RP454

EFFECT OF ZINC COATINGS ON THE ENDURANCE PROPERTIES OF STEEL

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ABSTRACT

The effect of the surface alterations, resulting from the application and presence of hot-dipped galvanized and electroplated zinc coatings, on the endurance properties of 0.02 per cent carbon open-hearth iron and 0.45 and 0.72 per cent carbon steels was determined by fatigue tests made with R. R. Moore rotating beam and Haigh axial loading machines.

Rotating beam tests were made on: (*a*) Polished but uncoated specimens, (*b*) specimens coated by the hot-dip galvanizing process, (*c*) zinc-plated specimens, and (*d*) on specimens acid pickled as for galvanizing. Axial loading tests were made on uncoated and galvanized specimens only.

The open-hearth iron was tested in the "as rolled" condition. The two carbon steels were tested in the normalized and annealed condition, in the quenched condition, and in the tempered condition, except that axial loading tests were not made on quenched specimens.

The results of the fatigue tests are given in conventional S–N diagrams and are summarized in a table, together with the results of tensile strength and hardness determinations. Photomicrographs showing the structures of the heat-treated steels and of the two types of coatings are given.

The endurance ratios (endurance limit : tensile strength) by the rotating beam method of test of the uncoated specimens varied from 0.38 to 0.70; by the axial loading method, from 0.31 to 0.59.

The decrease in fatigue limit from that of the polished uncoated materials caused by the acid pickling was more marked in the quenched steels than in the annealed and the tempered steels. The decrease varied from 0 to 40 per cent.

A still greater decrease, as much as 42.5 per cent, was caused by the presence of the hot-dipped galvanized coatings, The quenched and the tempered steels were affected more adversely than the annealed steels.

The fatigue limits of the zinc electroplated specimens were equal to or greater than those of the uncoated specimens.

The difference in the effects of the two types of coating is believed to be caused by the differences in the nature of the bond between zinc and steel and differences in the structure and hardness of the two coatings.

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I. INTRODUCTION

It is generally agreed that the character of the surface of a metal is an important factor in determining its resistance to repeated stresses. If an endurance limit is accepted as an intrinsic property of a metal, this limit is correctly determined only when smoothly polished specimens with generous fillets are used. The damaging effects of surface corrosion and of mechanically produced notches have formed the subject of numerous investigations on "fatigue of metals." The information gained from these investigations has shown the necessity for avoiding "notch effects" in highly stressed members subjected to repeated stresses. Careful removal of tool marks, protection from corrosion and use of adequate fillets at abrupt changes of section, aid materially in realizing in practice the normal endurance strength of metals.

Metallic coatings are frequently used on iron and steel to protect against corrosion. It is a matter of considerable interest to know what effect such metallic coatings may have upon the fatigue limit of metals when damage by corrosion is not involved. From a mechanical standpoint the presence of a metallic coating on a specimen of iron or steel introduces factors which complicate this problem. There are two surfaces, the free surface of the coating and that of the underlying steel, the characteristics of which may influence the fatigue limit of the composite specimen. Another factor is the endurance strength of the coating itself. Very little is known about this property of the various protective metallic coatings in general use, but it is probably low in comparison with the endurance strength of steels. The nature of the bond or interface between coating and steel is believed to have a very important influence on the endurance properties of the composite specimen. The nature of the surface of the steel, the kind of coating and the manner in which it is applied largely determine the character of the bond between coating and steel.

This investigation was restricted to a study of the effect of hot-dipped galvanized and electroplated zinc coatings on the endurance properties of low carbon open hearth iron and two carbon steels.

II. MATERIALS

Zinc coatings were chosen because they are the most commonly used protective metallic coatings on ordinary structural grades of iron and steel. Both hot-dipped galvanized and electroplated coatings were used because of the known difference in the nature of the bond between steel and zinc coating of these two types. Sherardized, "galvannealed," and sprayed zinc coatings were not studied. It is believed that the difference in the nature of the bond of hot-dipped galvanized coatings and sherardized or "galvannealed" coatings, and of electrodeposited coatings and sprayed zinc coatings, is one of degree rather than of kind. It is, of course, possible that each of the above-mentioned types of zinc coatings might affect the endurance properties of a given steel to a different degree.

The open-hearth iron and the two carbon steels were purchased from jobbers and were not specially made for this investigation. The chemical compositions of the three materials (ladle analyses) are given in Table 1.

TABLE 1.—*Chemical composition of steels*

	Carbon	Manganese	Phosphorus	Sulphur	Silicon
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Open-hearth iron	0.02	0.03	0.042	0.005	----------
0.45 per cent C steel	.45	.60	.015	.040	0.18
0.72 per cent C steel	.72	.31	.017	.019	.24

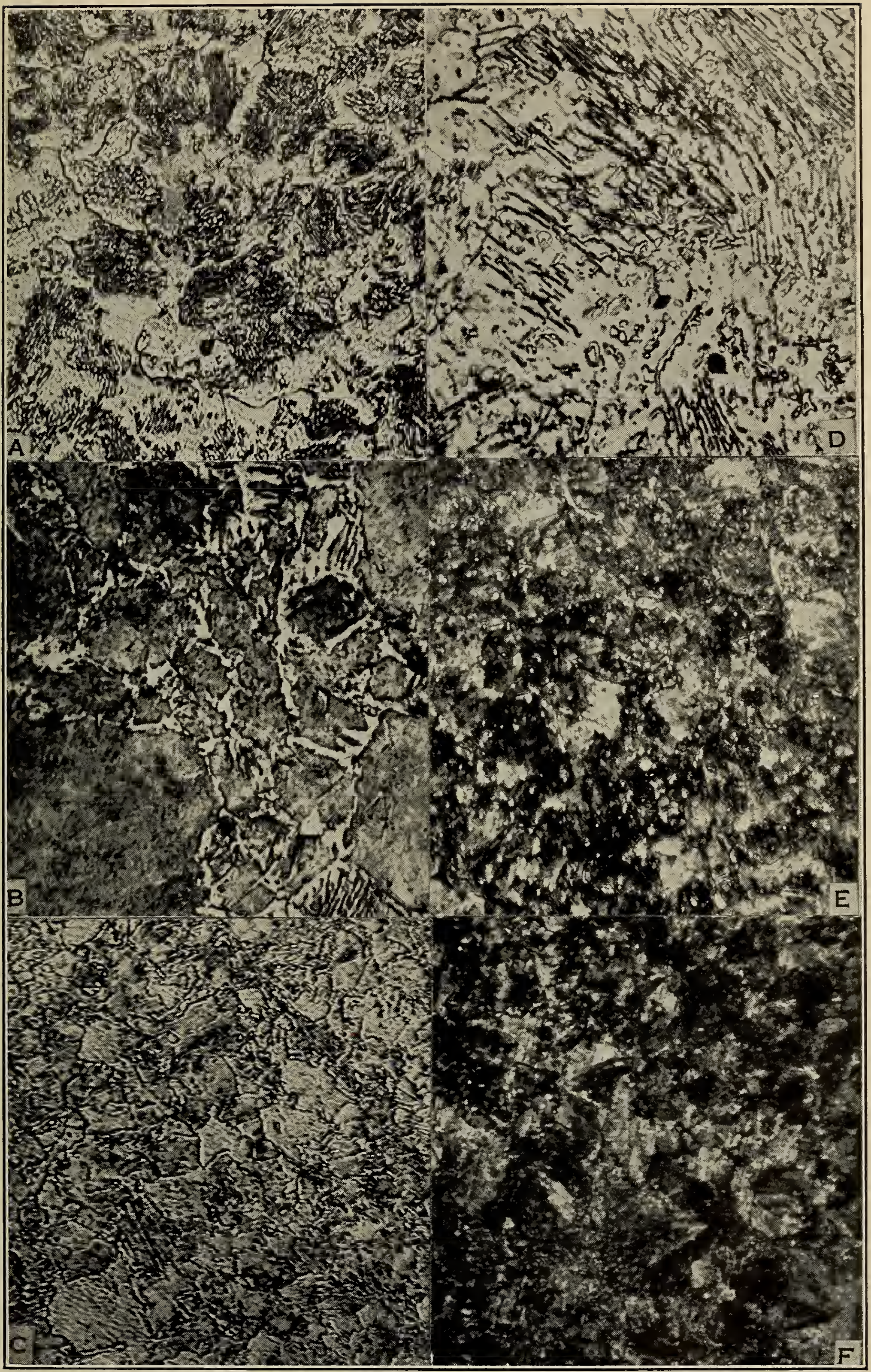

FIGURE 1.—*Structure of the carbon steels. Specimens were etched with nital (alcohol containing 2 per cent nitric acid).* × *450*

a, 0.45 per cent carbon steel, normalized at 875° C., annealed at 800° C.; *b*, 0.45 per cent carbon steel, normalized at 875° C., annealed at 800° C., quenched in oil from 830° C; *c*, 0.45 per cent carbon steel, normalized at 875° C., annealed at 800° C., quenched in oil from 830° C., tempered at 595° C.; *d*, 0.72 per cent carbon steel, normalized at 795° C., annealed at 765° C.; *e*, 0.72 per cent carbon steel, normalized at 795° C., annealed at 765° C., quenched in oil from 775° C.; *f*, 0.72 per cent carbon steel, normalized at 795° C., annealed at 765° C., quenched in oil from 775° C., tempered at 450° C.

