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Effect of intermittent polishing on low-cycle fatigue of pure aluminium

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Low-cycle fatigue tests of aluminium were interrupted in order to remove surface roughening and superficial cracks produced by prior loading. Depending on the frequency of intermittent polishing and the strain level considerable increases in endurance life were observed.

Nomenclature

$\Delta\epsilon_t$ total strain range.
$\Delta\epsilon_p$ plastic strain range.
$\Delta\epsilon_e$ elastic strain range.
N_p the number of cycles at which the intermittent polishing is carried out (single-step tests).
N_{mp} the number of cycles at which the last intermittent polishing action is performed in addition to preceding ones in every 50 cycles (multi-step tests).
N_{pf} the endurance life in the case of intermittent polishing (single- or multi-step tests).
N_f the endurance life without intermittent polishing.

1. Introduction

With very few exceptions, fatigue cracks nucleate at the surface. The discovery of fatigue extrusions [1] in aluminium alloys and the investigations of persistent slip bands [2] have focused attention on the fatigue crack nucleation mechanism. The importance of such surface phenomena was confirmed by demonstrating a definite extension of high-cycle fatigue life through polishing of these bands at regular intervals during testing [3, 4]. There are many other investigations establishing the fact that the cyclic plastic deformation becomes confined to reversible persistent slip bands. The persistent slip bands on the surface produce extrusions and intrusions. Such a surface roughening by concentration of cyclic deformation inside bands is a phenomenon common to all non-brittle materials and crack nucleation generally occurs at the boundaries of extrusions [5].

In the present investigation, the effects of removal of surface roughening and superficial cracks produced by low-cycle fatigue of aluminium on the endurance life are studied.

2. Experimental procedure

The tests were made at room temperature by reversed bending of a cantilever beam specimen with a frequency of 100 cycles $\min^{-1}$ under constant deflection conditions. The specimens were cut from extruded shapes of 99.6 wt% pure aluminium. A waist was introduced near one end by milling (Fig. 1). Subsequently the specimens were annealed at 400° C for 30 min. The final operation was the mechanical polishing to a 320-grit finish of the waisted area, parallel to the longitudinal axis of the specimens. Fig. 2 shows schematically the total strain range, with its elastic and plastic components, to which specimens were subjected. The total strain range was calculated from the deformation measured microscopically by the aid

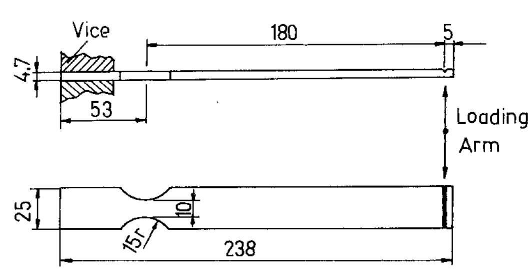

Figure 1 Schematic diagram of the test specimen (dimensions are in mm).

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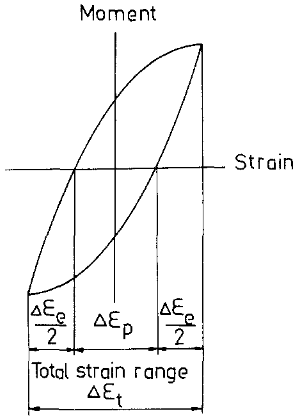

Figure 2 Schematic representation of a stabilized hysteresis loop.

of two marks closely spaced (500 μm) at the narrowest section. Total strain ranges chosen for the experiments were 0.9, 2.1, and 3.2%. The endurance life is taken as the number of cycles to the collapse of the bending moment due to full cracking indicated by means of a dial-gauge contacting the specimen at a point 5 mm from the vice. Triplicate tests were run and averaged for each testing condition.

For removal of surface roughening and of superficial cracks produced by cyclic plastic deformation, the tests were interrupted, in order to abrade the flat surfaces of the narrowest section with 320-grit silicon carbide paper. Each repolishing action resulted in a thinning of the test section by about 0.02 mm. The ivestigation included both single- and multi-step tests, i.e., repolishing only at a chosen cycle or every 50 cycles.

In order to check whether residual stresses produced by intermittent polishing have any effect on the endurance life, one set of specimens was stress relieved by annealing after repolishing, and

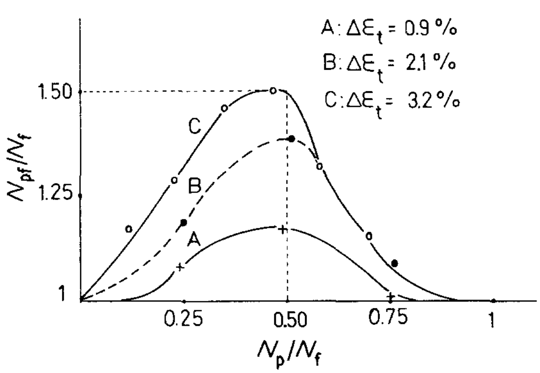

Figure 3 Graphical representation of results of single-step tests.

