S & T MEMO 2/66

THE INFLUENCE OF SHOT-PEENING AND SIMILAR SURFACE TREATMENTS ON THE FATIGUE PROPERTIES OF METALS

APPENDIX ON SELECTED CASE HISTORIES*

BY

F. Sherratt

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SELECTED CASE HISTORIES

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Summary

Nine case-histories giving experience over a wide range of circumstances and metals are given. Summaries and conclusions from the data are given in S & T Memo 1/66.

List of case histories

Case 1. Shot-peening plain rotating-bending specimens of high-strength steels.

Case 1a. Un-notched rotating-bending specimens of high-strength steel polished after peening.

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CASE 1.

Basic Feature. Shot-peening plain rotating-bending specimens of high-strength steels.

Main Sources. A. Mattson and Alemn (1944).
B. Harris (1961)

Materials. A : Steel X-4340 : U.T.S. 145,000 lb./sq.in.: Rockwell C23-26.

B : 3% Ni-Cr. Steel S.11 II. treated to U.T.S. 48.9 to 129.4 tons/sq.in.

Form of test piece. A : R.R. Moore specimens, longitudinal profile about 8" radius of curvature.

B : Plain rotating bending, otherwise not specified. Probably 0.3" or so diameter.

Peening. A : .040" to .055" iron shot: Almen strip 0.009A and 0.014A

B : .031" shot: 50 lb./sq.in. for 3 mins. at 6" nozzle/workpiece distance.

Residual Stresses. No measurements given. Estimates:-

A : 100,000 lb/sq.in., depth not known.

B : 92,000 to 125,000 lb/sq.in.: effective depth .010".

Fatigue Test Results. A : Fig.C1.1, in effect, no improvement due to peening.

B : Fig.C1.2. Improvement at lowest U.T.S. condition, but generally no improvement.

Other reports:- These are numerous. Two representative ones are McMurrich (1950), who found a 5% improvement in fatigue limit compared with a turned finish, (0.6C steel, U.T.S. 62 tons/sq.in.), and Coombs et al. (1956), finding fatigue limits after peening were very much the same as those due to a polished surface (0.77C steel, U.T.S. 116 tons/sq.in.).

Discussion. The twenty-years old report of Mattson and Almen (1944) was chosen as a main illustration in this case because it shows quite clearly, in spite of the small number of tests, that when stress-concentration effects are completely absent, shot-peening does not usually improve fatigue strength. Although this has been emphasized by a number of writers, it is still sometimes overlooked. The fatigue ratio for polished specimens is 0.48, indicating that failure is dominated by the criteria for crack initiation (or early shearing propagation ?): thus even the 100,000 lb/sq.in. residual compression predicted will do little to improve the fatigue limit.

Harris (1961) confirms and enlarges upon this picture, testing the S11 steel in different conditions of temper. For U.T.S. values between 64.8 and 111.7 tons/sq.in. shot peening causes no significant change as compared with the polished condition: at 129.4 tons/sq.in. the effect is detrimental, presumably because of the sensitivity of such a hard steel to geometrical surface damage. The low-temper condition, 43.9 tons/sq.in., gave an improvement, almost certainly due to its ability to work-harden: the 20% improvement in fatigue limit is amongst the highest reported in conditions like this, and could not be relied on for all similar materials.

Conclusion

Shot peening does not improve the rotating-bending fatigue strength of high-tensile steels (U.T.S. 60 tons/sq.in. upwards) in the un-notched condition. Lower-strength steels (50 tons/sq.in. or less) may be improved slightly, but this is due to the contribution of work-hardening, rather than the residual stress effect normally expected from mechanical surface treatments.

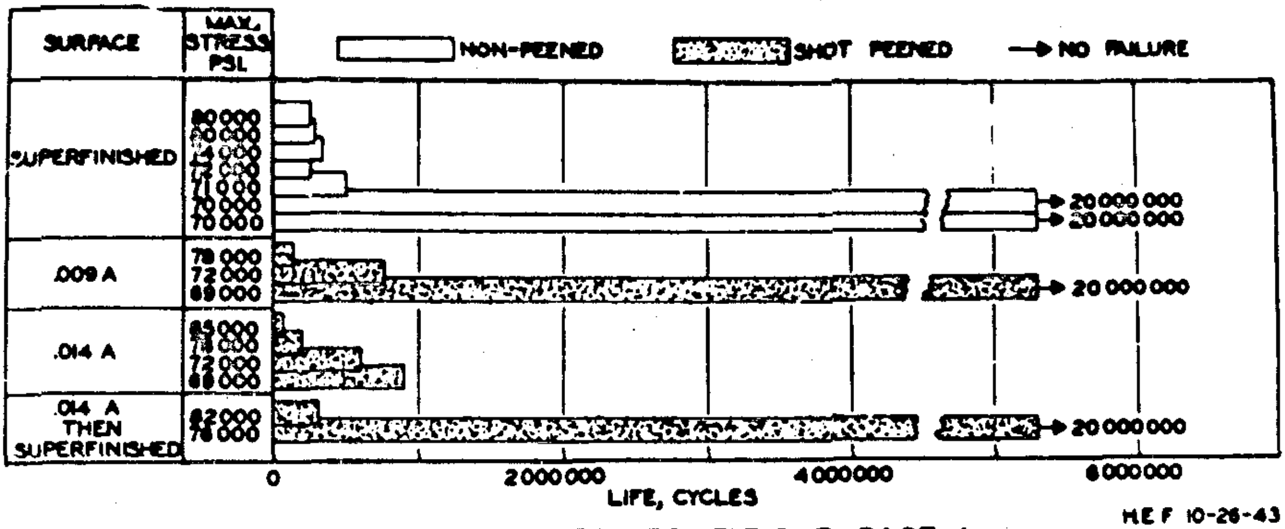


FIG. C1.1 TEST RESULTS, FATIGUE CASE 1.

EFFECT OF SHOT PEENING ON THE FATIGUE LIFE OF SUPERFINISHED ROTARY-BENDING TYPF SPECIMENS. ALSO EFFECT OF SUPERFINISHIN3 AFTER SHOT PEENING

U.T.S. tons/sq.in.	129.4	111.7	87.7	64.8	48.9
Fatigue (Not peened limit (Peened	60 58	55 55	41 41	31 31	23 28

Figure C1.2 The influence of shot-peening on the basic fatigue strength of S.11 steel in various heat-treatment conditions (Harris, 1961)

CASE 1a.

Basic Feature. Un-notched rotating bending specimens of high strength steel polished after peening.

Source. Coombs, Sherratt and Pope (1956).

Material. 0.77% C Steel, U.T.S. 116 tons/sq.in.

Form of test-piece. Rotating cantilever, critical diameter 9/64", longitudinal profile $1\frac{3}{8}$" radius.

Peening. Chilled iron shot, 0.060" dia.: nozzle pressures 30 and 50 lb/sq.in.: about 30 seconds exposure, specimen revolving 6" from nozzle.

Residual stresses. No measurements: estimated 180,000 lb/sq.in. about 0.015" deep.

Fatigue test results. Fig.C1a.1. Peening followed by polishing raises fatigue limit to about 58 tons/sq.in. (0.5 x U.T.S.), compared with 49 tons/sq.in. for both polished specimens without peening and peened specimens without subsequent polishing.

Other reports. Mattson and Almen (1944) using plain R.R. Moore specimens of X-4340 steel treated to 145,000 lb/sq.in. U.T.S., found that peening with 0.040" shot did not give as high a fatigue limit as superfinishing, but super-finishing after peening gave a higher fatigue limit than did superfinishing alone.

Discussion There is no doubt that polishing after peening gives a substantial improvement in this case. It is significant, though, that even peening plus polishing does not improve the fatigue limit beyond 0.5 times the U.T.S. This suggests that a fatigue ratio of 0.5 is still the highest achievable, even with the extra polishing process, and that if peening alone is nearly achieving this value, little extra benefit will come from a polishing operation. It may well be that a fatigue stress of 0.5 U.T.S. is high enough to initiate and propagate sub-surface cracks, and the authors did observe sub-surface crack formation in many of their specimens. Once this becomes the usual failure mode, modifications of the peening process cannot be expected to give any further improvement.

The authors suggest that polishing after peening causes an improvement because the layer having the greatest residual stress is thus brought to the surface. There is some doubt about the validity of this, since the maximum compressive stress is not always below the surface: it seems more likely that removal of the damaged surface layer, containing at least pits, and possibly short cracks, is a more important factor. A few results for the same steel tempered to a softer condition showed that peening did not give quite such a high fatigue limit as did polishing, so that peening is less effective on the softer steel. Examination of a peened strip, slit longitudinally after peening, indicated that surface damage, and particularly micro-cracking, was more severe on the softer steel for a given intensity of peening. Indirectly, this supports the view that removal of surface damage is an important factor.

C1a.1.

On the whole, the work succeeds in its main purpose, but some of the detailed conclusions are probably not generally applicable. The S-N curves for polished specimens show a rather low fatigue limit, and it seems likely that the steel contained a significant number of inclusions: in addition, the specimen shape chosen, with a rather steep longitudinal profile, is part-way between a completely plain specimen and a circumferentially notched one, and in this context could give odd results.

Conclusions

Polishing after peening can further improve fatigue strength on hard steels: it is likely that the improvement is still restricted to a maximum fatigue limit of 0.5 times the U.T.S.

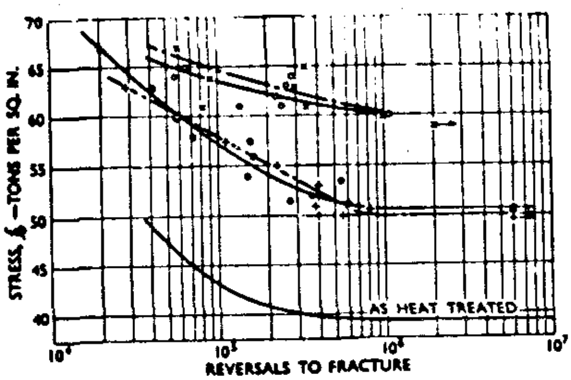


Fig. C1a. 1. *Influence of Polishing After Shot Peening on Fatigue Life Curves*

Specimens hardened from 800 deg. C. (1,472 deg. F.), oil-quenched, tempered 1 hour at 400 deg. C. (472 deg. F.).

- ● As-peened nozzle pressure 30 lb. per sq. in.; shot velocity 150 ft. per sec.
- + As-peened nozzle pressure 50 lb. per sq. in.; shot velocity 192 ft. per sec.
- o Peened at 30 lb. per sq. in. nozzle pressure; 0·007 inch polished from surface; 7μ in. finish.
- × Peened at 50 lb. per sq. in. nozzle pressure; 0·0039 inch polished from surface; 7μ in. finish.

CASE 1b.

Basic Feature. Shot-peening notched rotating-bending specimens of high-strength steels.

Main Sources. A. Harris (1961)
B. Takeuchi and Homma (1959).