The open-hearth iron test specimens were machined from the center of 1-inch diameter hot-rolled bars and the specimens of the two carbon steels from the center of corresponding bars of three-quarter inch diameter.

All of the specimens were carefully machined on a lathe and finish ground to size. They were then polished longitudinally until all traces of circumferential tool marks were eliminated with emery papers of successively finer grit, ending with 0000 paper.

Endurance limits of the two carbon steels, coated and uncoated, were determined with the steels in the normalized and annealed condition, in the oil-quenched condition, and in the tempered condition. The details of the heat treatments are given in Table 2.

To minimize any decarburization effect, an atmosphere of illuminating gas was maintained in the furnace during the heat treatments. As a further precaution the hardened specimens were machined oversize and a layer 0.005 inch thick was ground off the test length after the heat treatments.

The open-hearth iron was used in the "as rolled" condition. The microstructures of the two carbon steels in the three conditions of heat treatment are shown in Figure 1.

Table 2.—*Heat treatment of carbon steels*

	Temperature for—							
	Normalizing [1]		Annealing [2]		Quenching [3]		Tempering [4]	
	°*F.*	°*C.*	°*F.*	°*C.*	°*F.*	°*C.*	°*F.*	°*C.*
0.45 per cent carbon steel:								
Annealed	1, 607	875	1, 472	800	-----	---	-----	---
Quenched	1, 607	875	1, 472	800	1, 526	830	-----	---
Tempered	1, 607	875	1, 472	800	1, 526	830	1, 103	595
0.72 per cent carbon steel:								
Annealed	1, 463	795	1, 409	765	-----	---	-----	---
Quenched	1, 463	795	1, 409	765	1, 427	775	-----	---
Tempered	1, 463	795	1, 409	765	1, 427	775	842	450

[1] ¾-inch rods, heated with furnace, held 20 minutes, air cooled.
[2] ¾-inch rods, heated with furnace, held 40 minutes, cooled with furnace.
[3] Machined test bars, heated with furnace, held 20 minutes, quenched in oil.
[4] Machined test bars, heated with furnace, held 60 minutes, cooled with furnace.

The galvanized coatings were applied by the research division of the New Jersey Zinc Co. (of Pa.) by a method approximating commercial practice for hot-dip galvanizing. The specimens to be galvanized were first polished to the same degree as the specimens tested in the uncoated condition. They were then dipped in a hydrochloric acid solution (2 parts water to 1 part hydrochloric acid, specific gravity 1.19) for two minutes and immediately into the zinc bath held at 440° C. (824° F.). A high-grade zinc (containing 99.94+ per cent Zn) was used. The weight of coating obtained varied from 1.6 to 2.0 oz./ft.^{2} The galvanized coatings varied from 0.0017 to 0.0035 inch in thickness. This variation in thickness was probably caused by the fact that some of the specimens had to be dipped more than once to obtain a complete coating. The length of time in the zinc bath, accordingly, varied from 45 to 100 seconds.

In order to distinguish between the effect of the acid pickling and the combined effect of pickling and galvanizing, fatigue tests were made on specimens of each material which, after final polishing, had been dipped for two minutes into hydrochloric acid of the same strength used for the galvanized specimens.

The specimens of the quenched 0.45 and 0.72 per cent carbon steels which were not galvanized were dipped into a lead bath for 45 seconds at 440° C. (824° F.) so that they had the same heat treatment as the corresponding hot-dipped galvanized specimens. A final polish with 0000 emery paper was given to the lead-dipped specimens before they were dipped into the acid or tested.

The electroplated zinc coatings were applied at the Bureau of Standards.[1] The procedure was as follows: (*a*) cathode-electrolytic cleaning, two minutes, at 90° C.; (*b*) hot-water rinse; (*c*) cold-water rinse; (*d*) pickled in sulphuric acid (2 *N*), two minutes at 50° C.; (*e*) hot-water rinse; (*f*) hot alkali dip without current, two minutes; (*g*) scrubbed with cleaning solution, bristle brush; and (*h*) plated in acid zinc bath, 24 minutes 1.5 amperes, 35° C.

The electrolytic cleaner was made up as follows: Sodium carbonate, 30 g per liter; trisodium phosphate, 30 g per liter; and sodium hydroxide, 7.5 g per liter.

The zinc anodes for the electroplating process were of the same order of purity as the zinc used for the hot-dipped coatings. The thickness of the electrodeposited coatings varied from 0.0021 to 0.0031 inch, which is roughly equivalent to a 2-ounce coating.

III. TESTING PROCEDURE

The endurance limit determinations were made by both the rotating beam and the axial loading methods of stressing. The rotating beam tests were made on R. R. Moore machines and the axial loading tests were made on Haigh alternating stress testing machines, in which the specimens were subjected to alternating equal tensile and compressive stresses. The form of the specimens, methods of calibration of the testing machines, and testing procedure followed have been described previously by one of the authors.[2]

Axial loading tests were not made on zinc-plated specimens as it was believed that the effect of the electrodeposited coating on the endurance limit determined by this method, would be of the same order as was found for the rotating beam tests. As a further economy in number of specimens, axial loading tests were not made on the 0.45 and 0.72 per cent carbon steels in the quenched condition because these steels are seldom used in this condition. Rotating beam tests of electroplated specimens of the 0.72 per cent carbon steels in the quenched condition and of the 0.45 per cent carbon steel in the annealed and in the quenched conditions were also omitted.

Usually nine specimens were used in the determination of each endurance limit. One specimen of each series, except the pickled specimens, tested on the Moore machines was subjected to 25,000,000 cycles of reversed stress at the endurance limit and then restressed at a value 5,000 lbs./in.^{2} above the endurance limit. An annealed, a quenched, and a tempered specimen of the 0.45 per cent carbon steel and an annealed and a tempered specimen of the 0.72 per cent carbon

[1] The plating was done by the electrochemistry laboratory under the supervision of Dr. W. Blum.
[2] R. D. France, Endurance Testing of Steel: Comparison of Results Obtained with Rotating-Beam versus Axially-Loaded Specimens, Proc., Am. Soc. Testing Materials, vol. 31, pt. 2, p. 176, 1931.

steel were stripped of their galvanized coatings, after which they were tested at a stress just under the fatigue limit determined on the acid-pickled specimens of the corresponding materials.

The stresses applied to the acid pickled and the coated specimens were calculated on the diameter of the polished specimen before it was pickled or coated. The diameters were measured with a special micrometer capable of a precision of plus or minus 0.0001 inch. The change in diameter caused by either the acid treatment alone or the acid treatment and the application of the zinc coating was in all cases less than 0.0002 inch.

The tensile strengths of the three materials were determined on standard 0.505 inch diameter test bars, heat treated in the same way as the endurance specimens. Hardness determinations were made on the ends of the tensile and endurance test bars.

IV. RESULTS

The results of the fatigue limit determinations are given in Table 3, together with the tensile strength and hardness of the steels and the per cent change in fatigue limits caused by the pickling, by the pickling and galvanizing, and by the electroplating. The fatigue limits are also shown graphically in Figure 2.

