TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 917

THE EFFECT OF SURFACE FINISH ON THE FATIGUE PERFORMANCE OF CERTAIN PROPELLER MATERIALS

By H. W. Russell, H. W. Gillett, L. R. Jackson,
and G. M. Foley
Battelle Memorial Institute

Washington
December 1943

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 917

THE EFFECT OF SURFACE FINISH ON THE FATIGUE PERFORMANCE OF CERTAIN PROPELLER MATERIALS

By H. W. Russell, H. W. Gillett, L. R. Jackson, and G. M. Foley

SUMMARY

The effect of various surface finishes on the endurance of normalized X4130 and 4140 steels and 25S-T aluminum alloy has been investigated. It was found that the smoothness of the surface of a fatigue specimen was of less importance than other properties of the surface. All mechanically formed surfaces tested were stronger than electropolished surfaces. It is concluded that a smooth electropolished surface is an unstrengthened one. For this reason, removal of damaged surface by electropolishing is not so effective as mechanical methods of removal in prolonging fatigue life, because mechanical removal also strengthens the surface while electropolishing does not.

INTRODUCTION

Aircraft propellers are subject to failure by fatigue. Fatigue failure commonly originates at the surface, and it is, therefore, important that the initial surface finish be such as to insure maximum life under repeated stress. Furthermore, during the progress of fatigue, the surface metal must deteriorate, and it is desirable to determine whether, by the removal of the damaged surface metal, an increased over-all life may be secured.

Anodic electropolishing provides a means of removing amounts of metal up to a few thousandths of an inch thick and of leaving a smooth surface. If it is beneficial, electropolishing is commercially practical at a moderate cost. This investigation deals with the fatigue characteristics of electropolished propeller materials as compared with various mechanically finished surfaces.

This investigation, conducted at the Battelle Memorial Institute was sponsored by, and conducted with financial assistance from, the National Advisory Committee for Aeronautics.

EXPERIMENTAL WORK

Materials Used in the Investigation

Two heats of chromium-molybdenum steel were used. The National Bureau of Standards kindly supplied a large amount of X4130 steel in hot-rolled 5/8-inch diameter bars from Carnegie-Illinois Steel Company Heat No. 182983. The other steel was 4140, hot rolled to 3/4-inch rounds, from Bethlehem Steel Corporation Heat No. 1A159. The analyses of these heats follow, the X4130 analysis being by the Bureau of Standards, the 4140 analysis by Battelle Memorial Institute.

Steel	X4130 (percent)	4140 (percent)
Carbon	0.31	0.40
Manganese	.54	.70
Phosphorus	.017	.016
Sulphur	.022	.033
Silicon	.21	.23
Chromium	.86	.98
Molybdenum	.19	.18
Nickel	.06	———

Most of the aluminum alloy specimens were cut from a 25S-T rough propeller forging rejected because of a forging defect. The fatigue specimens were cut longitudinally from a slab cut from the middle of the forging. Careful account was kept of the locations in the forging from which the individual specimens came, but no difference could be found between specimens finished in the same way but coming from different locations in the forging.

A few aluminum alloy specimens were cut from a 25S-T billet. These were reheat-treated. They were put in an air-draw furnace at 970° F and held 3/4 hour before being quenched in water. They were then aged 15 hours at 330° F in an air-draw furnace. Most of these were tested as heat-treated.

All steel specimens were normalized by placing 12-inch lengths of the stock in a furnace at 1600° F, holding 1 hour, and cooling vertically in still air.

Surface Preparation of Specimens

All specimens were turned in a lathe to a longitudinal radius of 5.26 inches and a minimum diameter of 0.295 inch ± 0.001 inch (steel specimens) or 0.300 inch ± 0.003 inch (duralumin specimens). All abrasive polished steel specimens and some of the abrasive polished aluminum alloy specimens were polished longitudinally on a slowly rotating wheel of slightly less than 5.26-inch radius successively with no. 150, no. 320, 3/0, and 4/0 "Luminox" metal finishing cloth. The aluminum alloy polished too rapidly on the no. 150 cloth, so this grade was dropped in polishing later specimens with no perceptible effect on the endurance.

All of the electropolished steel specimens were finished by longitudinal polishing with no. 150 cloth before electropolishing. Many electropolished aluminum specimens were left as turned, since no effect of previous surface finish could be found after electropolishing.

Specimens to be electropolished were painted on the tapers to prevent polishing these areas. They were then vapor-degreased and electropolished.

Steel specimens were electropolished at a temperature between 100° F and 140° F at a current density of 200 amperes per square foot in the following bath:

	Percent
H_2SO_4	$4\frac{1}{2}$
H_3PO_4	75
CrO_3	7
Water	Balance

The specimens were rotated during polishing.

Aluminum alloy 25S-T specimens were polished at a temperature of 170° F and current density of 100 amperes per square foot in the following bath:

	Percent
H_2SO_4	14
H_3PO_4	59
CrO_3	6½
Water	Balance

The specimens were still during polishing.

The surface produced on steel specimens by electropolishing was bright and pit-free. A fairly bright surface was also obtained on aluminum, but there were many pits; and attempts to produce a pit-free surface were not successful.

Lathe-finished specimens were turned by a tool with a rounded edge with a cut of 0.007 inch. The speed was of 31 surface feet per minute and a feed of 0.0023 inch per revolution.

Ground specimens were made in the lathe using a Dumore grinder with the wheel rotating at 1800 surface feet per minute. The cut was 0.005 inch deep.

Equipment and Procedure

All fatigue testing was performed on modified R. R. Moore specimens in R. R. Moore machines running at 10,000 rpm. The modification of the specimens consisted in cutting them with uniform longitudinal radius from taper to taper thus eliminating the 1/8-inch radius fillet used on standard specimens. Specimens were measured carefully with ball-pointed micrometers reading in 0.0001-inch units. The minimum diameter was used to calculate the stress. The factors entering the stress calculation were known well enough so that the nominal stress was set to better than 0.3 percent in all cases.

Tension Tests

Tension tests were made on the SAE X4130 steel and on the 25S–T aluminum alloy. The test bar for the 25S–T aluminum alloy was cut transversely from the propeller forging – that is, at right angles to the direction in which the fatigue specimens were cut. The results are shown in table 1.