Materials. A: 3% Ni-Cr steel S.11: U.T.S. 130,000 lb/sq.in. (?)
B: Si-Mn spring steel, U.T.S. 200,000 lb/Sq.in.

Form of test-piece. Rotating cantilever of about 0.3" critical diameter: circumferential groove for notch in both cases (see Figs. for dimensions).

Peening. A: .031" shot: 50 lb/sq.in. for 3 mins. at 6" nozzle/workpiece distance.

B: No.24 C.I. shot (.051" average): 70 lb/sq.in.: Almen gauge 0.50 mm (.020 A or C ?): "coverage 100%".

Residual Stresses. No measurements given: estimates about 100,000 lb/sq.in. compression, about 0.010" to 0.013" depth in both cases.

Fatigue Test Results.

A: Fig.C1b.1. Large improvement, almost completely overcoming the effect of the deep circumferential notch ($K_T = 1.76$).

B: Fig.C1b.2. Large improvements:

33% for mild groove ($K_T = 2$) and

73% for sharp groove ($K_T = 3.1$).

Discussion. Rotating bending specimens with a circumferential groove consistently show large improvements due to shot peening; the circumstances are in fact ideal for demonstrating the possible benefits of peening.

Fine cracks will form in the base of the groove at quite low nominal stresses, and the fatigue limit will be determined by whether or not the cracks propagate: compressive residual stresses will have a strong effect on the propagation of these cracks, and hence a large effect on the fatigue limit. In addition, the tri-axial stress state at the base of the notch will help to prevent fading of the residual stress. Ideal peening should completely overcome the strength reduction effect of the notch, as Harris found. Failure to achieve this suggests that the residual stress field does not penetrate far enough below the base of the notch, although there is no direct experimental support for this hypothesis.

Conclusion. Shot-peening gives large improvements on circumferentially grooved rotating-bending specimens of high-strength steels. At best the strength-reduction effect of the groove can be completely overcome.

CASE 2.

Basic Feature. Reversed-bend fatigue of flat specimens of spring, shot-peened with and without applied strain.

Main Sources.
A. Mattson and Coleman (1954).
B. Mattson (1956).
C. Mattson and Roberts (1959).

Materials. Hot-rolled SAE 5147 steel, 0.220" x 1.75". Tempered at 725-760°F to R.C.48: yield stress about 220,000 lb/sq.in.

Form of test-piece. Strip 12" x 1.5" x 0.192" wrapped repeatedly round a shoe of chosen curvature; effectively a constant-strain-range machine, giving one-directional bending.

Peening. In Source C, air-blast to intensity 0.006C. Almen, S.A.E.230 chilled iron shot. Source A covers blasting pressures 10 to 80 lb/sq.in., shots 130, 230 and 660, and exposure times ½ to 30 minutes, but with less comprehensive fatigue tests. The main feature of the work is that varying amounts of strain, from 0.60% tension to 0.60% compression, were applied to the specimens while they were peened.

Residual Stresses. Measured by sectioning: see Fig.C2.1. Conventional peening gave about 80,000 lb/sq.in. compression, and about 0.012" total depth: peening under tensile strain gave compressive stress up to 160,000 lb/sq.in., depth being 0.015" or so.

Fatigue Test Results. The most significant ones are in Source C: Fig.C2.1. summarizes them. As-heat-treated the fatigue limit was about 80,000 lb/sq.in., raised to 128,000 lb/sq.in. by presetting. Conventional peening gave 140,000 lb/sq.in., and strain peening a claimed 194,000 lb/sq.in., although the Appendix lists one 0.6% strained-peened specimen which failed at 190,000 lb/sq.in.

Discussion. The three reports deal with what is essentially a single experimental programme on fatigue of leaf-spring type specimens. Source C is the most important for fundamental information, and gives a well-integrated set of data with fatigue tests and residual stress measurements. Fig.C2.2 correlates fatigue limit with residual stress, and elsewhere in the paper tests on stress-relieved peened specimens show that strain hardening contributes little to the fatigue benefits of peening. On the face of things, the evidence is clear-cut: only residual stress has any significant effect, and there is a direct relationship between the magnitude of the residual stress, and the resulting fatigue limit. Although the U.T.S. is not stated, the highest achieved fatigue limit of 190,000 lb/sq.in. is clearly in excess of 0.5 times the U.T.S., and apparently one of the principles supported in Section A, Section 5, has been upset.

The major unusual feature of this test programme lies in the applied stress cycle: this is from zero to tension in all cases, and all quoted fatigue limits represent the maximum stress in each cycle. To compare these with the usual rotating-bending or axial push-pull tests, a factor of 2 needs to be

	Fatigue limit: tons/sq. in.
Unnotched - polished	28
Notched	17
Notched - peened	28

Specimen form: Rotating bending, 0.2375 in. diameter; semicircular groove K_T = 1.76

Figure C1.b.1 The mitigation of geometric stress concentration by shot peening S.11 steel (Harris, 1961)

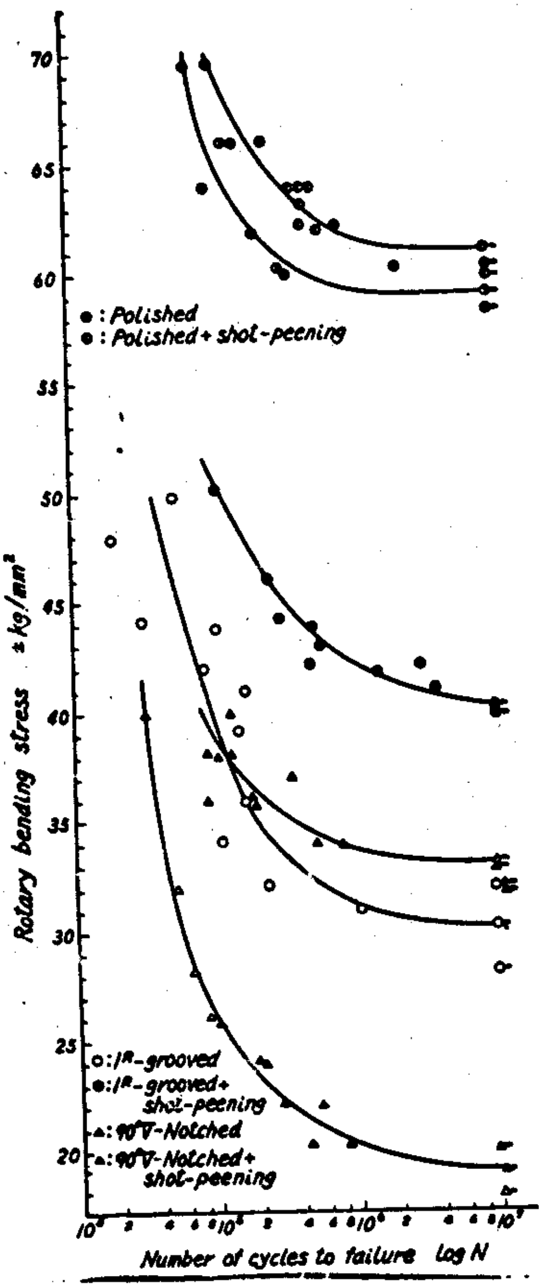


Fig. C 1b.2. Effect of shot-peening on the S-N diagram for polished, 1 R-grooved and 90°-V notched Si-Mn spring steel.

introduced when the range of stress is being considered. The statement that steel fatigue limits may approach 0.45 or 0.50 times the U.T.S. refers to rotating bending, with zero mean stress: applying the same argument to the present circumstances and assuming a U.T.S. of 240,000 lb/sq.in. then the total RANGE of applied cyclical stress is potentially about 210-220,000 lb/sq.in., as compared with the 190,000 lb/sq.in. achieved in practice. The results do not therefore conflict with the principles already suggested.

The dominant feature of these tests seem to be the difficulty of achieving adequate compressive residual stress in a rather hard material. It should be possible to induce and retain stresses of the order 70,000 + 0.2 x 240,000 lb/sq.in., i.e. about 120,000 lb/sq.in., and the 90,000 lb/sq.in. from conventional peening seems rather low: the 140,000 lb/sq.in. fatigue limit of these specimens is correspondingly lower than the ideal. Strain-peening is then seen as a means of overcoming this defect in conventional peening, and raising the residual stress to a more effective level. One confusing factor is that the flat specimens were peened on one side only, and initial residual stresses refer to the "free" condition, i.e. released after peening and allowed to spring to a curved shape. Figures given for this curvature suggest that the residual stress in the "clamped" condition, or peened on both sides, would be higher by about 20,000 lb/sq.in. in the conventionally peened case, and it seems likely that the benefits of applying strain while peening are more marked when only one face of a specimen is to be peened.

Source C is well worth detailed scrutiny, and there is certainly a spectacular increase in fatigue limit with increase in residual stress. The points which need watching when applying the results more generally, though, are:-

1) All tests had a considerable tensile mean stress, and the semi-RANGE of stress naturally never exceeded 0.5 times the U.T.S. of the material: similar reversed-bending tests would be unlikely to improve the fatigue limit beyond ± 120,000 lb/sq.in. regardless of how high the residual compression became.

2) The comparatively thin (0.192") specimens would have a steep stress gradient, and increasing the depth at which failure initiated would give appreciable improvements: the strain-peened specimens are shown as having failure origins 0.020" to 0.030" below the surface. Axially-stressed specimens would gain little from this effect.

3) A tensile mean stress superimposed on the compressive residual stress means that the residual stress will fade if there is any tendency for the core to creep under the action of the tensile mean. This would be a limiting factor if softer materials were being considered.

Other reports. Almen (1950), includes the original suggestion for strain-peening, and some data. Elsesser (1957) gives information on fading of residual stresses in flat leaf specimens under cyclic loading: this could be pertinent in applying Mattson's work to other circumstances.

<u>Conclusions</u>: Holding a surface under tensile strain during peening causes the final residual compressive stresses to be greater; <u>if</u> the applied fatigue stresses contain a significant mean tensile component, and <u>if</u> the peened material is hard enough to retain the residual compression under fatigue loading, the fatigue limit will steadily improve with increasing residual compression. The maximum improvement reported gave a semi-range of fatigue stress of about 0.4 times the U.T.S.

Applied strain during peening %	-0.60	-0.30	zero	preset only	+0.30	+0.60
Maximum residual stress; k.s.i.	-160	-140	-80	-30	-10	+60

Figure C2.1 Variation of residual stress with applied strain (Mattson and Roberts, 1959)

Maximum residual stress; k.s.i.	-160	-140	-80	-30	-10	+60
Fatigue limit: k.s.i.	194	170	140	130	70	50

Figure C2.2 Variation of fatigue limit with residual stress (Mattson and Roberts, 1959)

CASE 3

Basic Feature. Shot-peening rotating-bending specimens of aluminium alloy, plain and notched, including the effect of polishing after peening.

Main Sources. A : Harris (1961)
B : Sherratt and Pope (1960)

Materials. A. (i) Duralumin L1 :
(ii) D.T.D.683, 5½% Zn Mg alloy.