Conventional *S–N* diagrams for all of the fatigue limit determinations are given in Figures 3 to 9.

TABLE 3.—*Physical properties and results of endurance tests*

Material (per cent carbon)	Heat treatment	Tensile strength	Hardness		Rotating beam								Axial loading			
					Uncoated		Pickled		Galvanized		Electroplated		Uncoated		Galvanized	
			Brinell hardness number	Rockwell number	Endurance ratio [1]	Endurance limit	Fatigue limit	Change in fatigue limit	Fatigue limit	Change in fatigue limit	Fatigue limit	Change in fatigue limit	Endurance ratio [1]	Endurance limit	Fatigue limit	Change in fatigue limit
		Lbs./in.[2]				*Lbs./in.*[2]	*Lbs./in.*[2]	*Per cent*	*Lbs./in.*[2]	*Per cent*	*Lbs./in.*[2]	*Per cent*		*Lbs./in.*[2]	*Lbs./in.*[2]	*Per cent*
0.02	Hot rolled	44,000	90	51 B	0.61	27,000	22,000	−18.5	26,000	−4.0	27,500	+1.8	0.59	26,000	22,500	−13.5
.45	Annealed	81,000	153	84 B	.44	36,000	33,000	−8.0	27,000	−25.0	-------	-------	.31	25,500	24,500	−4.0
.45	Quenched	121,500	248	28 C	.65	80,000	60,000	−25.0	46,000	−42.5	-------	-------	-------	-------	-------	-------
.45	Tempered	102,000	207	98 B	.45	46,500	46,500	0	40,000	−14.0	49,000	+5.5	.45	46,000	30,000	−35.0
.72	Annealed	92,000	192	93 B	.38	35,000	31,500	−10.0	30,500	−13.0	35,000	0	.31	29,000	28,500	−2.0
.72	Quenched	176,000	340	39 C	.70	124,500	75,000	−40.0	75,500	−40.0	-------	-------	-------	-------	-------	-------
.72	Tempered	168,500	332	37 C	.56	94,000	87,000	−7.5	54,500	−42.0	105,000	+11.0	.37	62,500	47,000	−25.0

[1] Endurance ratio$=\frac{\text{Endurance limit}}{\text{Tensile strength}}$.

V. DISCUSSION

The fatigue limits of the specimens that had been dipped in acid were lower than the fatigue limits of the polished uncoated specimens of the corresponding materials. The decrease was not uniform for the different materials but ranged from zero for the tempered 0.45

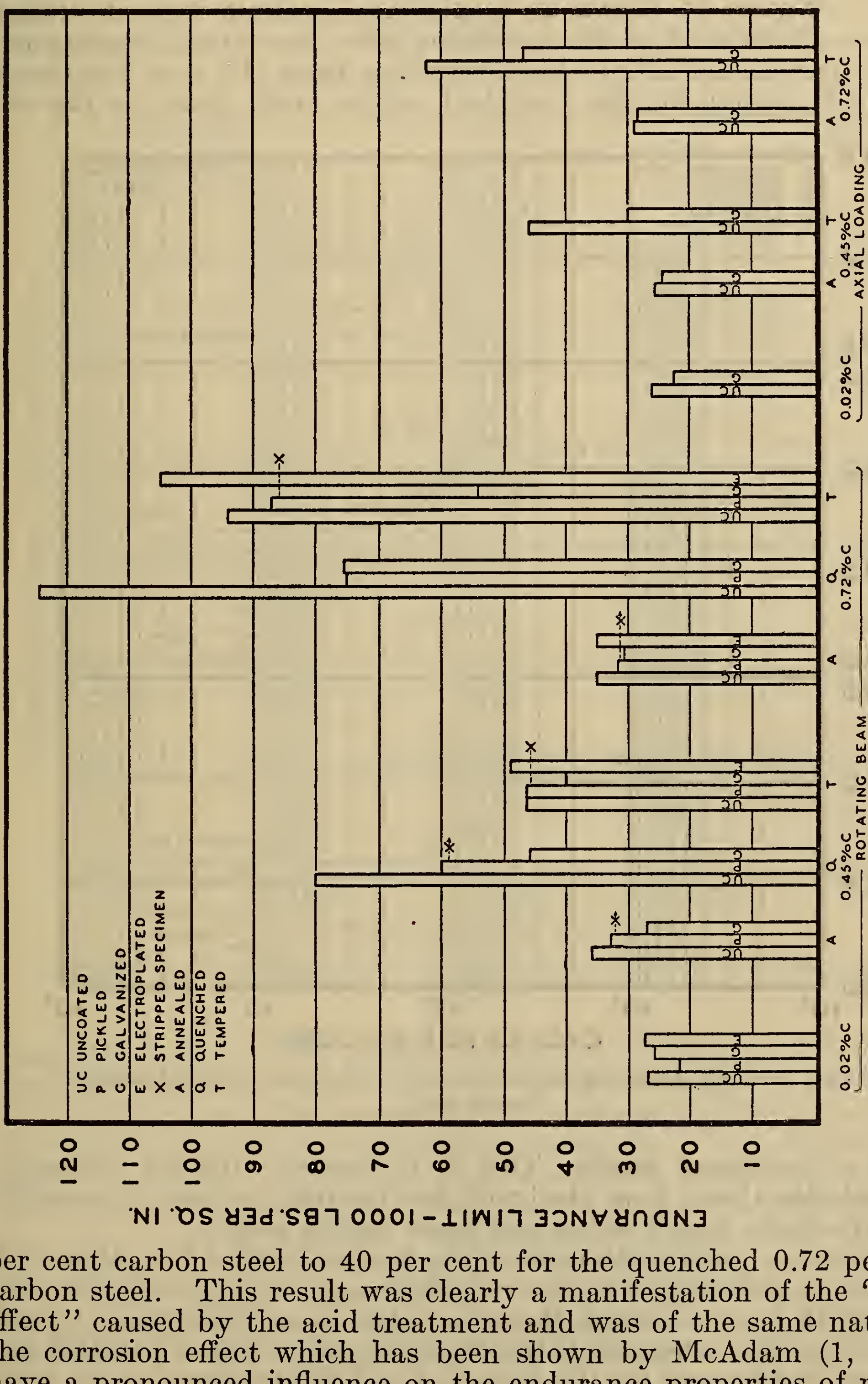

FIGURE 2.—*Fatigue limits determined by rotating beam and axial loading methods for open-hearth iron, 0.45 and 0.72 per cent carbon steels, in the annealed, quenched, and tempered conditions*

per cent carbon steel to 40 per cent for the quenched 0.72 per cent carbon steel. This result was clearly a manifestation of the "notch effect" caused by the acid treatment and was of the same nature as the corrosion effect which has been shown by McAdam (1, 2),[3] to have a pronounced influence on the endurance properties of metals.

[3] The numbers in parentheses here and throughout the text refer to the papers listed in the selected bibliography appended to this paper.

The variations in the effect of the acid treatment on the fatigue limits are undoubtedly associated with different solubility rates of the materials in the three conditions of heat treatment. The difference in the surface contours of the steel in different specimens of any one series was of about the same magnitude as the difference between the three series of specimens (acid pickled, galvanized, and electroplated). Figure 10 shows, in longitudinal section, typical surface contours of the steel of the specimens after the various treatments.