Fatigue Tests

Fatigue tests on abrasive polished and electropolished specimens are reported in tables 2 to 4 and are plotted in figures 1 to 3.

The endurance of abrasive polished specimens is always better than that of electropolished specimens. The relative endurance limits are:

Material	Life	Stress Abrasive Polished / Stress Electropolished (percent)
X4130	At endurance limit	107
4140	———do———	108
25S–T	10^6 cycles	113
25S–T	10^7 cycles	106

Sufficient specimens of X4130 and 4140 were broken as finished on the lathe and also as finished by circumferential grinding to establish rough fatigue curves for these surfaces. The results of the tests are given in tables 5 and 6 and in figures 4 and 5. The endurance limits found for these various surfaces are:

Finish	Endurance limit—p.s.i. X4130	4140
Electropolished	45,500	60,500
Abrasive polish	49,500	65,700
Lathe finish, unpolished	48,500	61,500
Ground circumferentially	52,000	66,500

The endurance limits for the various surfaces can be expressed as percentages of the endurance limit of an electropolished surface, as follows:

Surface	Endurance Limit X4130 (percent)	Endurance Limit 4140 (percent)
Electropolished	100	100
Abrasive polish	109	109
Lathe finish, unpolished	107	102
Ground circumferentially	114	110

It is apparent that the effect of various surface finishes differs in these steels which are closely similar in composition; it is quite possible that even in the same steel small differences in the preparation of surfaces of supposedly duplicate specimens will change the endurance markedly. It may be noted from figures 1 and 2 that the consistency of results on electropolished steel specimens is better than is usually obtained in laboratory fatigue tests.

A number of aluminum alloy specimens were tested at a single stress after various methods of surface finishing. The results are shown in table 7. The rough longitudinally polished and rough circumferentially polished surfaces were made with No. 320 abrasive cloth. None of the surfaces tested were as strong in fatigue as the fine longitudinally abrasive polished surface.

EFFECT OF ELECTROPOLISHING ON ENDURANCE

The results obtained from fatigue tests on fine longitudinally abrasive polished specimens are usually considered to be "standard" and the endurance of such specimens to be better than the endurance of specimens with other surfaces. The preceding results show that this is not necessarily true and that specimens with deep circumferential scratches may have better endurance than polished ones.

The interesting fatigue properties of the surfaces tested may be clarified somewhat by a study of the taper sections of some of the samples tested as shown in figures 6 to 9. The taper sections were prepared by electroplating a coating of nickel on the surface to be studied. The plated specimen was then ground and polished metallographically so that the surface revealed is at a small angle with the steel surface being studied. The effect at the junction of steel with nickel is as if a sea of nickel had washed up at a small angle to the steel surface; the nickel enters scratches as if they were valleys. The irregularities of the surface are magnified in a direction perpendicular to the junction of steel and nickel. The thickness of layers in planes parallel to the steel surface is also magnified.

A close scrutiny of figure 7, a taper section of an abrasive polished fatigue specimen, reveals a layer of distorted metal grains which is not present in the electropolished specimen (fig. 6). A layer clearly differentiated from the body of the specimen is also present on the surface of the turned specimen (fig. 8) and the ground specimen (fig. 9). In the latter case, the outermost layer is of a white material which was not darkened by tempering at 500° F and has not been identified.

The distorted material on the surface of the mechanically finished specimens may be stronger in fatigue than the body of the specimen and thus may be, in part, the cause for the good endurance of the mechanically finished specimens.

Mechanically finished surfaces are also quite likely to have stresses remaining in them from machining operations. J. O. Almen (reference 1) points out that the endurance is much better under compressive stress than under tension stress, and that a compressive stress in the surface layers of a part will superpose on the applied cyclic stress giving longer life at the same applied stress. No investigation was made of the internal stresses in the specimens used here, but it is possible that the mechanical finishing treatments did produce the desirable compressive stress in the surfaces.

It is, of course, possible that the electropolishing damages the material. In duralumin, it is quite possible that this has happened, since the pits produced by electropolishing are certainly not desirable. On the other hand, it did not seem likely that damage which was not obvious on the surface could be caused by the electropolishing. The gas given off at the specimen, oxygen, is not known to diffuse to an important extent through metals at room temperature, and no other cause for weakening seems likely. Steel specimens were electropolished and then abrasive-polished and had the same strength as ordinary abrasive polished specimens.

Eighteen specimens were made from a billet of 25S-T aluminum alloy. Six of these were abrasive-polished, six were electropolished, and six were left as turned. All were then heat-treated as described under "Preparation of Specimens" (p. 3). The six turned specimens were then electropolished. The other 12 specimens were tested as heat-treated.

The results of the tests are given in table 8. The specimens polished before heat treatment fall within a close enough range to be considered equal specimens. The specimens electropolished after heat treatment are erratic and, at the lowest stress used, comparatively weak.

The test is thus not an entirely satisfactory demonstration that electropolishing is not damaging. The only explanation which comes quickly to mind for the erratic behavior of the specimens electropolished after heat treatment is that the damaging effect of the pits produced in electropolishing the duralumin is minimized by the heat treatment, or that the pits produced by electropolishing a freshly heat-treated surface are more damaging than those produced by polishing a machined surface.

EFFECTS OF SHOT-BLASTING AND ELECTROPOLISHING

The striking improvement in endurance obtained by shot-blasting the surface of parts subject to fatigue stress has been reported in several papers by J. O. Almen and others (reference 1).

Some question has been raised as to whether excessive shot-blasting would not damage the surface or at least reduce its endurance below that of a less severely peened surface (reference 2). It seemed possible that electropolishing might remove some of the stress-raisers in an excessively shot-blasted surface and so produce a stronger surface than could shot-blasting alone.

This expectation was borne out in connection with grit-blasted surfaces, but it was found not true in respect to shot-blasted ones.

The performance of specimens grit-blasted in a commercial blasting machine is shown in table 8. The electropolished specimens showed very good consistency of performance relative to the unpolished specimens.