B. D.T.D.683 : ¾" bar stock : U.T.S. 40 tons/sq.in.
0.1% Proof 38 tons/sq.in.

Form of test piece. A : Wohler plain, and with circumferential groove of K_T 1.76.

B : Wohler plain, longitudinal radius 4", critical diameter 0.3 ins. Similar with circumferential groove, K_T 1.35. (Figs. C3.3 and C3.4).

Peening. A : (i) Vapour blast (ii) Peening, probably with 0.031" shot.

B : 0.060" chilled iron shot : 35/40 lb/sq.in.: nozzle to workpiece 6" : 30 seconds exposure: Almen .010C to .015C.

Residual Stresses. No measurements. Estimated, for L1, 50,000 lb/sq.in.; for D.T.D.683, 65,000 lb/sq.in. to about 0.015" depth in source A, and to 0.030" depth in source B.

Fatigue Test Results. A : *Figs. C3.1 and 2.* Clear *improvement* of notched specimens of both alloys.

B : Figs. C3.5 to C3.9. Clear improvement of notched specimens: possible improvement by peening and polishing plain specimens, but definite reduction from peening alone applied to plain specimens.

Discussion. There is little ambiguity about the results in either case: shot peening substantially improves the fatigue limit of the specimens with a circumferential groove; grit blasting and vapour blasting also improve the grooved Duralumin specimens, although the improvement is substantially less than can be obtained by shot-peening. In sharp contrast, Fig.C3.6 shows a clear reduction in fatigue life when plain specimens of D.T.D.683 are shot peened with 0.090" diameter shot, and other tests in the same report show a consistent reduction in fatigue life at 17.0 tons/sq.in. for 0.060" shot used at various exposures and nozzle pressures.

The main feature of Source B, though, concerns the effect of polishing after peening (Fig.C3.7 for plain specimens, and Fig.C3.11 for notched). The damaging effect of peening can be removed from the plain specimens by polishing the surface, and under optimum conditions the S/N curve is generally improved as compared with the untreated, polished tests; notice, though, that the improvement is not large, and that optimum conditions require a large proportion (0.020") of the peened layer to be removed. In contrast, polishing notched specimens gives an appreciable improvement (10^8 limit raised from 13 to over 15 tons/sq.in.), and the greatest improvements occur when only 0.004" to 0.006" is removed from the surface; another feature is that on notched specimens the peened surface can be removed by turning, rather than polishing, with no apparent ill effects.

The most striking point requiring explanation comes from comparing Fig.C3.10 with Figs.C3.6 and 7. The best peening-plus-turning condition does more than overcome the strength reduction effect of the notch, giving a fatigue limit which is not only higher than the plain fatigue limit of the material, but also exceeds the best that peening-plus-polishing can achieve on plain specimens. It seems that in this case the notch makes an essential contribution to the mechanism by which peening raises the fatigue limit. Two ways in which this could happen are (a) the triaxial stress state at the base of the notch could be preventing the fading of residual compression, or (b) the form of the notch could be favouring tensile type propagation as opposed to shearing propagation. Strong support for (b) comes from the form of fracture seen in the plain (4" longitudinal radius) specimens, which had jagged mating surfaces on the broken halves, in contrast to the classic transverse fracture of the notched specimens.

Applying the ideas of Section A to these results, a reasonable pattern emerges. Plain specimens fail by the formation of shearing cracks which, in these particular circumstances, are seen to propagate for considerable distances (probably the heavy anisotropy of the ¾" extruded bar is an important factor). In a soft material such as this, compressed for half the cycle, residual stresses will very likely fade rapidly. The circumstances, then, are particularly unfavourable to shot-peening, and the result is a reduction in fatigue life. The peened and polished specimens which showed a small improvement had only a thin skin of peened material left on them when tested, and it seems unlikely that residual compression is the prime factor: the implication is that the work-hardened skin inhibits the initiation of fatigue cracks.

On the other hand the notched specimens fail by the formation of cracks in the base of the groove, the fatigue limit being decided by whether or not the cracks propagate in tension across the section; the form of the specimen prevents extensive shearing propagation from playing a major part. Residual compression at the base of the groove is very effective in these circumstances, preventing cracks from propagating away from the surface: peened-and-turned specimens quite often showed a type of sub-surface failure. The notch is essential both to prevent the residual stresses from fading and to prevent extensive shearing cracks; the results are therefore not as anomalous as they seem at first. Several subsidiary factors fit easily into this pattern. Turning instead of polishing is successful as a final finish because surface geometry does not matter when sub-surface cracks are the limiting factor. Vapour-blasting and grit blasting do not give such large improvements as shot-peening because the <u>depth</u> of the worked layer is a major factor when suppression of crack propagation is involved, and the depth of layer from these processes does not penetrate below the stress raising effect of the groove. Similar arguments can be put forward for several of the other details touched upon in Source B.

Conclusions. The effect of shot-peening on rotating-bending specimens of structural aluminium alloys depends strongly on the form of specimen taken. Plain specimens may be reduced in strength, but deep circumferential grooves show marked improvements, and favourable peening will give a fatigue limit at least equal to the un-notched strength. Polishing after peening improves both plain and notched specimens, but only the notched forms show a great enough increase to be of real interest: peened-and-turned notched specimens may have fatigue limits (10^8, on nominal stresses) higher than the best that can be achieved on plain specimens.

CASE 4

Basic Feature. Shot-peening and vapour blasting in association with other surface finishes, as applied to high-strength aluminium alloys.

Main Source. Brown (1960)

Materials. (a) D.T.D.363 Al-Zn-Mg alloy: 0.1% Proof. 34/39 tons/sq.in.: U.T.S. 39/42 tons/sq.in.

(b) D.T.D. 364 Al-Cu: 0.1% Proof 27/31 tons/sq.in.: U.T.S. 32/34 tons/sq.in.

Form of test piece. Dumbell suitable for Schenk axial-load machines. Two forms:-

(i) Plain specimen with central parallel portion 0.7" diameter.

(ii) "Unloaded hole" specimen, with transverse hole 0.1875" dia. through 0.832" dia. central portion.

Surface treatments. A variety of treatments, such as anodising (two processes), etch priming etc. in association with capri-honing. Also shot-peening in association with anodising: peening with 0.011" dia. shot at 20 lb/sq.in. to Almen 0.008".

Residual stresses. No measurements given: will vary considerably over the different conditions.

Fatigue test results. All tests were carried out with a substantial mean tensile stress, 10.0 tons/sq.in. for the plain specimens, and 8.0 tons/sq.in. for the holed ones. Figs.C4.1. to C.4.4 summarize the results, but it must be appreciated that the lines shown on these graphs are an attempt to simplify the information, which usually comprises 6 to 10 test results for each condition, spread over a range of stress levels, and showing considerable scatter. Small differences between the lines for different treatments are therefore unlikely to be significant.

Other reports. Harris (1961) gives the results shown in Figs. C4.5 and C.4.6 for various blasting treatments in association with hard anodizing, using rotating-bending specimens. Peening and vapour blasting very effectively overcome the strength reduction effect of the hard anodising, giving fatigue limits higher than the plain polished condition.

Discussion. No clear-cut picture emerges from Brown's test results. Although the graphs reproduced show variations between the treatments, the scatter in the full results from the original report means that only the more extreme variations are significant, e.g. sulphuric acid anodising gave very poor results on both types of specimen in both materials. Capri-honing seems to give improvements in most conditions, but surprisingly did not help in association with Bengough-Stuart anodizing on a plain specimen. The B.S. anodizing did not seem to be reducing the fatigue properties by any large amount, though, and it is possible that capri-honing might show a greater effect if it preceded sulphuric-acid anodizing, with its pronounced strength reduction.

C.4.1.

(a) Unnotched specimens

Condition	Unnotched - polished	Unnotched - vapour blast
Fatigue limit: tons/sq.in.	9.8	9.8

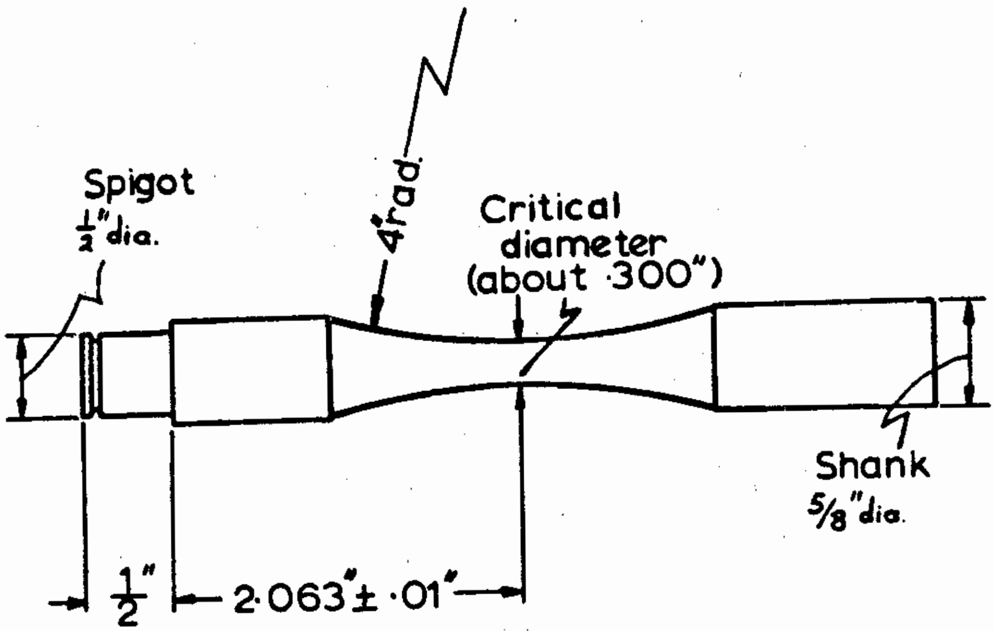
(b) Notched specimens; $K_T = 1.76$

Condition	Notched	Vapour blast	Grit blast	Shot peened	Shot peened + re-heat
Fatigue limit: tons/sq. in.	4.5	6	6.8	12.2	4

Figure C3.1 Effect of surface treatments on Duralumin L1 (after Harris, 1961)

Condition	Notched $K_T = 1.76$	Notched, shot peened	Notched, shot peened and re-heated
Fatigue limit: tons/sq. in.	5.9	11.7	4.3

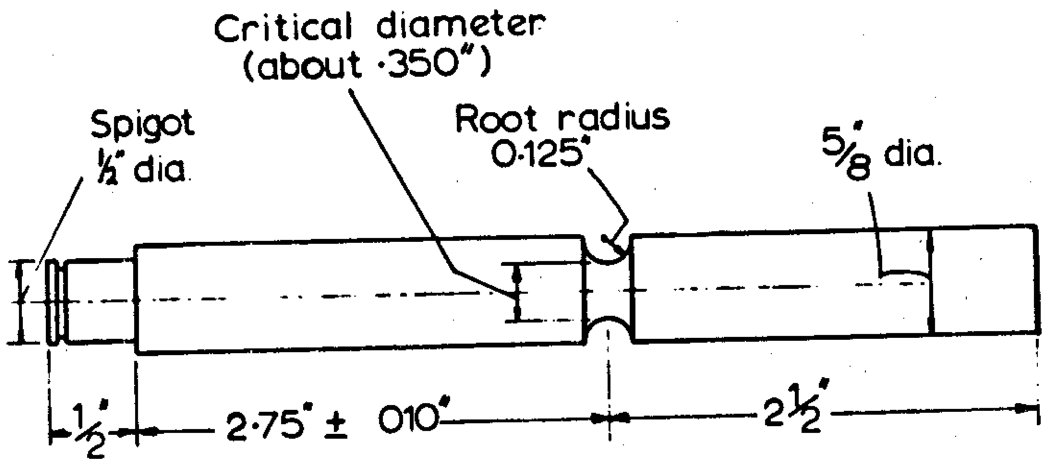
Figure C3.2 The influence of shot peening on notched specimens of D.T.D. 683 (after Harris, 1961)



ROTATING BENDING SPECIMEN
TYPE III, (UN-NOTCHED).