The decrease in fatigue limit resulting from the acid treatment was much greater for the quenched carbon steels than for the an-

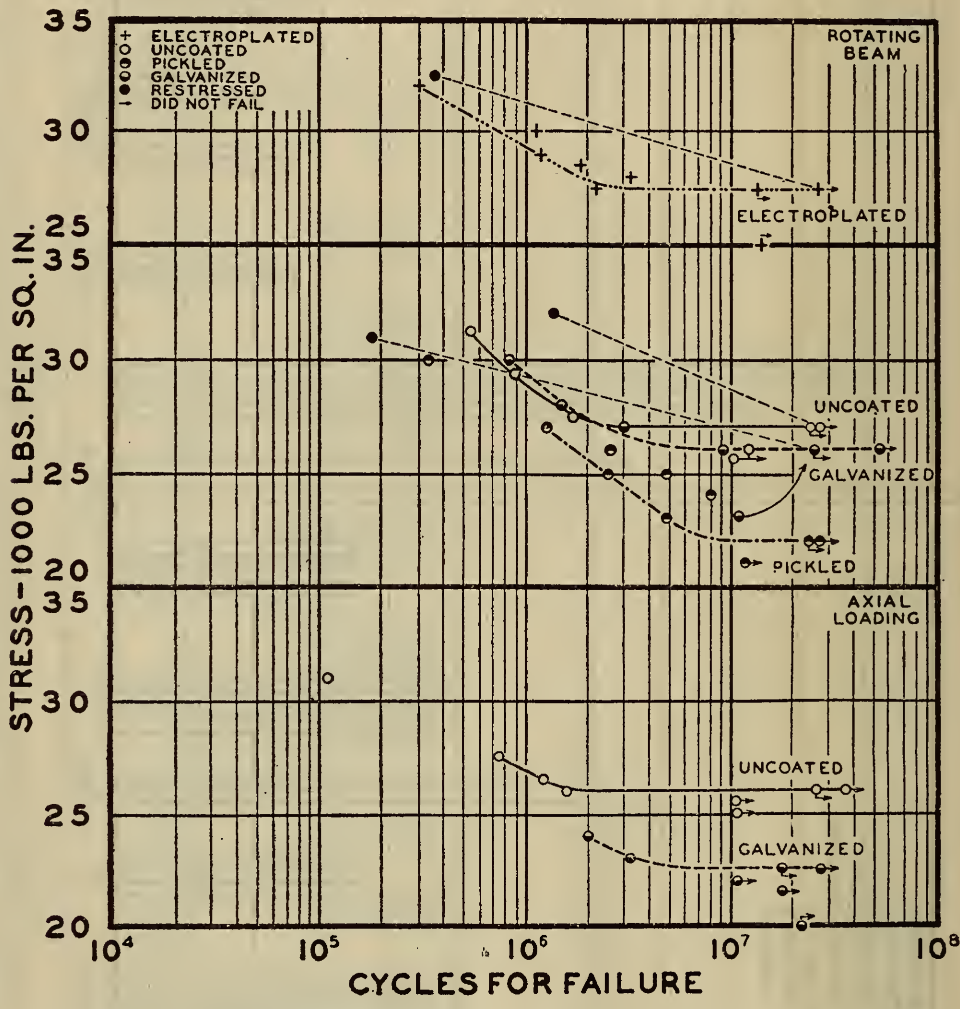

FIGURE 3.—*S–N diagrams for fatigue tests of 0.02 per cent carbon open-hearth iron*

nealed or tempered steels. This is in accord with the generally accepted idea that a hard steel with low ductility is more susceptible to notch effects than a softer and more ductile steel.

There was a marked decrease in the fatigue limit of the galvanized materials as determined by the rotating-beam method except for the open-hearth iron, for which there was little if any difference (4.0 per cent). For the carbon steels the decrease ranged from 13 to 42.5 per cent, and was greater for the quenched and the tempered steels than for the annealed steels. By the axial loading method of test the decrease for the open-hearth iron was 13.5 per cent and for the carbon steels the decrease was much greater in the tempered steels than in the annealed steels.

Except for the open-hearth iron and the quenched 0.72 per cent carbon steel, the decrease in fatigue limit was greater for the galvanized than for the acid-pickled material. It might be considered that this further decrease was caused by an increased pitting or notch effect on the surface of the steel by the action of the zinc in the galvanizing process. That this was not the only cause is indicated by the fact that galvanized specimens of the annealed and the

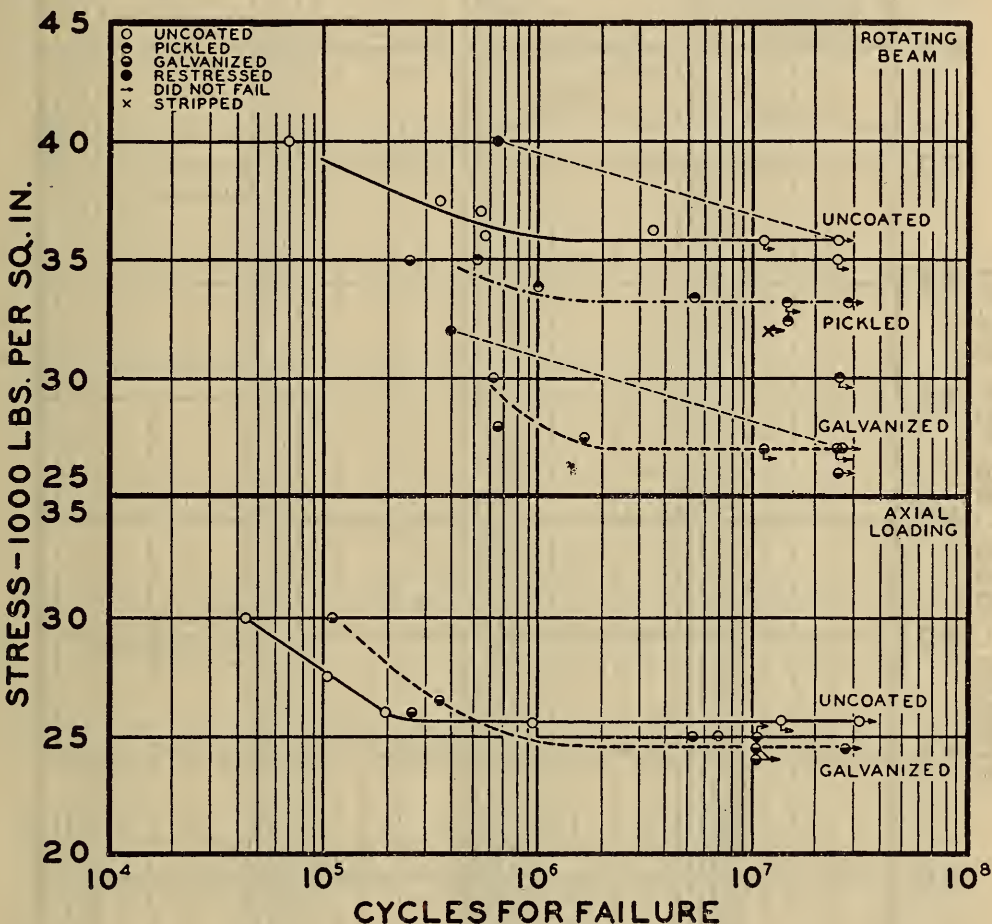

FIGURE 4.—*S–N diagrams for fatigue tests of 0.45 per cent carbon steel, annealed*

quenched 0.45 per cent carbon steels, and of the annealed 0.72 per cent carbon steels, when stripped of the zinc coating[4] did not fail in 10,000,000 cycles in the rotating beam machines at stresses just under the fatigue limits of the acid-pickled materials. The stripped specimen of the tempered 0.45 per cent carbon steel failed after 3,500,000 cycles which indicated that its fatigue limit was not much lower than the stress at which it failed. The stripped specimen of the tempered 0.72 per cent carbon steel failed after 300,000 cycles, but at a stress 32,000 lbs./in.^{2} higher than the fatigue limit of the galvanized material.

Hence it is believed that the conclusion is warranted that the presence of a hot-dip galvanized coating causes a serious lowering

[4] The zinc coatings were dissolved in hydrochloric acid (specific gravity 1.19) containing 1 ml of antimony chloride solution [32 g of $SbCl_3$ in 1,000 ml HCl (specific gravity 1.19)] to 100 ml of acid. A. S. T. M. specification A 90–30.

of the fatigue limit of carbon steels below that which would be obtained in the same steels in the polished but uncoated condition.