Several specimens were then shot-blasted by courtesy of Mr. J. O. Almen and his associates at the General Motors Research Laboratory. This work was under much better control than the previous grit-blasting. Four specimens were peened under 15 pounds per square inch air pressure to the machine used and four with 80 pounds per square inch air pressure. Three of the lightly peened specimens were blasted with shot 0.031 to 0.041-inch diameter producing 0.036 to 0.41 percent elongation of the specimens. The fourth, F1-22, was peened with shot 0.055 to 0.065 inch diameter, producing 0.057-percent elongation. This specimen was not very different from the other tested in the same state. The heavy peening was done with the 0.031 to 0.041-inch shot, and the elongation resulting was from 0.094 to 0.099 percent.

The results in table 10 show that the heavily shot-blasted specimens, instead of being damaged, were even stronger than the lightly peened ones, although the difference in performance of the two heavily shot-blasted specimens is relatively greater than that between the lightly shot-blasted ones.

ELECTROPOLISHING TO IMPROVE ENDURANCE

The fact that electropolished surfaces are initially weaker in fatigue than are abrasive polished and other surfaces lessens considerably the probability that a useful improvement in life can be obtained by electropolishing to remove the surface damaged by fatigue. If the life of an electropolished specimen is only one-half or one-third that of an abrasive polished one, the increase in life obtained by providing a totally undamaged electropolished surface, after most of the initial life has been used, will be negligible.

In view of the fact that, while electropolishing may remove damaged metal, it also removes strengthened layers (resulting from mechanical polishing), it appears that electropolishing is not a suitable tool for prolonging the life of parts under fatigue stress. It is of interest to note, however, that when results of removal of metal by electropolishing are referred to original electropolished surfaces as a base, it is possible to obtain an increased life by repolishing the surface during the test. Table 9 summarizes results of this type for the X4130 steel. From this table, it will be noted that, for all steel test pieces, a longer total life was obtained by repolishing. It should also be noted, however, that the longest life obtained by this method was comparable with what could be expected from an abrasive polished test piece without any repolishing or removal of damage.

Table 11 also presents results of similar tests on the 25S-T aluminum alloy. Here, the improvement is not so clear-cut, and the results suggest an interesting speculation concerning the balance between damage and strengthening during a fatigue test.

It will be noted from table 11 that some of the 25S-T test pieces which were run for 200,000 cycles before repolishing were apparently weakened; the same is true for those run 150,000 cycles before repolishing. This suggests that, if, during a fatigue test, damage extends to a greater depth than the surface strengthening, then electropolishing can be of no help in prolonging the life of the test piece; whereas, if the strengthening extends to a greater depth than the damage and the electropolishing does not remove this stregthened layer entirely, an improvement can result.

The same experiment was tried on shot-blasted aluminum alloy specimens. The improvement in life got by repolishing during the run can hardly be evaluated because of the wide range of the results on virgin shot-blasted specimens. From a practical point of view, an improvement of two or three times in life would have to be obtained for the technique to be given much consideration, and such an improvement was not obtained.

The practical failure of this technique is undoubtedly caused by the relatively poor performance of the original electropolished surface. The multiple polishing technique gives considerable improvement only if its performance is compared with that of virgin electropolished specimens. If the surface left by the polishing method is, when used on virgin material, satisfactorily strong, then reasonable improvements in total life may be expected when this polishing method is used to remove fatigue damage.

CONCLUSIONS

It has been found, both in the case of normalized alloy steels and of a forged aluminum propeller alloy, that the endurance of specimens finished by electropolishing is less than that of specimens prepared mechanically.

The relative weakness of electropolished surfaces of small laboratory specimens was so great that it is unlikely that electropolishing can be usefully employed to prolong the life of aircraft propellers or other aircraft parts subjected to repeated stressing. It is possible, however, that electropolishing may not be as damaging to large parts as was indicated by the laboratory specimens.

It is suggested that most, if not all, of the advantage of mechanically finished surfaces is due to the presence of a worked or stressed layer on these surfaces. While it is thought that a smooth electropolished surface in neither a damaged nor a strengthened surface, no direct proof of the statement can be given at present.

The fatigue results on smooth electropolished specimens appear to have higher consistency than is usually expected from laboratory fatigue specimens.

The data used in this report are all of those contained in B.M.I. Laboratory Record Books Nos. 947 and 1114.

Battelle Memorial Institute,
Columbus, Ohio, August 13, 1943.

REFERENCES

1. Almen, J. O. and others: Peened Surfaces Improve Endurance of Machine Parts. Metal Progress, vol. 43, Feb. 1943, p. 209.

2. Battelle Memorial Institute: Prevention of Failure of Metals. John Wiley & Sons, Inc., New York, 1941, p. 153.

TABLE 1. TENSION TESTS ON SAE X4130 STEEL AND 25ST ALUMINUM ALLOY

Property	SAE X4130	25ST
Yield Strength*	65,500 p s i	44,500 p s i
Ultimate Strength	106,500 p s i	64,100 p s i
Elongation in 2 inches	20%	17%
Reduction of Area	50.8%	24.1%

*0.2% Offset.

TABLE 4. FATIGUE TESTS ON SPECIMENS OF 25ST ALUMINUM ALLOY

Specimen Number	Specimen Diameter-In.	Stress p s i	Cycles to Failure
Abrasive Polished Specimens			
3-1	0.2975	50,000	20,000
2-26	0.2964	45,000	62,000
F1-7	0.2977	40,000	107,000
B3-6	0.2973	35,000	228,000
F2-7	0.2972	30,000	1,270,000
1-1	0.2967	"	1,287,000
F1-3	0.3018	"	1,179,000
F1-21	0.3025	"	1,175,000
1-26	0.2986	27,000	3,956,000
3-26	0.2985	"	2,648,000
B2-7	0.2971	26,000	9,292,000
F3-6	0.2985	25,000	11,451,000
1-23	0.2967	24,000	31,169,000
3-23	0.2968	19,000	113,673,000 unbroken
Same, stress raised to		30,000	700,000
Electropolished Specimens			
B2-21	0.2993	50,000	23,000
F2-8	0.2985	40,000	65,000
2-24	0.2973	30,000	299,000
F3-20	0.2992	"	229,000
2-1	0.2945	"	1,170,000
2-23	0.2965	"	342,000
B3-20	0.3012	"	410,000
1-2	0.2985	27,000	869,000
B2-20	0.2973	24,000	10,136,000
F3-9	0.2992	23,000	50,250,000
F2-9	0.2970	19,000	116,629,000 unbroken
Same, stress raised to		30,000	288,000