RULING DIMENSIONS

FIG. C3.3



ROTATING BENDING SPECIMEN
TYPE VA (NOTCHED).
RULING DIMENSIONS.

FIG. C3.4

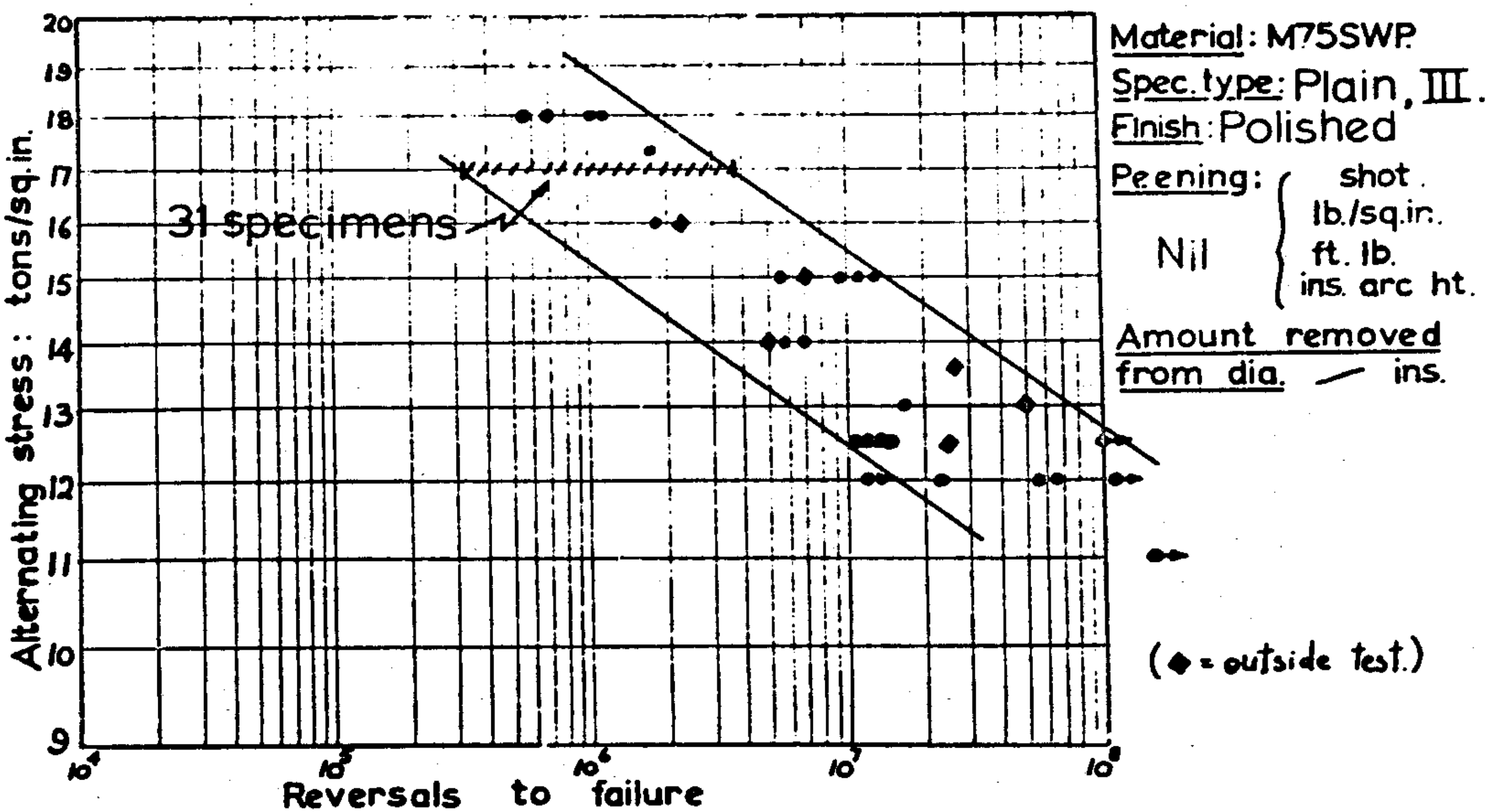
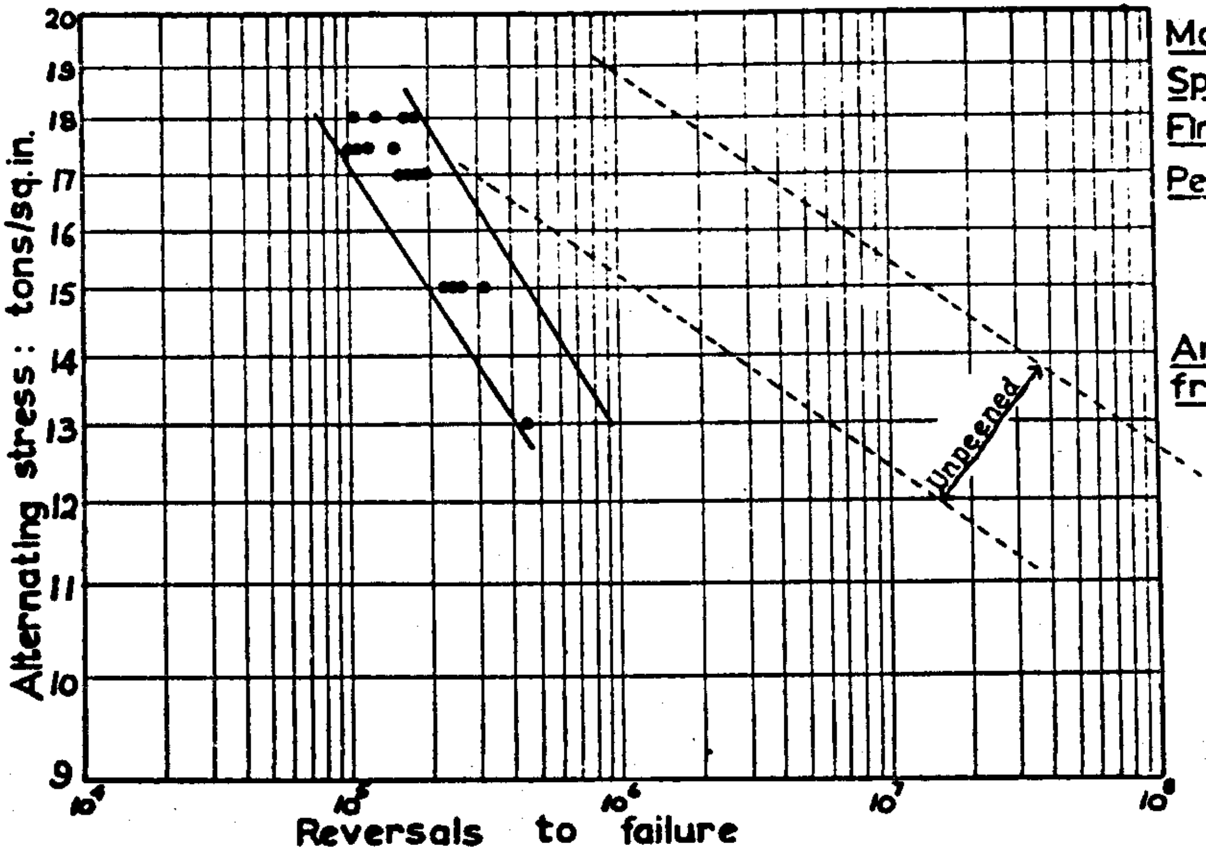


FIG. C3.5 S/N FOR STANDARD MATERIAL, M75SWP FROM 3/4" BAR.



Material: M75SWP.
Spec. type: Un-notched 3
Finish: As-peened
Peening. 9 shot.
25 lb./sq.in.
500 ft. lb.
- ins. arc ht.
Amount removed from dia. Nil ins.