TABLE I Variation of N_f with $\Delta\epsilon_t$

$\Delta\epsilon_t$ (%)	N_f (cycles)
0.9	5150
2.1	968
3.2	428

tested under identical conditions with specimens not stress relieved. The results have shown no significant effect due to stress relieving.

3. Results and discussion

Fig. 3 shows the results of the single-step tests, based on data given in Tables I and II. It will be noted that the endurance life increases due to intermediate polishing and the increase reaches a maximum at the ratio N_p/N_f of about 0.50. This phenomenon can be attributed to the following effects:

(a) The removal of the surface roughening reduces the stress concentration factor. Further cycling produces less roughening since the material has already been work-hardened.

(b) Some of nucleated cracks are eliminated, and those which can not be totally removed become shorter.

(c) Less-strained fresh material is exposed at the surface.

Nevertheless, it must be explained how the removal of material, 0.02 to 0.03 mm thickness, at about 0.5 N_f, can be so effective. In fact, around these cycles, cracks with lengths of the order of 0.2 mm were observed during the tests. It is also observed that cracks nucleating first and propagating perpendicular to the longitudinal specimen axis do not lie in the same plane. They are joined at later stages by new cracks parallel to the axis, which might be called secondary cracks. In this case, the

TABLE II Results of single-step tests

$\Delta\epsilon_t$ (%)	N_p (cycles)	N_{pf} (cycles)	N_p/N_f	N_{pf}/N_f
0.9	1250	5558	0.24	1.08
0.9	2500	6003	0.49	1.17
0.9	3750	5167	0.73	1.00
2.1	250	1174	0.25	1.19
2.1	500	1371	0.51	1.39
2.1	750	1078	0.76	1.09
3.2	50	502	0.12	1.17
3.2	100	552	0.23	1.29
3.2	150	625	0.35	1.46
3.2	200	640	0.47	1.50
3.2	250	565	0.58	1.32
3.2	300	492	0.70	1.15

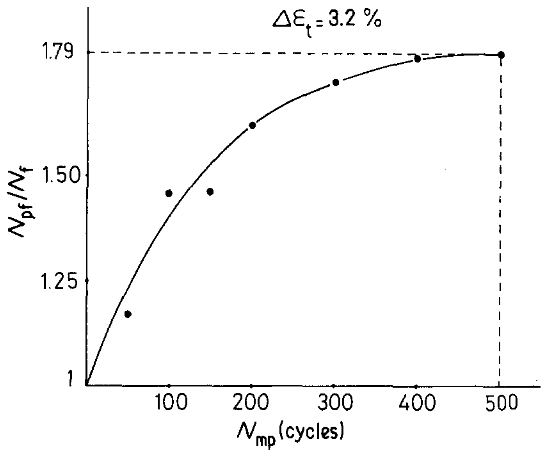

Figure 4 Graphical representation of the results of multi-step tests.

effects (a), (b) and (c) mentioned above retard, in particular, the formation of secondary cracks and, thus, the failure. Another interesting point is that the increase in endurance life due to intermittent polishing is more pronounced at high strain levels; for example, a maximum of 50% at $\Delta\epsilon_t = 0.2\%$, whereas only 17% at $\Delta\epsilon_t = 0.9\%$. This indicates that with increasing strain level, the damage is more concentrated near the surface, which then can be eliminated largely by repolishing.

Fig. 4 shows the results of the multi-step tests based on data given in Tables I and III. It will be noted that the maximum increase in endurance life is greater than that obtained in the single-step tests performed for $\Delta\epsilon_t = 3.2\%$, and indeed is 79% instead of 50%. This is probably because the effects of (b) and (c) are increased with regard to both primary and secondary cracks. On the other

TABLE III Results of multi-step tests

$\Delta\epsilon_t$ (%)	N_{mp} (cycles)	Steps	N_{pf} (cycles)	N_{pf}/N_f
3.2	50	1 × 50	502	1.17
3.2	100	2 × 50	625	1.46
3.2	150	3 × 50	624	1.46
3.2	200	4 × 50	695	1.62
3.2	300	6 × 50	736	1.72
3.2	400	8 × 50	760	1.78
3.2	500	10 × 50	766	1.79

hand, the decreasing slope of the curve points to a damage accumulation in the sub-surface which cannot be eliminated. It is obvious that the shape of such curves and the resulting N_{pf}/N_f values should be dependent on the frequency of intermittent polishing during the endurance life corresponding to a certain strain level.

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