A similar conclusion can be drawn from the results of investigations by Harvey (3, 4), Haigh (5), and Fuller (6) of the protection against corrosion fatigue afforded to steels by galvanized or other types of metallic coatings. Although their results showed that the endur-

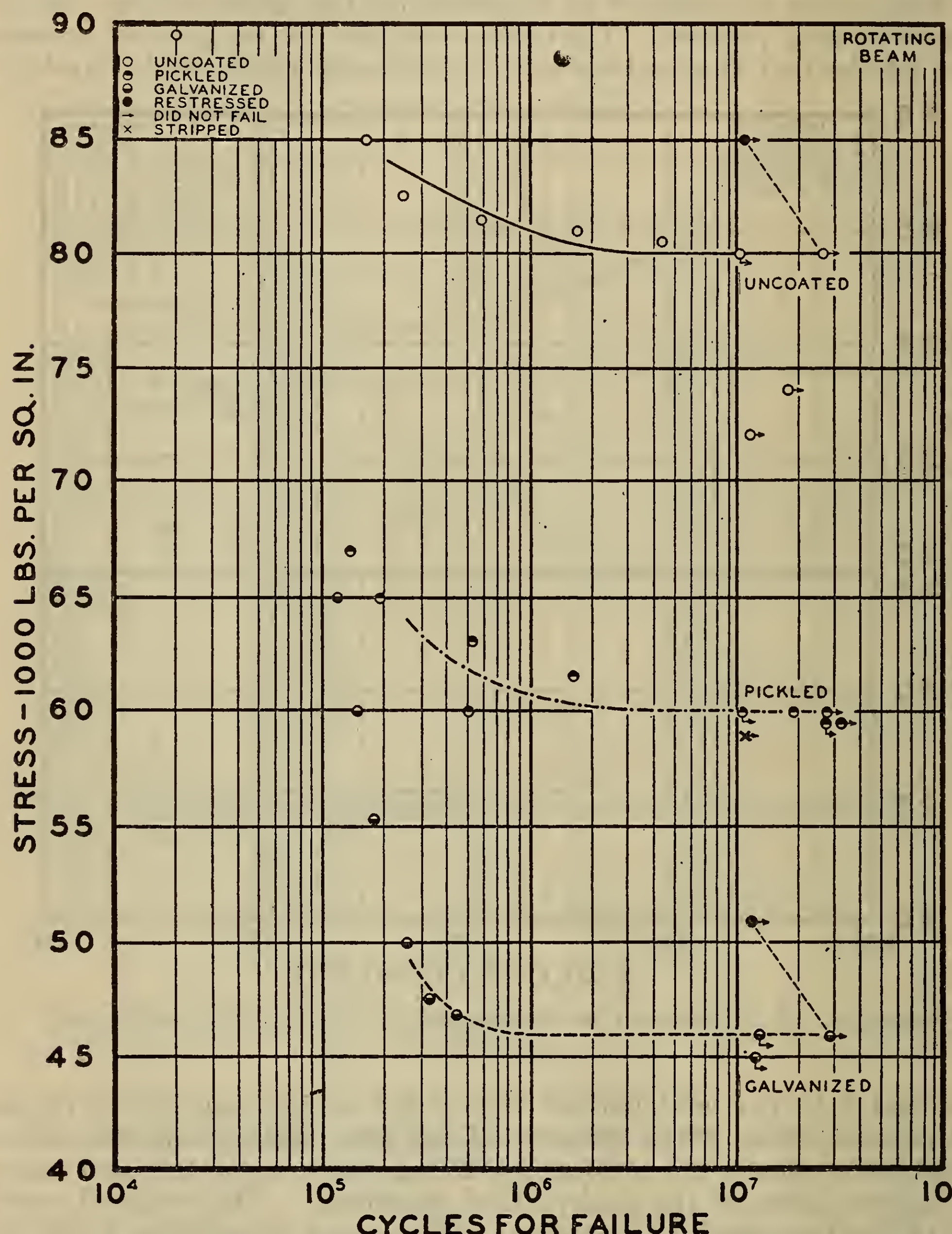

FIGURE 5.—*S–N diagrams for fatigue tests on 0.45 per cent carbon steel, quenched*

ance properties of the coated metals were definitely better than for the uncoated metals, when subjected to simultaneous stress and corrosion, the corrosion-fatigue limits of the galvanized materials were at the same time lower than the endurance limits of the uncoated materials not subjected to corrosion.

In marked contrast to the lower fatigue limit of the galvanized specimens, the fatigue limits of the zinc-plated specimens of the softer steels were equal to those of the corresponding uncoated specimens. The fatigue limits of the zinc-plated specimens of the tempered steels were higher than those of the corresponding uncoated specimens by 5.5 per cent for the medium carbon and 11 per cent for the higher carbon steel.

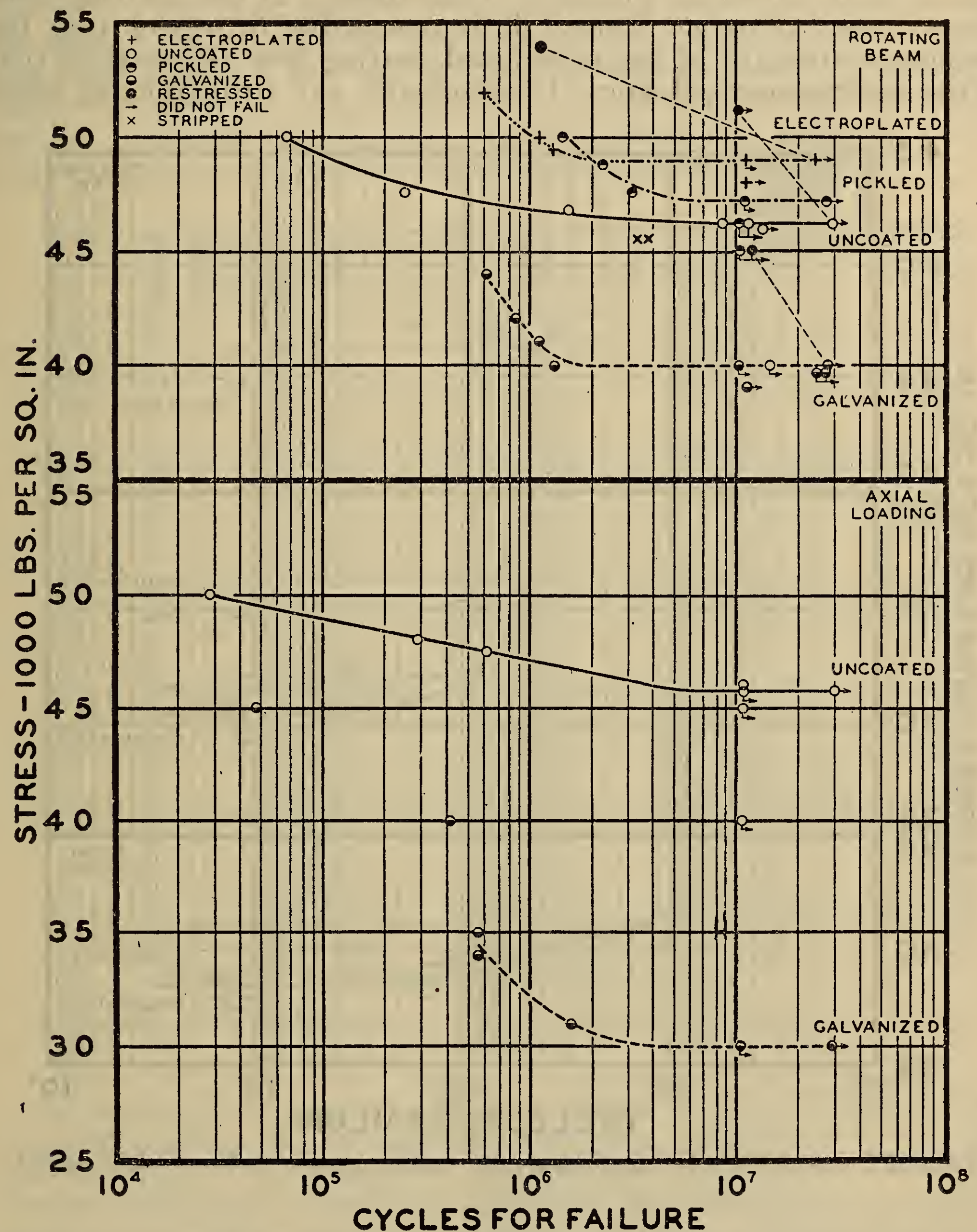

FIGURE 6.—*S–N diagrams for fatigue tests on 0.45 per cent carbon steel, tempered*