FIG. C3.6 S/N : UN-NOTCHED SPECIMENS WITH AS-PEENED SURFACE

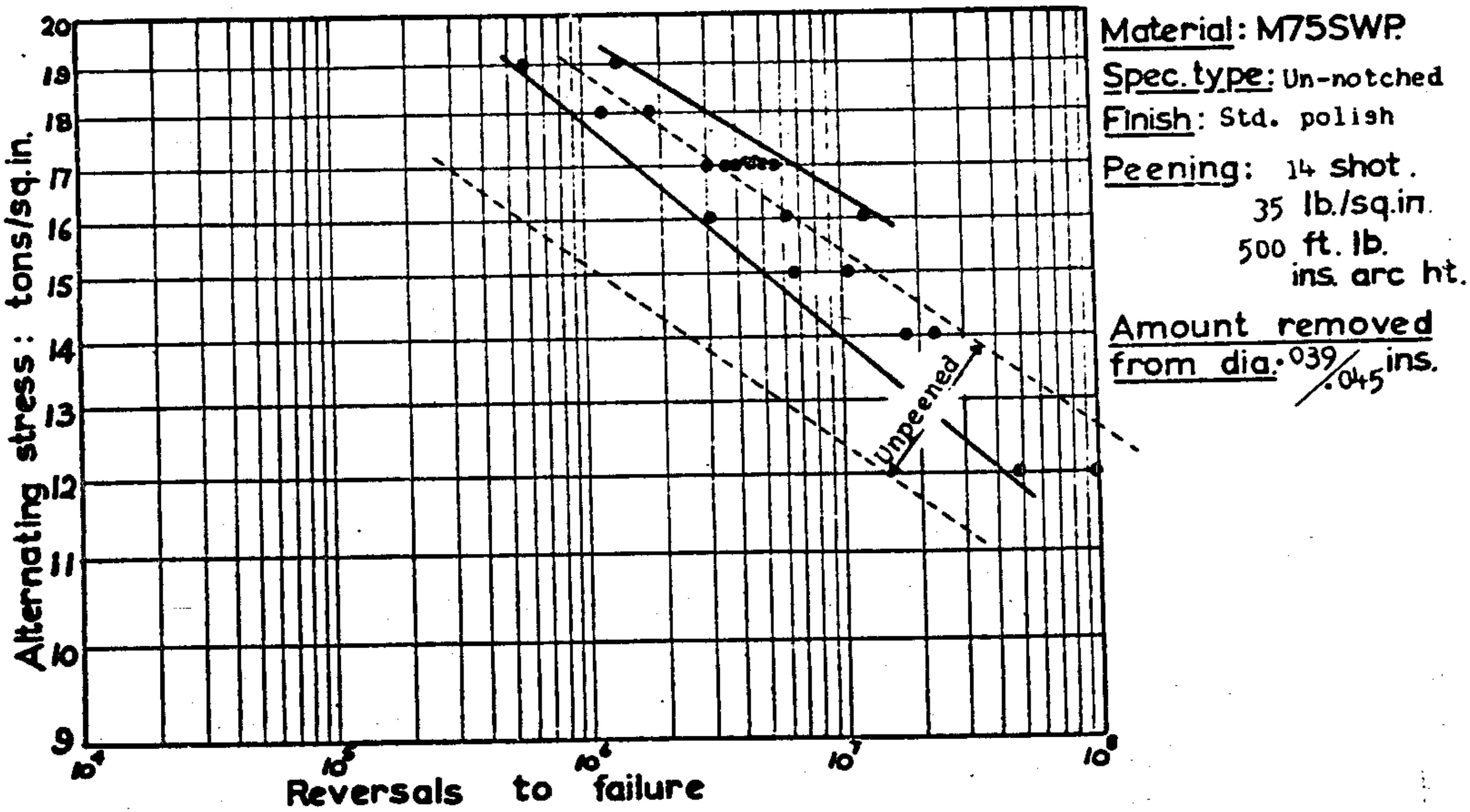


FIG. C3.7 S/N FOR INTERIM OPTIMUM PEENING PLUS POLISHING CONDITION

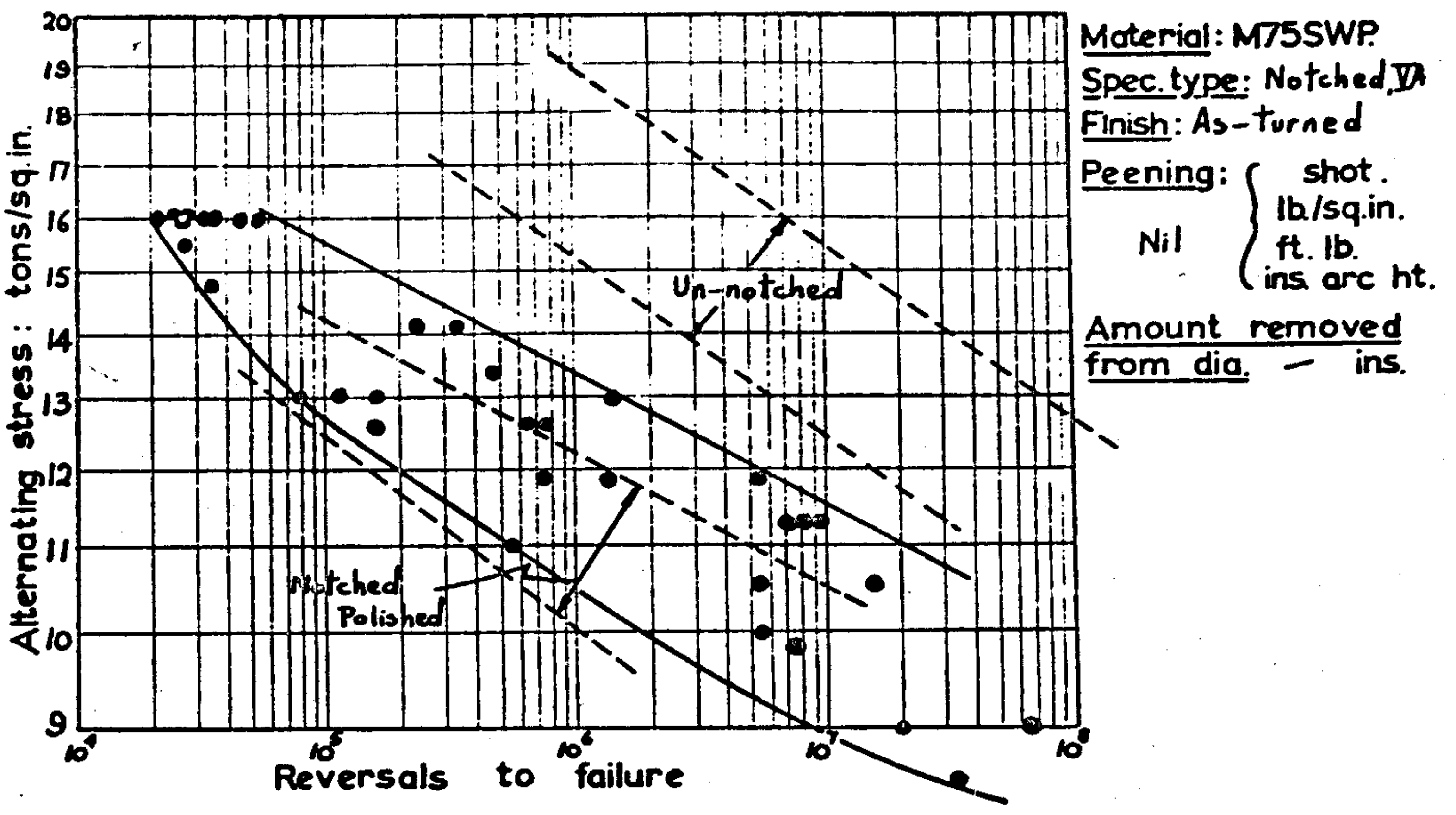


FIG. C3.8 S/N FOR CIRCUMFERENTIALLY GROOVED SPECIMENS WITH AS-TURNED FINISH.

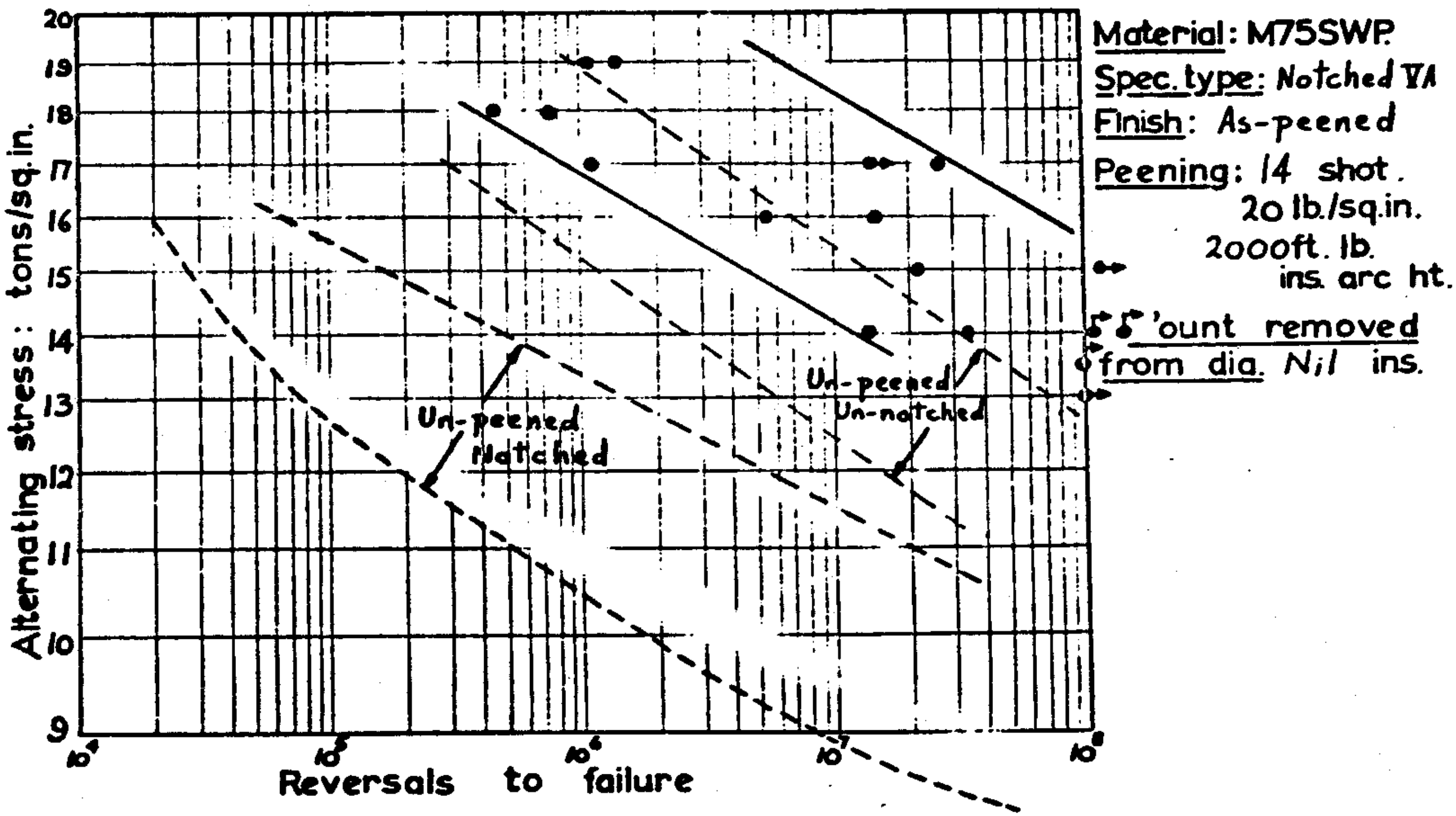


FIG. C3.9 S/N; NOTCHED SPECIMENS PEENED ONLY (Optimum conditions).