TABLE 2. FATIGUE TESTS ON SPECIMENS OF NORMALIZED SAE X4130 STEEL

Specimen Number	Specimen Diameter-In.	Stress p s i	Cycles to Failure
Abrasive Polished Specimens			
A3	0.2941	69,850	30,000
A4	0.2943	59,870	79,000
A7	0.2942	55,040	135,000
A9	0.2946	52,570	386,000
A11	0.2941	52,070	438,000
A5	0.2936	49,840	1,406,000
A12	0.2936	49,040	17,320,000 unbroken
Same, stress raised to		55,075	1,168,000
A8	0.2945	49,030	1,027,000
A10	0.2934	48,570	1,373,000
A6	0.2941	48,045	13,222,000 unbroken
Same, stress raised to		55,095	267,000
Electropolished Specimens			
B1	0.2944	69,880	25,000
B2	0.2935	59,820	70,000
C1	0.2931	55,050	182,000
B7	0.2939	54,990	101,000
B3	0.2937	49,910	415,000
B12	0.2933	49,030	370,000
B4	0.2933	48,050	606,000
B5	0.2944	46,000	920,000
B11	0.2929	45,980	1,325,000
B10	0.2933	45,070	10,764,000 unbroken
Same, stress raised to		55,080	144,000
B6	0.2929	44,030	14,326,000 unbroken
Same, stress raised to		54,990	146,000

TABLE 3. FATIGUE TESTS ON SPECIMENS OF NORMALIZED SAE 4140 STEEL

Specimen Number	Specimen Diameter-In.	Stress p s i	Cycles to Failure
Abrasive Polished Specimens			
J 9	0.2998	80,000	90,000
J 1-2	0.3004	75,000	176,000
J 3	0.2988	65,000	35,149,000 unbroken
Same, stress raised to		75,000	227,000
J 4	0.3002	70,000	751,000
J 5	0.3008	68,000	1,535,000
J 1-6	0.2997	67,000	1,840,000
J 7	0.3001	66,000	2,286,000
J 1-8	0.3002	65,500	14,315,000 unbroken
Same, stress raised to		75,000	226,000
Electropolished Specimens			
J 1-10	0.2993	66,000	605,000
J 11	0.2979	65,000	1,022,000
J 1-12	0.2966	63,000	1,274,000
J 13	0.2977	61,000	4,486,000
J 14	0.2990	60,000	11,015,000 unbroken
Same, stress raised to		75,000	98,000

TABLE 5. EFFECT OF VARIOUS SURFACE TREATMENTS ON FATIGUE PROPERTIES OF NORMALIZED SAE X4130

Specimen Number	Diameter Inch	Stress p s i	Life in Cycles		
			I. Expected From Abrasive Polish	II. Expected From Electropolish	III. Actual Life
Effect of Lathe Finish					
E1-1	.2944	47,940	Indefinite	550,000	16,375,000 unbroken
Same, stress raised to		55,050	260,000	140,000	266,000
E1-2	.2946	55,120	155,500	100,500	158,000
E1-3	.2950	50,040	950,000	302,000	506,000
E1-4	.2948	49,000	Indefinite	400,000	1,457,000
E1-5	.2952	65,000	43,000	37,000	37,000
Effect of Surface Grind					
F1-1	.2952	48,000	Indefinite	550,000	17,706,000 unbroken
Same, stress raised to		55,020	260,000	140,000	743,000
F1-3	.2943	55,040	155,000	100,500	252,000
F1-2	.2953	49,000	Indefinite	400,000	35,637,000 unbroken
Same, stress raised to		55,050	1,020,000	140,000	17,700,000 unbroken
" " " "		65,000	---	---	88,000
F1-4	.2964	51,000	600,000	240,000	16,334,000 unbroken
Same, stress raised to		60,000	---	---	277,000
F1-5	.2954	53,000	300,000	170,000	2,086,000

TABLE 6. EFFECT OF VARIOUS SURFACE TREATMENTS ON FATIGUE PROPERTIES OF NORMALIZED SAE 4140

Specimen Number	Diameter Inch	Stress p s i	Life in Cycles		
			I. Expected From Abrasive Polish	II. Expected From Electropolish	III. Actual Life
Effect of Lathe Finish					
J15	0.2994	66,000	2,400,000	630,000	750,000
J1-16	0.2998	62,000	Indefinite	1,200,000	2,802,000
J17	0.2998	61,000	Indefinite	4,000,000	14,447,000*
Same, stress raised to		70,000	---	---	458,000
J1-18	0.2995	70,000	750,000	260,000	156,000
J19	0.2998	75,000	200,000	90,000	111,000
Effect of Ground Finish					
J1-22	0.3006	66,000	2,400,000	630,000	13,368,000*
Same, stress raised to		75,000	220,000	99,000	316,000
J21	0.2998	70,000	750,000	260,000	485,000
J23	0.2999	68,000	1,400,000	400,000	1,449,000
J1-24	0.3002	67,000	1,800,000	500,000	1,519,000
J20	0.2990	75,000	220,000	99,000	188,000

*Specimen unbroken.