Both the hot-dip galvanized and the electroplated specimens had been subjected to comparable acid treatments before the coatings were applied. Furthermore, the steels of each series were identical in composition and had received the same heat treatments. Hence any differences in fatigue properties of the galvanized and electroplated specimens of the same series can not be ascribed to differences in the steels themselves, particularly to any suspected differences in rate of notch propagation. It is believed that the increased fatigue limits of the electroplated coatings were not the result of a strengthening effect of the zinc coating. Numerous cracks were found in both types of coatings in the more highly stressed portions of the specimens after they were removed from the testing machines. This indicates that the maximum fiber stresses in the coatings were above their endurance limits. It is reasonable to expect that the endurance strength of the galvanized coating was higher than that of the electrodeposited zinc. Consequently any strengthening effect

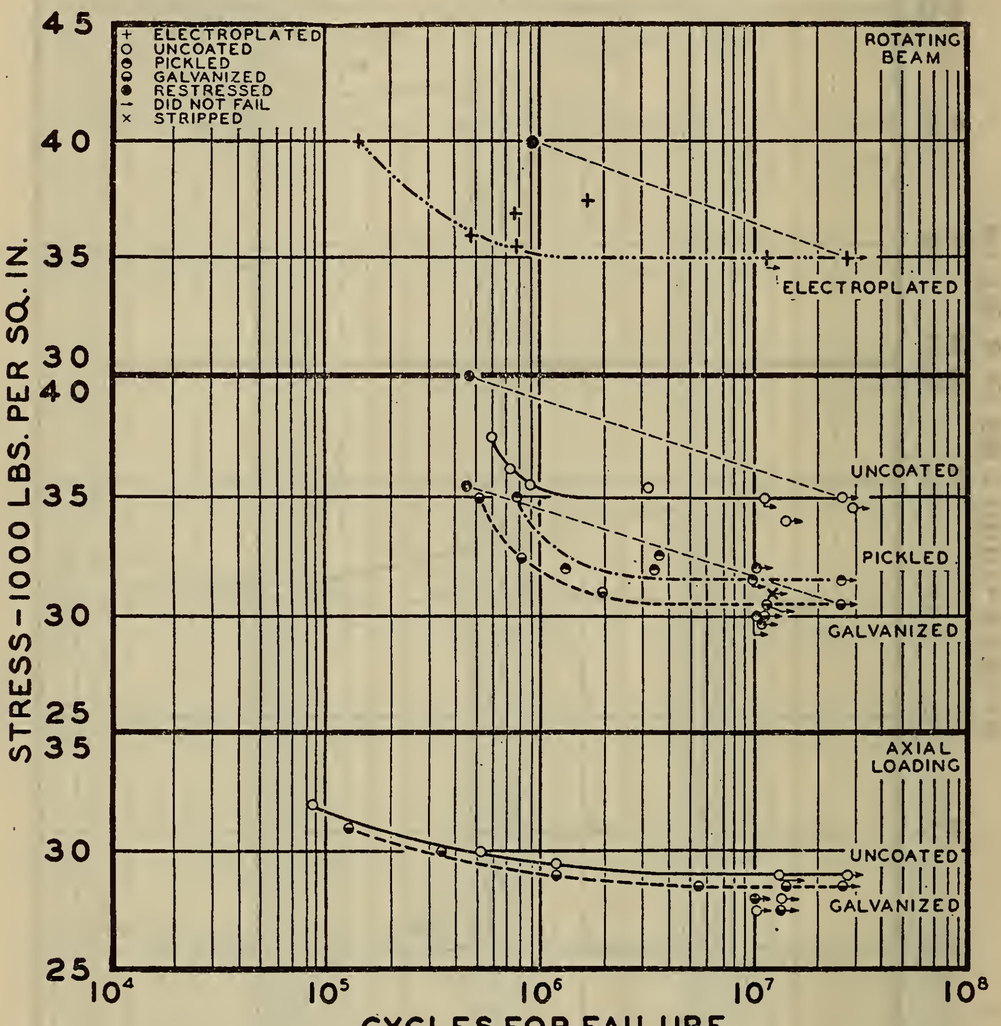

FIGURE 7.—*S–N diagrams for fatigue tests on 0.72 per cent carbon steel, annealed*

from the coating would be expected to be derived from the galvanized rather than from the electrodeposited coating.

The two types of coating are different in many respects. The electrodeposited coatings, as would be expected, were homogeneous throughout. The bond between zinc and steel may have been a "molecular bond," but at the interface there was little, if any, diffusion of iron into the zinc. Figure 11 (*a*) shows a typical cross section of the electroplated steel specimen.

The structure of hot-dipped galvanized coatings on steel has been studied by a number of investigators (7, 8, 9). Without going into a detailed discussion of the composition of the layers it suffices at this time to state that the galvanized coatings on the specimens used in this investigation consisted of at least three layers. The outer layer was predominantly pure zinc, the innermost layer consisted largely of the more or less well-known iron-zinc intermetallic compounds. The intermediate layer consisted largely of intermetallic compound or compounds interspersed in a zinc matrix. On the annealed steel and the open-hearth iron specimens the intermediate layer was relatively much thicker than the innermost layer, whereas, on the quenched and on the tempered steels the thickness of the innermost layer approached that of the intermediate layer.

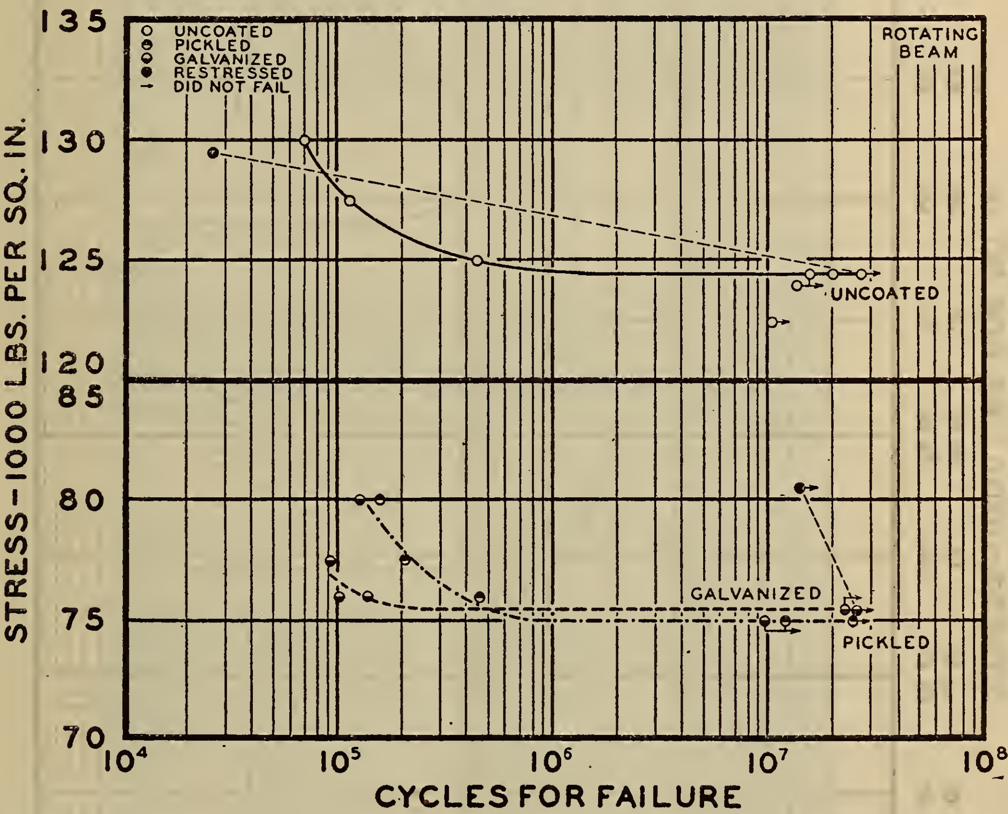

FIGURE 8.—*S–N diagrams for fatigue tests on 0.72 per cent carbon steel, quenched*

Micrographs (*c*) and (*d*) Figure 11 show in cross-section the galvanized coatings on an annealed and on a quenched 0.45 per cent carbon steel. The difference in thickness of the inner, iron rich, layers is marked. Possibly a difference in solubility in zinc of the heat-treated steel, and the annealed steel or open-hearth iron is responsible for the difference in thickness of the alloy layers.