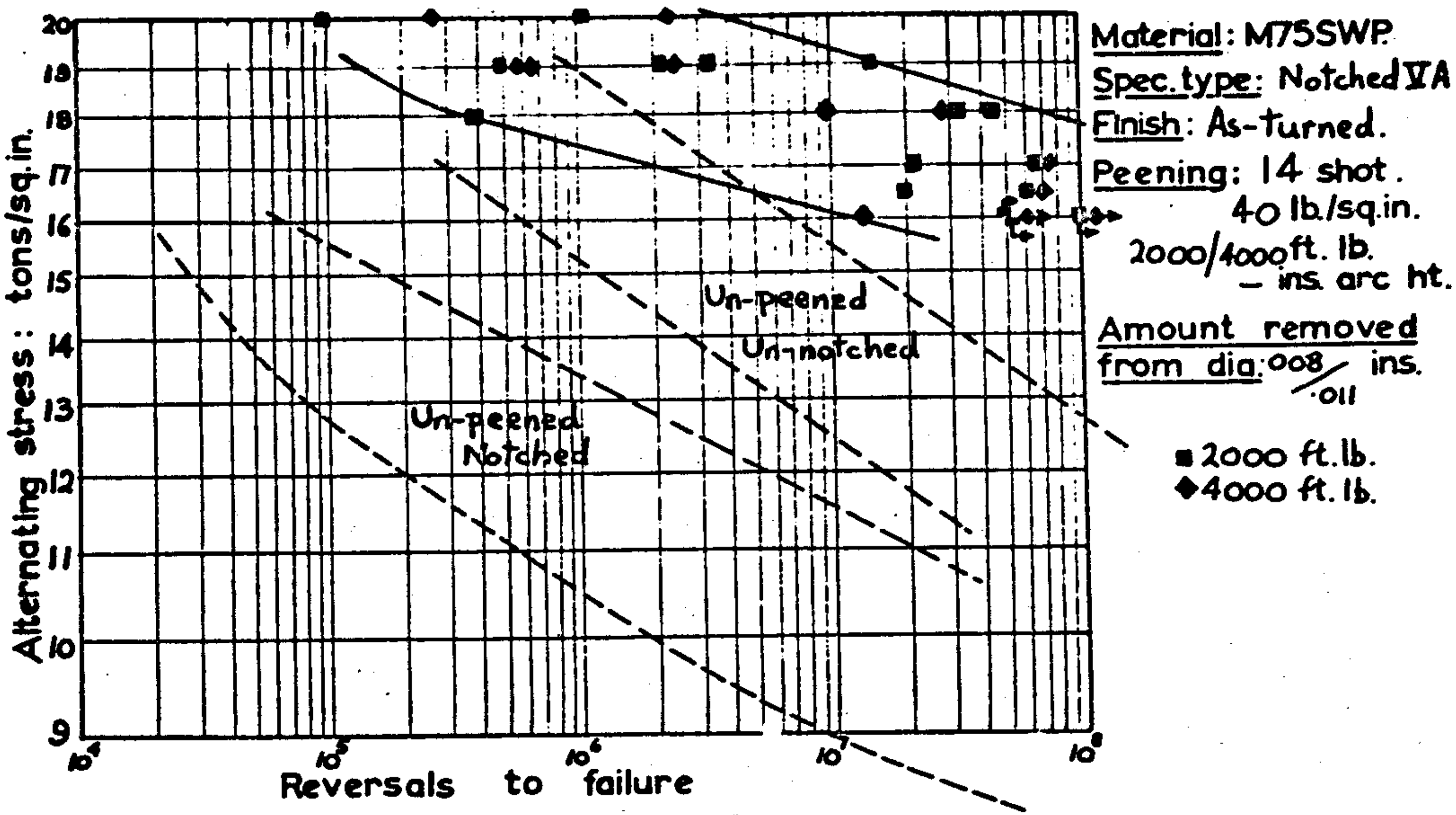


FIG. C3.10 S/N; NOTCHED SPECIMENS PEENED AND TURNED (Approx. optimum depth)

On the holed specimens, capri-honing could be giving an improvement, but again detailed examination of the test results makes this doubtful. The transverse hole is a difficult stress-raiser on which to use mechanical blast treatments, as a fatigue crack might well form inside the hole, where the untreated surface left by the drill is the dominant factor, rather than the peened or vapour-blasted surface: this was appreciated by the author, who suggests that more optimistic results might be obtained on "fully exposed concentrations such as radii".

The shot-peening tests on plain D.T.D.363 show a clear improvement at high stresses and low lives, but there is no evidence that the fatigue limit is improved: anodising after peening reduces the strength slightly, but again the B.S. anodising does not seem to be disastrous either with or without peening.

In contrast to Brown's results, those by Harris show clear benefits from both shot-peening and vapour-blasting, and small improvements from the milder aqua-blast. It is unlikely that the difference in material would account for this, since Duralumin,L1 and D.T.D.364 are both copper-bearing alloys. Other differences lie in the stress-cycle used, and the final coating. Harris's hard anodizing seems to have a much greater strength reduction effect than B-S anodizing, and it is in overcoming this reduction that shot peening gives such favourable results.

Applying the ideas of Section A to this problem, the function of shot-peening is to introduce residual compression into the parent metal, immediately below the coating: this helps to prevent cracks propagating from the coating into the parent metal. Large benefits can be expected if the original process, without peening, has the following features:-

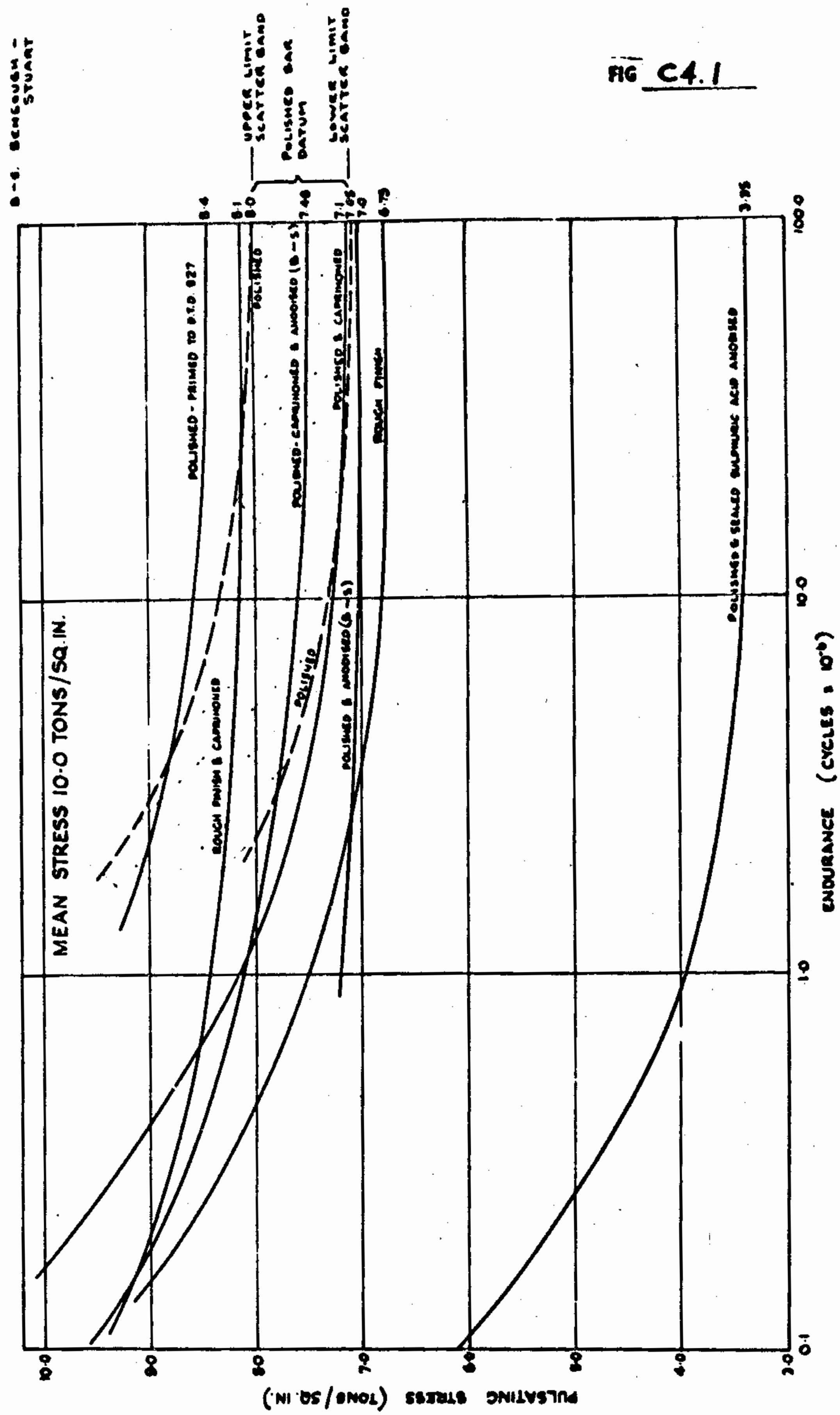
1. Residual tensile stresses in the parent surface.
2. A coating in which fatigue cracks could easily form.
3. An appreciable depth of coating.

These circumstances acting together will cause large reductions in fatigue strength. Using Frost's figure of $\sigma^3 = 0.2$ for a $4\frac{1}{2}\%$ Cu-Al alloy, the minimum alternating stress needed to propagate a crack already 0.001" long would be less than 6 tons/sq.in. The hard anodic coating (.001" to .002" thick) gives a fatigue limit of 7 tons/sq.in., which is not quite as damaging as we would expect on the assumption that the anodic coating is effectively cracked early in the life, but the general trend suggests that the propagation or non-propagation of cracks is at least one of the pertinent factors.

One factor not considered so far is the differences in the stress-cycle between the two sets of tests, Brown's axial-loading cycle with high mean stress, as compared with the roating bending tests of Harris. There is a general feeling that surface compression will not be as beneficial in axial loading as in bending, and this is logical since the stress gradient in a bending test becomes a favourable factor if the treatment succeeds in producing sub-surface failures. A general assumption that high mean stresses give less favourable conditions is not so valid, though, as was seen from Mattson's tests in Case 2. High mean stresses will only detract from peening benefits if they are so oriented as to cause relief of the residual stresses during fatigue cycling. In this case a tension-tension cycle is less likely to cause plastic deformation of a compressively-stressed surface than a tension-compression cycle would be, and it is necessary to imagine the core of the specimen progressively extending under repeated loading. There is no information to help directly on this, but Pattinson and Dugdale (1962) certainly found that repeated stresses of $\pm$ 2.5 tons/sq.in. caused significant fading at more than 10^6 cycles on a $4\frac{1}{2}$% Cu-Al alloy.