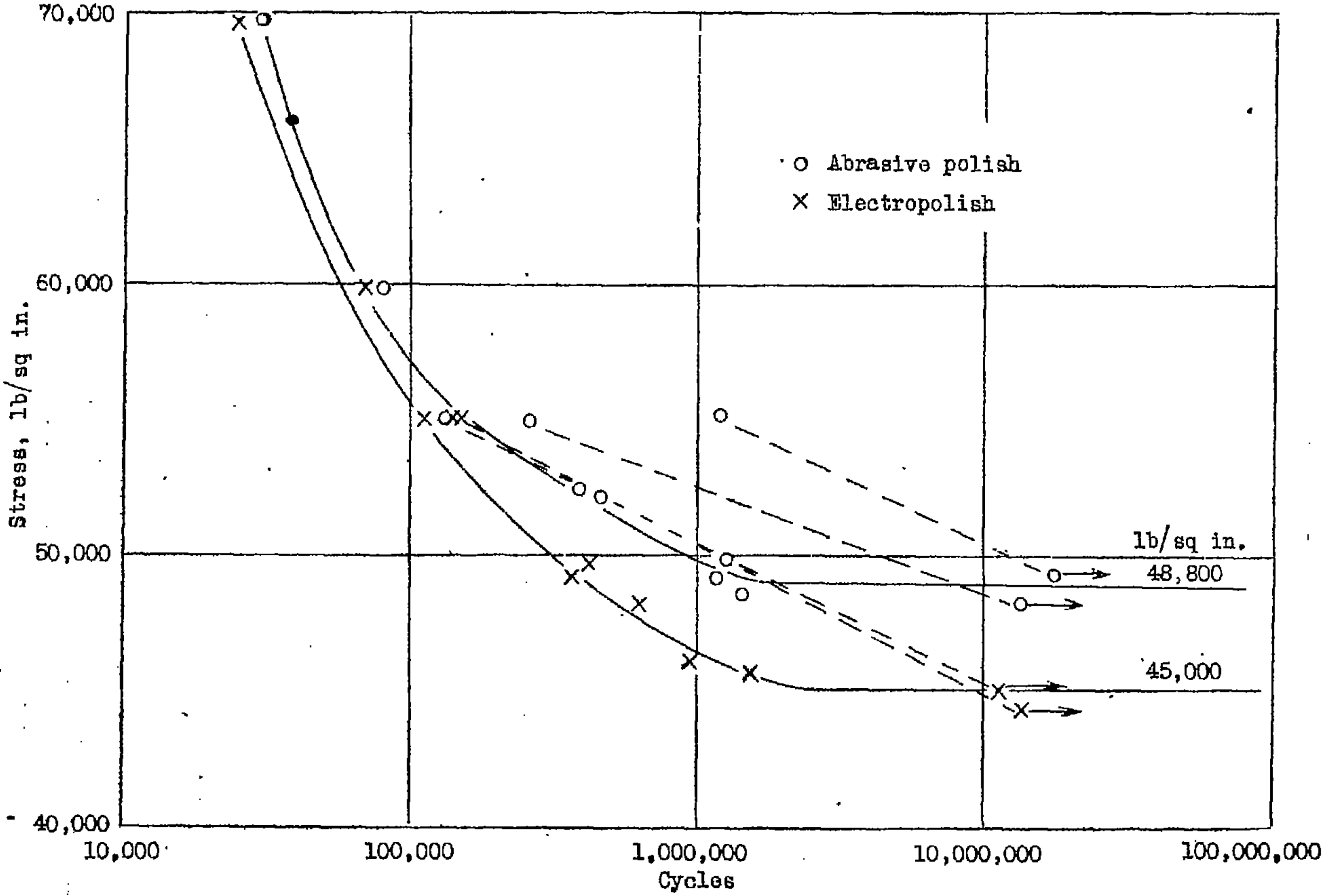

Figure 1.- Fatigue curves on normalized X4130 steel.

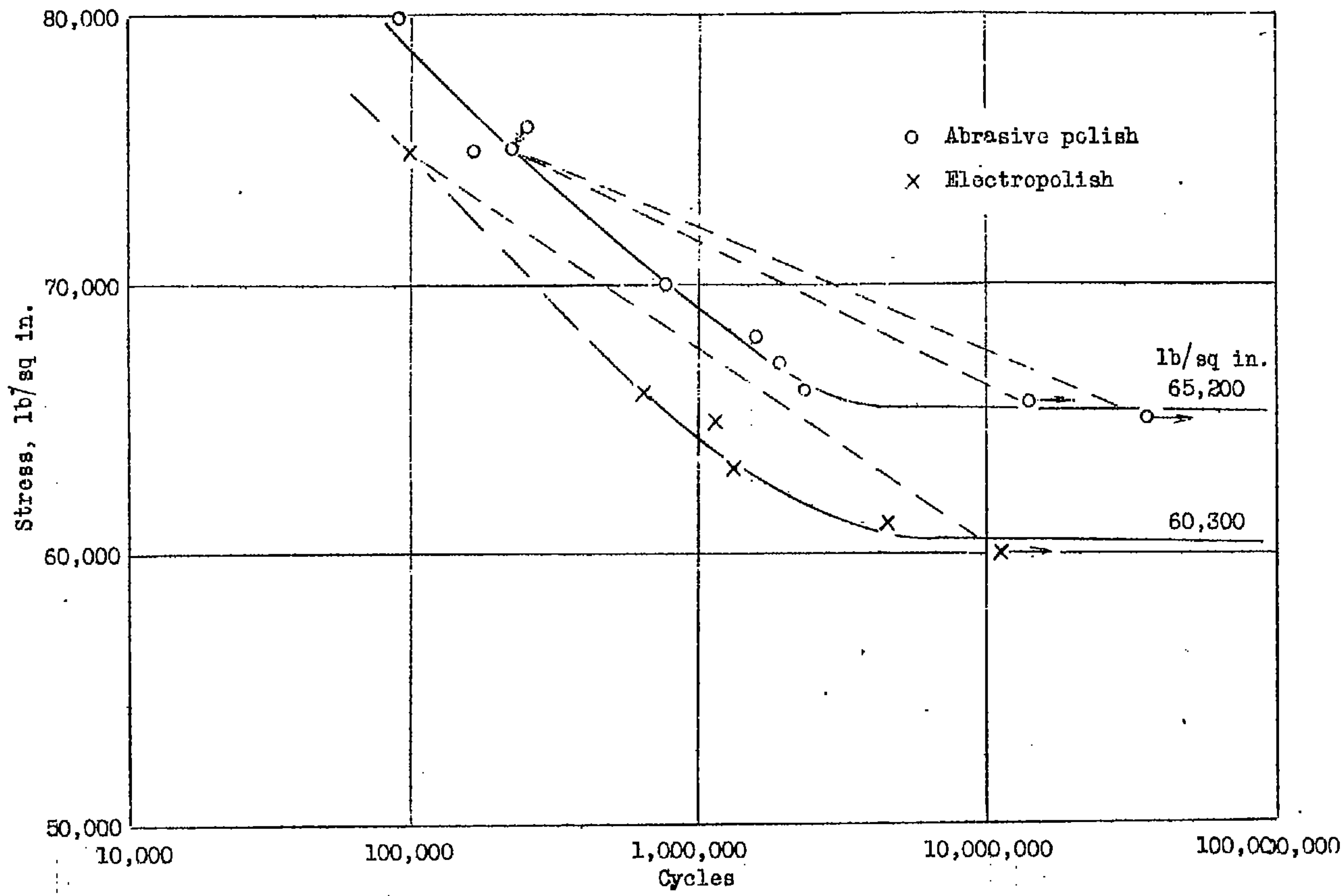

Figure 2.- Fatiguo curves on normalized 4140 steel.