The scratch hardness of the two types of coating indicated that the outer layer of the galvanized coatings was of the same order of hardness as the electrodeposited coatings. The intermediate and innermost layers of the galvanized coatings were increasingly harder as the steel surface was approached. This is illustrated in the micrographs (*e*) and (*f*) of Figure 11. The alloy layer adjacent to the steel (*e*) appears to be even harder than the steel itself.

As stated before, there were numerous cracks in both types of coating of the tested specimens. In the electrodeposited coatings

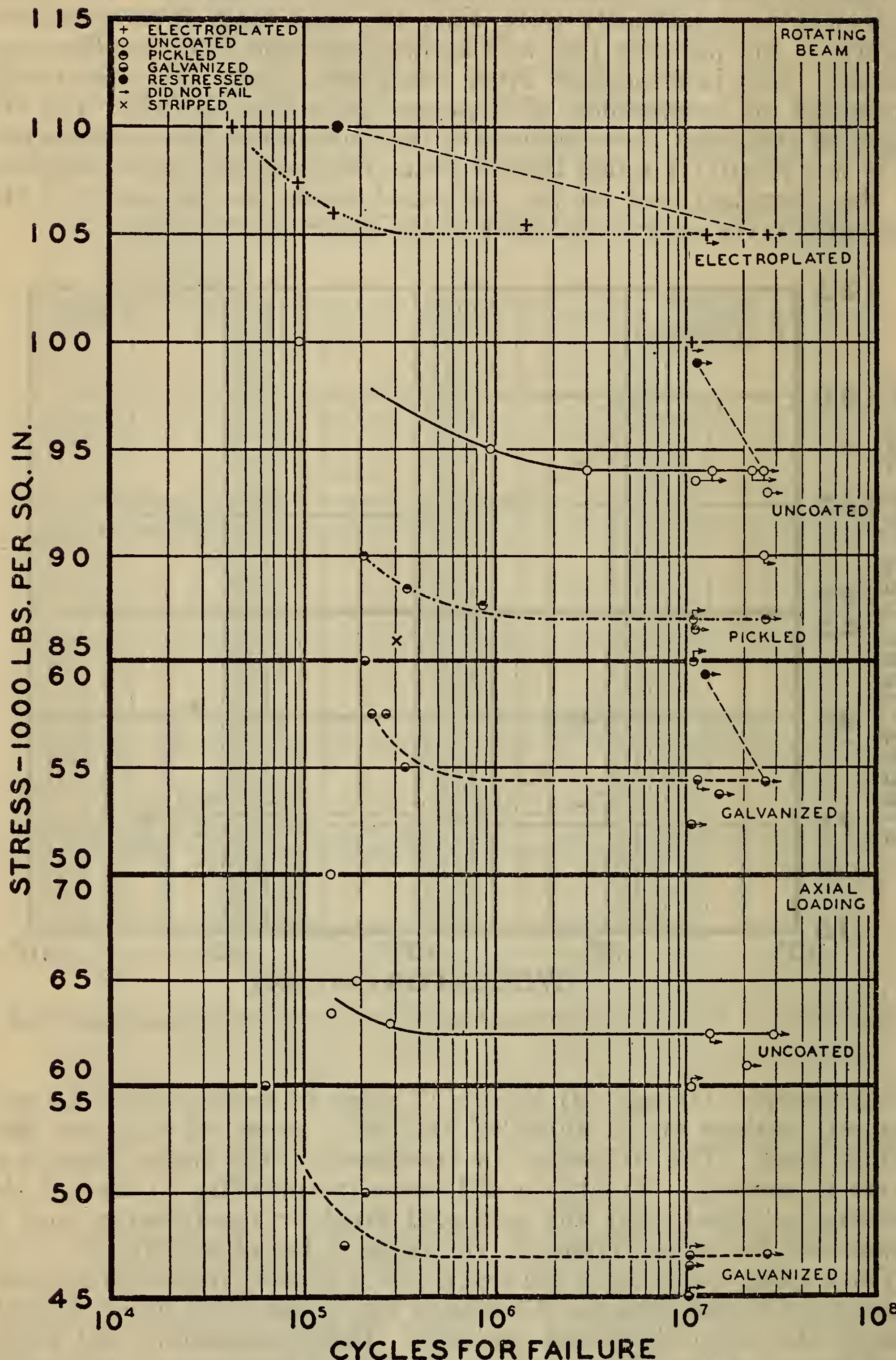

FIGURE 9.—*S–N diagrams for fatigue tests on 0.72 per cent carbon steel, tempered*

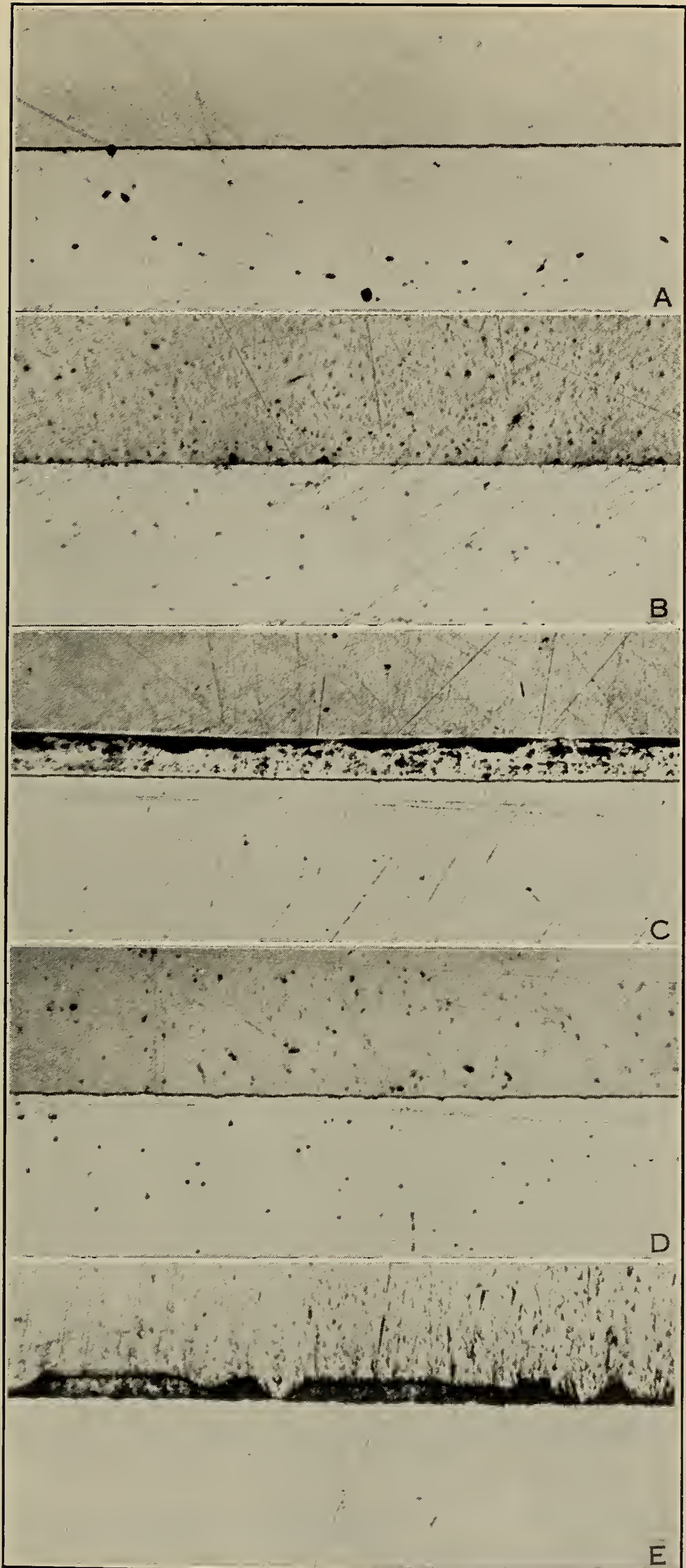

FIGURE 10.—*Typical contours of the steel surface of specimens unetched.* × 50

a, Polished; *b*, polished and then acid pickled; *c*, polished, acid pickled, and then galvanized; *d*, polished, acid pickled, galvanized, and then stripped; and *e*, polished and then electroplated.

