Water rinse</td>
<td>Brightener A. 0.125% by volume</td>
</tr>
<tr>
<td>Anodic treat in concentrated H₂SO₄ at 6 volts for 1 minute</td>
<td>Non-pitter 0.08 oz/gal</td>
</tr>
<tr>
<td>Water rinse</td>
<td>Brightener B. 0.5 oz/gal</td>
</tr>
<tr>
<td>Note: With Solution B, residual compressive stress of 5,400 psi has been measured.</td>
<td>pH 3.5 to 4.5, temp 115 to 140 F</td>
</tr>
</tbody>
</table>

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.

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.
pressive 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 suggests 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 elements has not seemed important.

In rebuilding highly stressed machine parts by electrodeposition, 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.

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
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.

REFERENCES