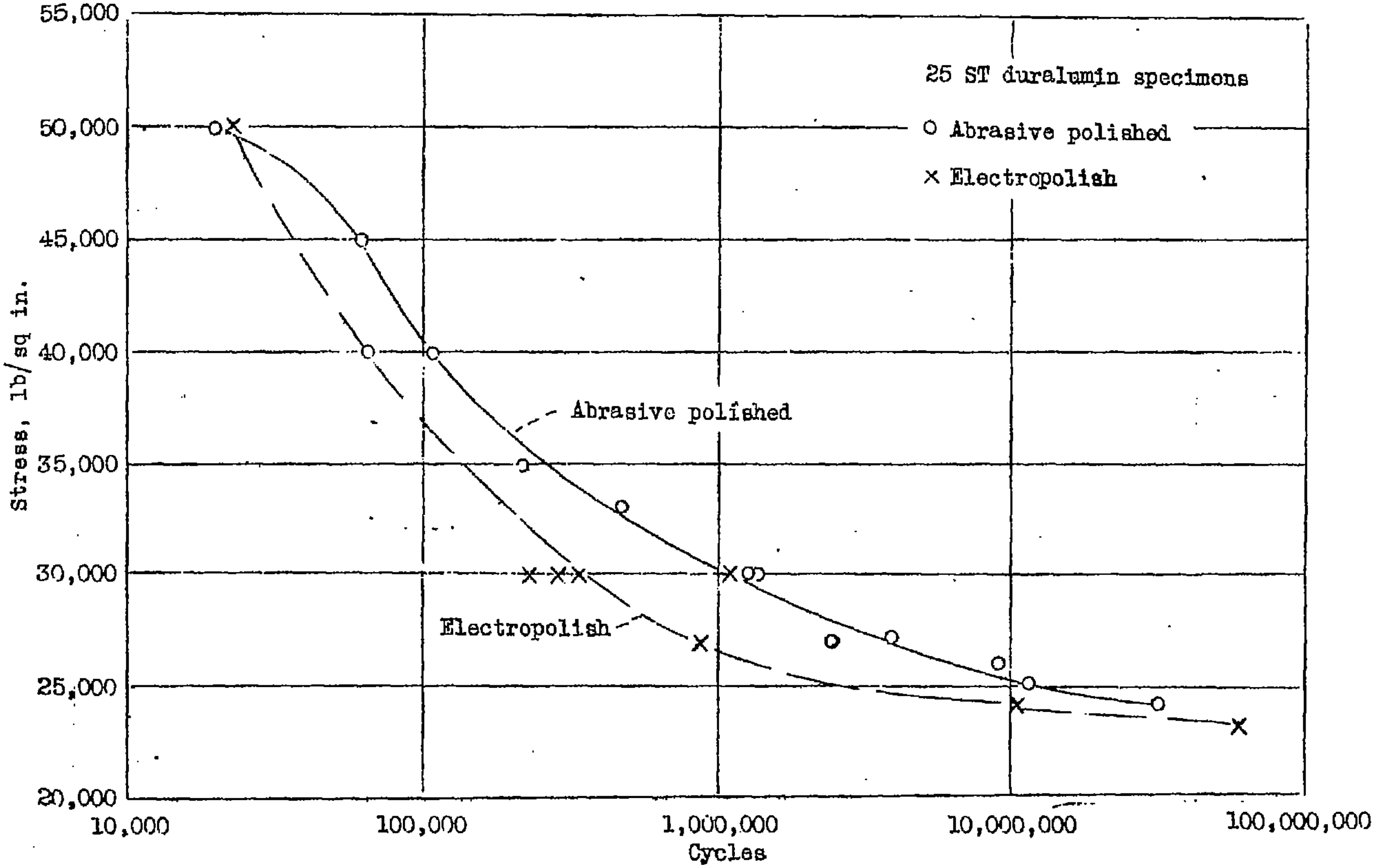

Figure 3.- Fatigue curves on 25 ST aluminum alloy.