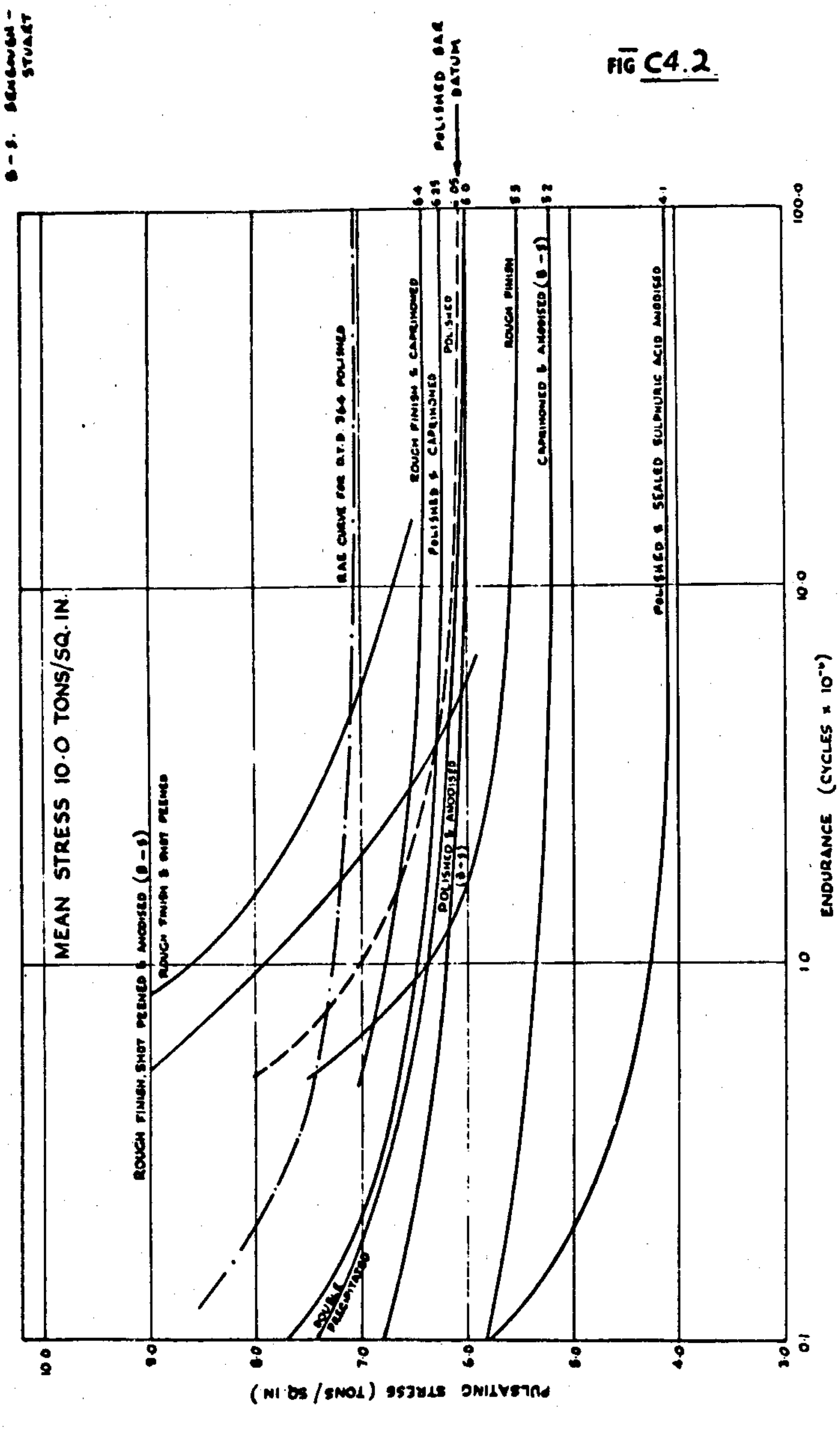
Conclusions. On the whole there are many unresolved factors, but the general pattern is that both shot-peening and vapour blasting are likely to overcome the deleterious effects of a surface coating applied to an aluminium alloy, but unlikely to improve a condition in which a coating process has already been modified so that it causes no marked reduction in fatigue properties.

FIG C4.1



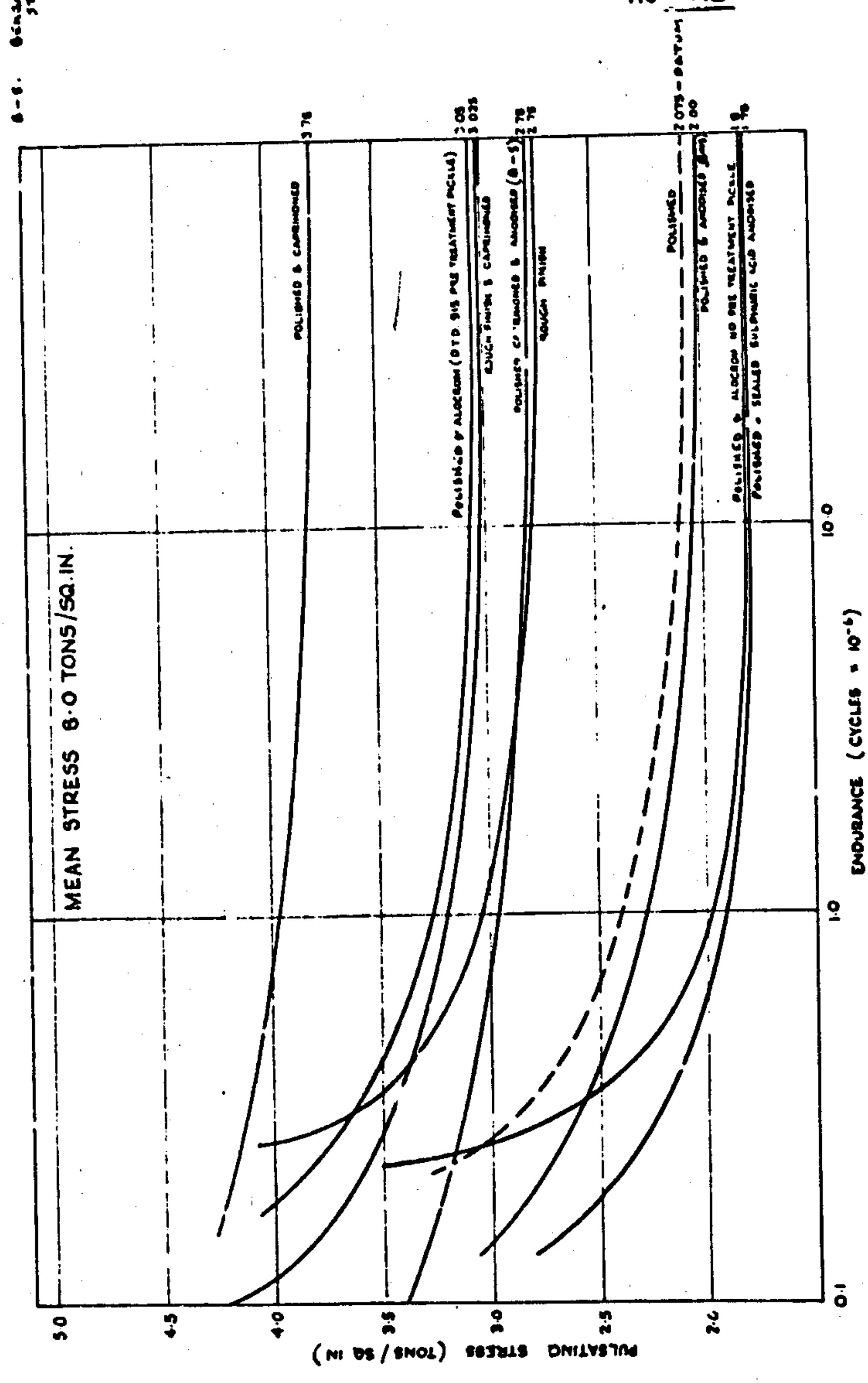
D.T.D. 364. PLAIN BAR. TENSION LOADING.

FIG C4.2



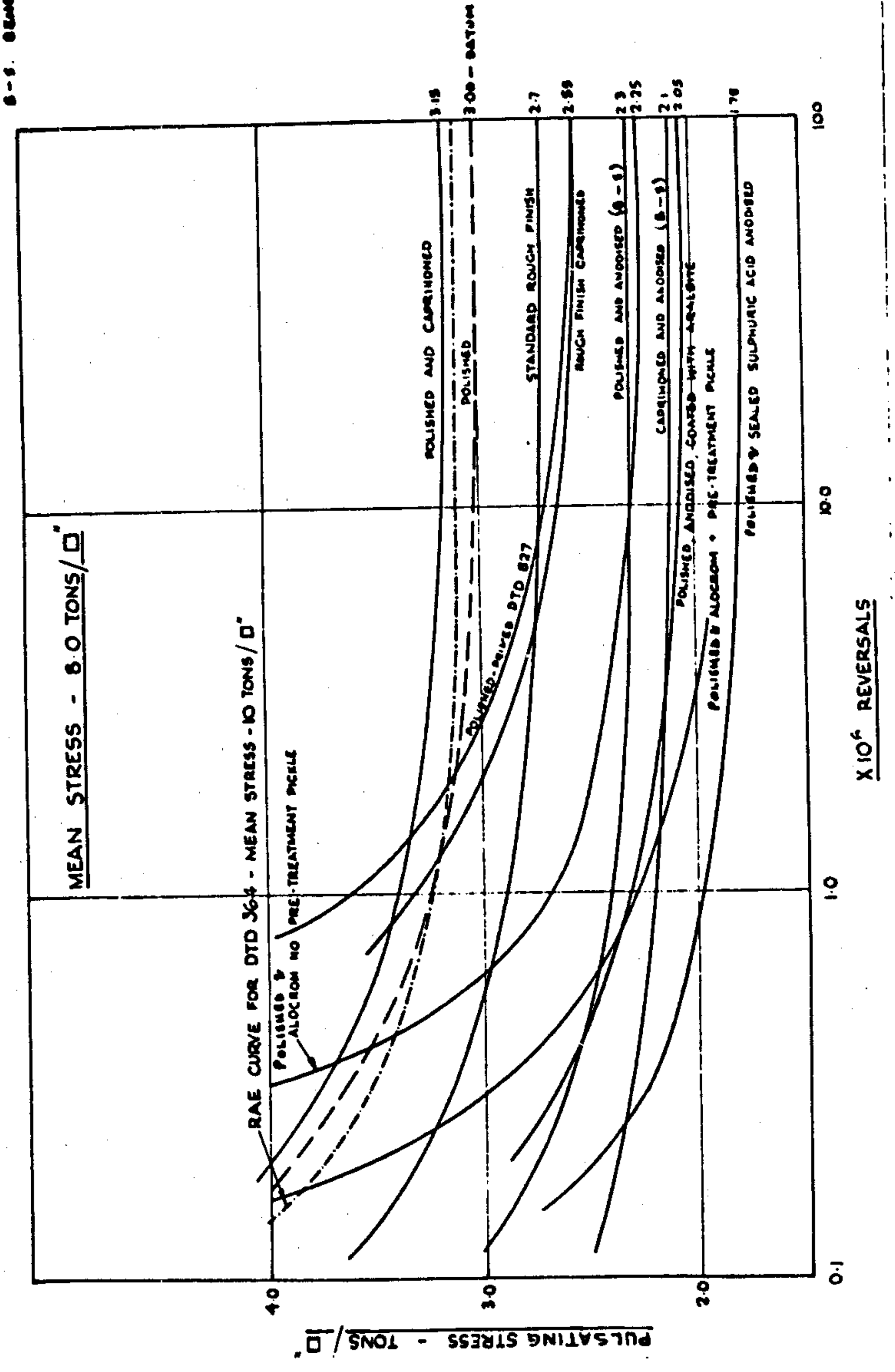
D.T.D. 363. PLAIN BAR — TENSION LOADING.

FIG C4.3



D.T.D. 364. UNLOADED HOLE. TENSION LOADING.