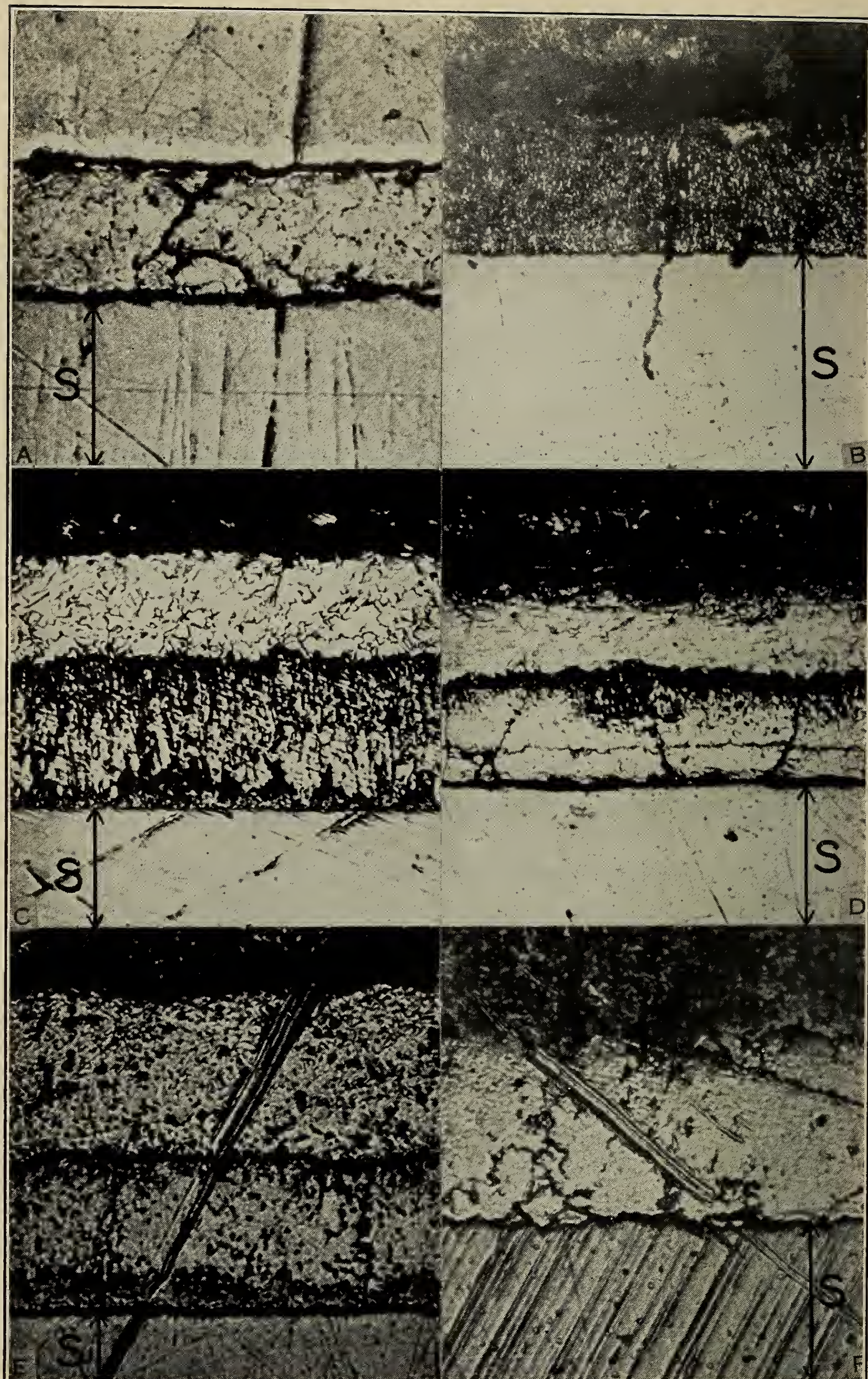

FIGURE 11

a, Structure of electrodeposited zinc coating on 0.72 per cent carbon steel, annealed; *b*, crack in galvanized coating extending into steel, 0.45 per cent carbon, annealed; *c*, structure of galvanized coating on 0.45 per cent carbon steel, annealed. Note the relatively thick intermediate layer, the thin innermost layer, and the light colored outer layer of relatively pure zinc; *d*, galvanized coating on 0.45 per cent carbon steel tempered. Note the thickness of the inner, hard, brittle layer adjacent to the hardened steel as compared with the thin layer of similar composition next to the softer steel of photograph *c*; *e*, scratch made with Bierbaum microcharacter across galvanized coating on tempered 0.45 per cent carbon steel. Note differences in width of scratch in the outer zinc layer and the intermediate and innermost iron-zinc alloy layers. Note that the innermost alloy layer appears to be harder than the steel; *f*, scratch made with Bierbaum microcharacter across electrodeposited zinc coating on tempered 0.72 per cent carbon steel. Discontinuity of scratch between zinc and steel was caused by difference in elevation between zinc and steel. Etched with chromic acid solution containing sodium sulphate (20 g CrO_3, 1.5 g Na_2SO_4 in 100 ml H_2O). ×275. Arrows indicate steel base.

the cracks were irregular (*a*) Figure 11, and appeared to be intergranular. In the galvanized coatings there were many more cracks in the intermediate and innermost layers than in the outer layer. Many of the cracks appeared to have started in the layer adjacent to the steel and to have progressed toward the outer surface, and in some instances the surface was not quite reached. In many instances the cracks undoubtedly originated at the surface and progressed inwardly toward the steel.

Of the broken specimens which were sectioned for examination under the microscope, two were found in which there was a crack in the steel which was a continuation of a crack in the innermost layer of the galvanized coatings. One of these is shown in (*b*) Figure 11. Although there were many cracks in the galvanized coatings, the evidence indicated that only a few had advanced into the steel. The probability is that none of the cracks in the electrodeposited coatings had extended into the steel, and that the cracks which caused failure of the electroplated specimens in the fatigue test originated in the steel itself.

The explanation of the lower fatigue limits of the galvanized specimens as compared with the uncoated or electroplated specimens is believed to lie: (*a*) In the difference in the stress conditions at the bottom of a crack in the inner, relatively hard, layers of the galvanized coating and those in a similar crack in the softer electrodeposited zinc; and (*b*) in the difference in the nature of the bond between zinc and steel in the two types of coatings.

It has been shown (10) that in relatively soft and ductile metals subjected to repeated stresses, slip lines form either previously to, or subsequently to, the appearance of cracks and that the cracks advance in the direction of the slip lines. The slip lines are an indication of plastic deformation under an applied stress which decreases when the deformation occurs. It is believed that the zinc of the electrodeposited coatings had sufficient ductility to deform around the bottom of an advancing crack, and that the resulting decrease in stress concentration when the crack had advanced to the steel was sufficient to stop the crack at that point. The discontinuity between zinc and steel was an additional aid in halting further advance of the crack. Consequently, the normal endurance limit of the steel was attained.

In the case of the galvanized specimens, a crack advancing into the relatively hard and very brittle inner layers did not meet with any conditions conducive to a decrease of stress concentration. The crack progressed to the outer steel fibers with undiminished stress. The intimate bond between coating and steel offered no obstacle to the advance of the crack into the steel. Naturally not every crack produced in the coating in the course of the fatigue test penetrated into the steel. A fortuitous combination of maximum stress concentration and conditions at the surface of the steel most favorable to the propagation of the stress, determined the location of the crack which led to failure of the specimen. Consequently since the presence of a hot-dipped galvanized coating promotes stress concentrations, the fatigue limit of such a coated specimen was appreciably lower than the normal endurance limit of the steels.

The data obtained on the specimens which were restressed at 5,000 lbs./in.^{2} above the fatigue limit, after they had been subjected to 25,000,000 cycles of stress at the fatigue limit, indicated that only the quenched and the tempered steels were appreciably strengthened by the previous understressing. All of the annealed carbon steel and open-hearth iron specimens tested failed to "run" at the higher stress. The 0.72 per cent carbon steel specimen, uncoated and the two electroplated specimens of the 0.72 and the 0.45 per cent carbon steel, in the tempered condition, also failed to run.

The interesting observation was made that distinct spangles were developed on the surface of the zinc of the galvanized specimens shortly after they were placed in operation in the rotating beam machines.

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