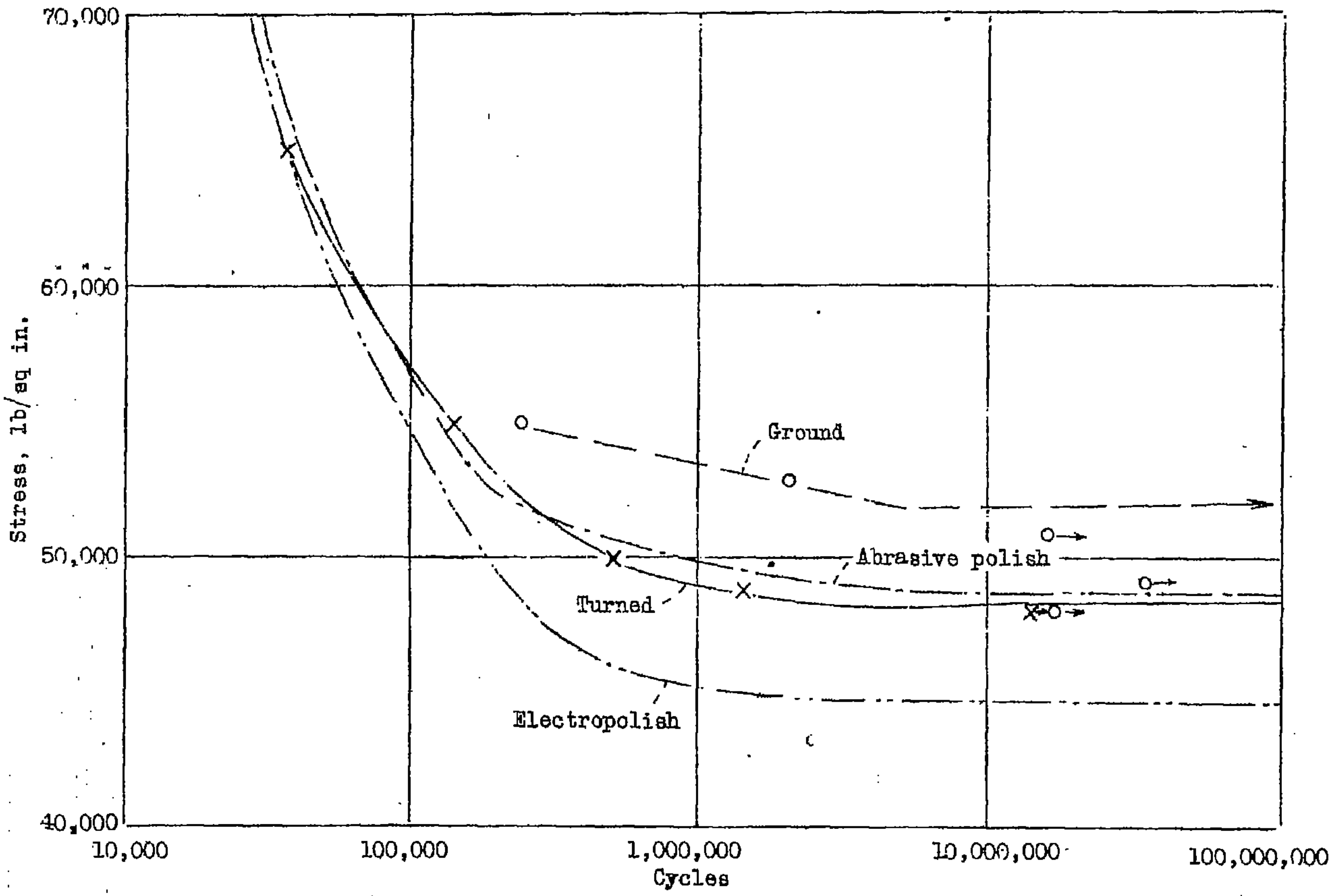

Figure 4.- Fatigue curves on X4130 steel with various surface finishes.

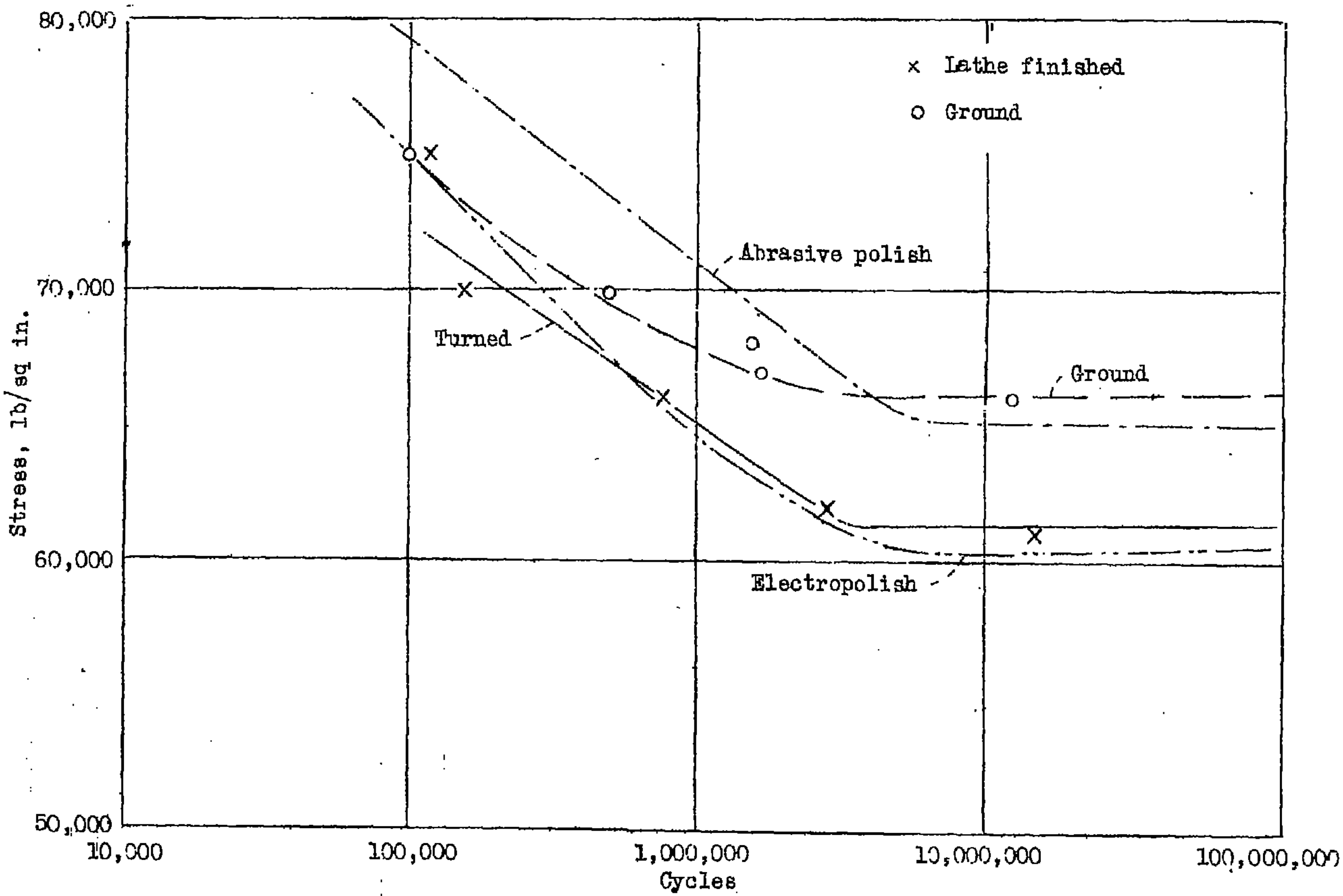

Figure 5.- Fatigue curves on 4140 steel with various surface finishes.