FIG C4.4



DTD 363 UNLOADED HOLE TESTS - TENSION LOADING

Condition	Not anodized	Hard anodized	Shot peened and hard anodized
Fatigue limit: tons/sq. in.	10.5	7.2	11.4

Figure C4.5 The influence of hard anodizing and shot peening on Duralumin L1 (after Harris, 1961)

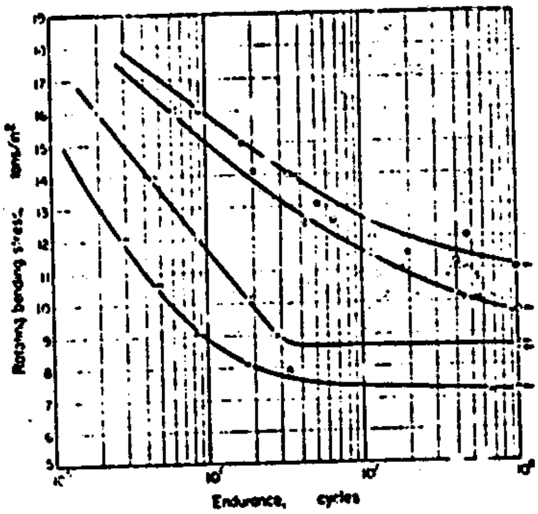


Fig. Ch. 6 The influence of hard anodizing and vapour blast treatments on the fatigue strength of Duralumin (L1)

Un-notched fatigue properties

- Polished
- Polished and hard anodized
- Polished and vapour blast
- Polished and vapour blast and pickle
- Polished and vapour blast and pickle and hard anodized
- Polished and aqua blast and hard anodized

CASE 4a

Basic Feature. Grit blasting in association with metal-spraying, applied to high-strength aluminium alloys tested under corrosion conditions.

Sources. Fulmer Research Institute Reports:- R.106/5/June 1960: R170/1/Sep. 1961: R.170/3/Oct. 1962.

Materials. (a) D.T.D.683 and D.T.D.687, Al-Zn-Mg alloy in bar and sheet form: U.T.S. 41 tons/sq.in. (bar) and 38 tons/sq.in. (sheet).

(b) HE 15 (bar) and HS 15 (sheet): Al-Cu alloy: U.T.S. 31-34 tons/sq.in.

Form of test piece. (i) Axially loaded, 0.226" dia. (rod) or 0.5" width (sheet): (ii) Rotating cantilever, dia. 0.263": (iii) Reversed bend, 0.5" wide.

Blasting. Grit blasted with Blastyte Grits Nos.1, 2 and 5: arc heights on a 0.050" thick Almen-type strips, made from NS 4 ½ Hard were 0.040" for No.1 Grit, 0.010" for No.2, and 0.003" for No.5.

Residual Stresses. No measurements: probably about 65 to 70,000 lb/sq.in., .002" to .004" deep on D.T.D. 683 and 687; slightly lower on HE 15.

Fatigue Test Results. Various results given, stress systems covering axial load, with and without mean stress as well as the reversed and rotating bending tests. Air fatigue and Na Cl corrosion limits (3×10^7 cycles) are quoted. None of the air fatigue values for un-notched specimens shows an improvement due to grit blasting alone: in fact No.5 grit caused a small reduction, and the coarse No.1 Grit a marked reduction in strength for both D.T.D.683 and HE 15, tested under both axial and rotating bending loads. The corrosion tests give a slightly more optimistic picture: grit blasted specimens have higher strengths (at 3×10^7 cycles) than untreated material for most of, but not all, the conditions. There is no obvious pattern to the exceptions, though, and grit blasting is certainly less effective than a metal sprayed coating for improving corrosion resistance.

Some notched specimens were tested in fluctuating tension, the notch being a 60° groove, 0.016" deep, 0.002" root radius, $K_T = 5.1$. Specimens were either blasted with No.3 grit, or metal sprayed. For D.T.D.683 bar both treatments gave air fatigue strengths at 3×10^7 of 5.5 ± 5.0 tons/sq. in., the same as the notched strength without treatment. Under NaCl corrosion the untreated and metal sprayed both dropped to 4.0 ± 3.6 tons/sq.in., but the grit blasted was lower at 2.8 ± 2.5 tons/sq.in.

Discussion. None of the conditions investigated shows grit blasting as a process worth using as a way of improving either air fatigue or corrosion fatigue strength at 3×10^7 cycles; in fact grit blasting causes a reduction fatigue strength in nearly all unnotched air fatigue conditions. The notched results are even more significant: the residual compression induced by blasting completely failed to give an improvement, even when a circumferential groove was present. This contrasts with the results of Case 3, where two independent reports show that shot peening gives marked improvements on similar aluminium alloy specimens with circumferential grooves. Apart from the difference in treatments (grit blasting in this case, shot peening in Case 3), the main difference lies in the form of stress-raiser. Both Harris and Sherratt in Case 3 used grooves with comparatively mild K_T values, (i.e. large radii at the groove base), and full penetration of shot into the groove base was achieved; in addition deep, large-radius grooves ensure tensile-type crack propagation. The shallow, sharp groove used in the Fulmer tests was probably not completely penetrated, even though the particle size was smaller than the Case 3 tests, and although there is no information about the form of the fractures, shearing crack propagation might still be possible. Specific mention is made in the June 1960 report of the 45°, or shearing type, cracks observed on D.T.D.683 axially-loaded specimens, tested under corrosion with zero mean stress; fluctuating tension produced tensile cracks, lowering the fatigue range from $\pm$ 5.3 tons/sq.in. to 4.8 $\pm$ 4.4 tons/sq.in., and applying a cathodic current to zero-mean-stress specimens also changed the fracture from shearing to tensile form, this time with an improvement in strength. There is obviously room for a full investigation and discussion of the type of failure in various circumstances, but for the present discussion we can only note a tendency for shearing type fractures to occur when conditions happen to be favourable, i.e. corrosion present, and mean stresses tending towards compression. Under the hypotheses suggested in Section A of this review, residual compression will be effective in suppressing tensile cracks, but if this is superseded by shearing propagation at a range of stress very little higher than that needed for tensile propagation, the net gain will be small. Again, if sharp grit causes sufficient damage to give the shearing cracks an easy start, the overall effect of blasting will be to reduce the fatigue strength. The general failure of grit blasting to achieve fatigue improvement can be linked with several factors, then, including

(a) the geometrical surface damage caused by the process

(b) the shallowness of the residual compression induced

(c) the tendency for the alloys treated to fail by shearing-type crack propagation when circumstances do not favour tensile failure.

Conclusion. Grit blasting does not generally improve the fatigue strength of aluminium alloys to specifications D.T.D.683 and 687 or HE 15 and HS 15. Air fatigue strengths are generally reduced, and although corrosion fatigue strengths are raised in a few circumstances, there is no clear-cut indication of circumstances under which grit-blasting would be useful in itself as a production process for improving the fatigue strength of aluminium alloys. Where metal sprayed coatings require a rough key to be formed on an existing surface, though, grit blasting is a convenient means of providing the key.

C4a.2.

CASE 5

Basic Feature. Wet blasting of titanium with .001" glass beads.

Source. Reed and Viens (1960).

Material Titanium alloy 6 Al 4V : Rockwell C.30-32.

Form of test piece. Krouse plate fatigue specimens, 0.90" wide x 0.200": longitudinal profile 0.85" radius on each edge.

Peening. 0.001" diameter glass beads, 90 lb/sq.in. air blast with water.

Residual stresses Surface removed by acid etching and stresses estimated from curvature measurements. Compression 108,000 lb./sq.in. at the surface, decreasing to zero at about 0.0025" depth.

Fatigue tests. Endurance (10^7) limits determined by staircase method, with 2,500 lb./sq.in. load increments. Vacuum-annealed specimens had reversed-stress endurance limit of 41,500 lb./sq.in., which was raised to 53,900 lb/sq.in. by the glass-bead blasting (nearly 30% improvement.).

Discussion. The investigation was concerned mainly with the effect of different grinding methods on fatigue of titanium, and the report includes endurance limits for ground specimens with tensile residual stresses up to 62,000 lb./sq.in. A steady improvement in endurance limit was found as the residual stress moved more into compression, and the authors suggest that $F_s = F_p - \frac{S}{10}$, where F_s is the endurance limit when a residual stress S is present, and F_p is the endurance limit of vacuum-annealed material (lb/sq.in. throughout). This is a useful empirical relationship, but some of the points to watch are:-

(a) There is no information about the form of the fractures, except for a statement that "..... the edges of the specimens were broken and shot peened with No.110 cast-steel shot to prevent breakage at the edges." This seems to imply that without this peening cracks would form at the edges, perhaps modifying the whole of the results.

(b) If the empirical relationship is accepted, the specimens showing most deviation are the stress-free ones, having an endurance of 41,500 lb./sq.in., compared with 45,000 lb/sq.in. at 25,000 lb./sq.in. compression, and 42,500 lb./sq.in. at 23,000 lb./sq.in. tension. The authors point out themselves that un-notched rotating-bending specimens give endurance values nearer 70,000 lb./sq.in., and associate the lower values found here with "... the size and shape of the fatigue specimen", i.e. the specimens are effectively notched, but the exact nature of the stress raiser is not investigated.

(c) Staircase testing does not give complete information, and 10^7 is fairly short for test duration in this type of work: ten specimens were used in each condition, though, which should offset this to some extent.

Conclusions. Wet blasting with glass beads improves the fatigue limit of titanium: the induced residual stresses are high but shallow. Substantial improvement may only be expected when the untreated specimens are giving endurance values less than the plain, polished figures, i.e. the specimens are effectively "notched". The technique could probably find wide application on other alloys where contamination by iron "pick-up" would be a drawback to conventional iron-shot peening.

CASE 6

Basic Feature. Peening of aluminium alloy with aluminium shot.

Source. Berry (1960).

Material. Aluminium alloy to spec. L65.

Form of test piece. Reversed bend from $\frac{1}{8}$" flat material, 2" wide.

Peening. "Granal" shot, an aluminium alloy shot of Swiss origin: 10 lb/sq. in. pressure was used, and L65 strips 3" x $\frac{3}{4}$" x 0.057" gave an arc height of 0.022": this seems to represent saturation for these strips.

Residual Stresses. No measurements. Could be as high as 60,000 lb/sq.in., but there is little evidence from other work to enable estimates to be made.

Fatigue test results. Peening certainly gives an improvement compared with the as-extruded condition, but the results show considerable scatter, and no specimens were run without failure to 10^8 cycles. Comparisons based on tests at a stress of 10.78 tons/sq.in. show improvements in life of about 5:1 due to peening.

Discussion. Apparently spectacular increases in specimen life can result from tests which move the failure stress level by only a minor amount, and the tests reported here must therefore be regarded as qualitative only. They show that aluminium specimens having a poor surface (e.g. as-extruded) are improved by Granal peening, and that the improvement extends over the whole range of stresses investigated, but no firm conclusions can be drawn about the 10^8 fatigue limit in either the peened or unpeened condition. The eccentric-chuck type machines used in the investigation have drawbacks compared with constant load machines for this type of work.

Conclusions. In circumstances where contamination by iron shot is likely to lead to corrosion, aluminium alloys may be successfully peened with aluminium alloy shot.

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