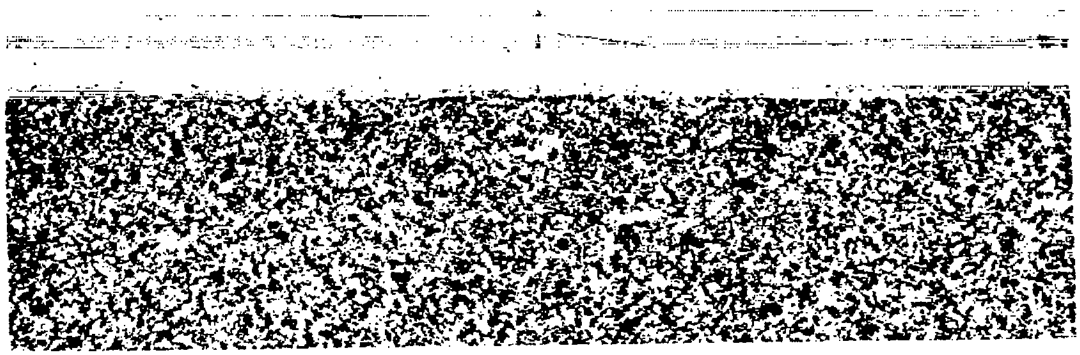

Figure 6. Taper Section of Electrolytically Polished SAE X4130 Fatigue Test Specimen. Horizontal Magnification 100X, Vertical Magnification 1000X. Etched With Nital.

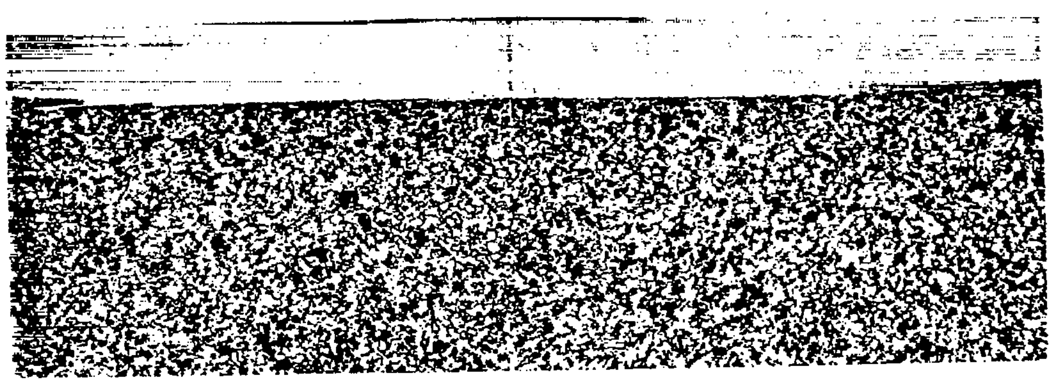

Figure 7. Taper Section of Abrasive Polished SAE X4130 Fatigue Test Specimen Horizontal Magnification 100X, Vertical Magnification 1000X. Etched With Nital.

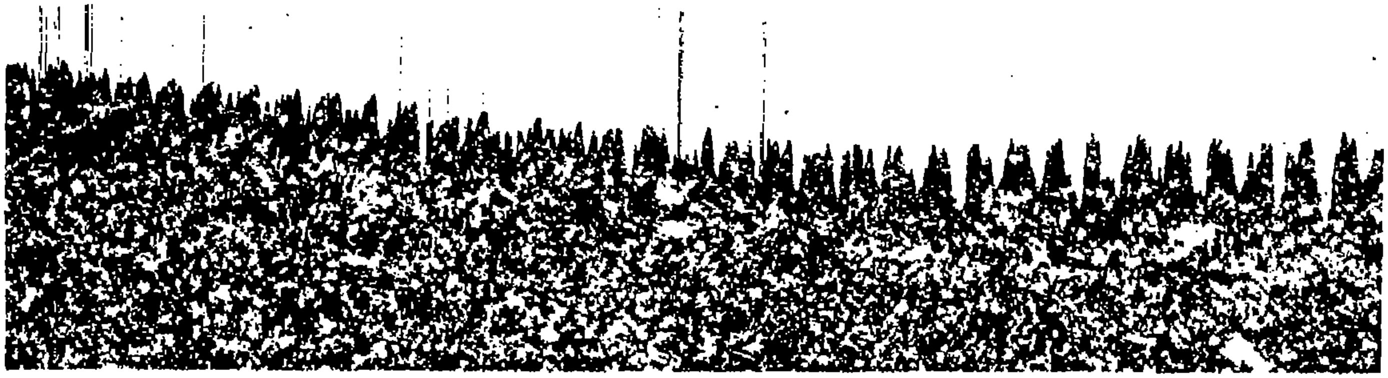

Figure 8. Taper Section of Lathe Turned SAE X4130 Fatigue Test Specimen. Horizontal Magnification 100X, Vertical Magnification 1000X. Etched With Nital.

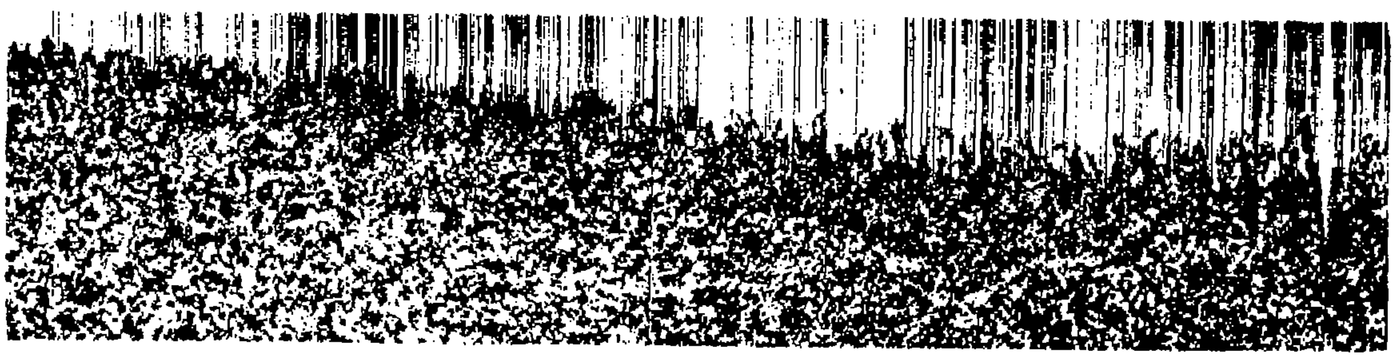

Figure 9. Taper Section of Ground Surface on SAE X4130 Fatigue Test Specimen. Horizontal Magnification 100X, Vertical Magnification 1000X. Etched With Nital.