JOURNAL OF APPLIED ELECTROCHEMISTRY 4 (1974) 229–234

*Effect of surface finish obtained by electrochemical machining on the fatigue life of some titanium alloys**

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Received 1 February 1974

Electrochemical machining (ECM), depending upon the conditions of operation, may bring about a variety of surface finishes. This is particularly true for electrochemically machined titanium and its alloys, and as it is known that surface defects act as stress-raisers, a study of fatigue life was made. A number of different surface finishes was obtained in a study of the dissolution of titanium alloys, and these will be discussed in terms of the metallography of the alloy and of the machining conditions. For example, differential dissolution and hence a poor, uneven finish was frequently obtained in the case of the two-phase alloys under conditions where the single phase alloys showed a bright finish. Using a vibration generator producing a constant bending moment at mains frequency, the effect of electrochemically machined surface on fatigue life was found to be only small although samples with surfaces damaged by intergranular oxidation or by sparking showed reduced lives.

1. Introduction

1.1 *Fatigue failure and the importance of surface finish*

The theory of fatigue failure is now well-documented [1]. Two main stages have been identified, the first being that of crack initiation, where slip bands in the metal migrate and coalesce to bring about extrusion and intrusion [2], and hence deformation of the surface. This produces stress raisers in the surface and the production of cracks. This is followed by the second stage, that of crack propagation, which is a process of plastic deformation alternating with shearing and is characterized by the markings left on the fracture surface of the failed component.

After a slip band has formed, the dislocations no longer exist in the bulk of the material, having been dissipated at the surface or at a grain boundary. Thus there is no interior evidence that slip has occurred and it has been shown that partially fatigued specimens may be rejuvenated by removal of surface layers [3]. This suggests that surface preparation plays an important part in the fatigue life of a component. Simple stress considerations lead us to anticipate a longer fatigue life from an electropolished component than from a pitted one or one with grain boundary dissolution. Concentration of stress occurs more in association with a notch than with a hollow and more with a single defect than with a series of them. Thus if we are unable in electrochemical machining (ECM) to produce the perfectly flat surface, a surface is frequently acceptable which is made up from continuous shallow hollows or pits. In fact, a theory of electropolishing [4] suggests that the polished surface arises from the merging of many bright-bottomed pits.

1.2 *Different surfaces obtained by ECM*

Unpublished studies in this laboratory on the efficiency of dissolution of some titanium alloys,

* Presented at the First International Conference on ECM held at Leicester University, 26–27 March 1973

produced surfaces ranging from bright to dull and coral-like. The efficiencies of the dissolution based on a four-electron process,

$$Ti \rightarrow Ti^{4+},$$

were frequently in excess of 100%, suggesting that perhaps particles of undissolved metal were being removed from the anode by the undermining of grains. The removal of material in this way is an extreme example of etching when the grain boundaries have dissolved much more rapidly than the grains themselves. Etching was one of a number of surface finishes identified by Hoar and co-workers [5, 6] and set out in a diagram of anode potential against electrolyte concentration. The Hoar diagram [7] is a very general plot and the demarcation lines are usually ill-defined. For example, see Fig. 1, a zone of

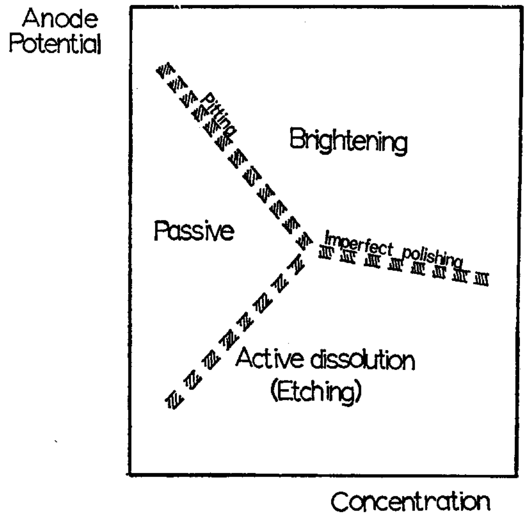

Fig. 1. The regimes of different surface finish obtained in anodic dissolution.

imperfect polishing or mild grain boundary attack may be seen between etch and polish; and pitting, often blending into a zone of bright hemispherical pitting, is usually found between passivity and polish. With a knowledge of the Hoar diagram, it may be possible to select machining conditions that avoid the undesirable pitting and intergranular etching. To date, however, it has not been possible to identify the polish regime for the titanium alloys, and the purpose of the present work was to study the effect that poorer surface finishes may have on the fatigue life of samples formed from titanium alloys. In addition comparison was made with samples prepared mechanically, with some prepared mechanically and then stress-relieved, and with some prepared by electrochemical grinding.

2. Experimental

2.1 *Materials used*

Laboratory reagent-grade potassium bromide 98·5%) and sodium chloride (99·5%) were used with tap water to form the electrolyte. The titanium alloys used are shown in Table 1. The figures refer to percentage constituent; the balance is titanium.

Table 1. *The composition of the titanium alloys*

IMI 130	Commercially-pure titanium
IMI 230	Ti-2.5Cu
IMI 550	Ti-4Al-4Mo-2Sn-0.5Si
IMI 685	Ti-6Al-5Zr-0.5Mo-0.25Si

IMI 130 and 230 are single-phase (α) alloys, 550 is a two-phase ($\alpha+\beta$) alloy and 685 is a 'near α', i.e. a predominantly single-phase alloy with a small amount (cement) of β. The 130 and 230 alloys were received from the manufacturers in the form of 20 mm diameter bar in the 'annealed' state, the 685 as 25 mm bar and the 550 as 50 mm bar after being heat-treated by oil-quenching from 1050°C followed by ageing for 24 h at 550°C. The samples were cut longitudinally from the bars.

2.2 *Experimental procedure*

The test specimens were 1·27 mm thick and are shown in Fig. 2. The shape was chosen to facilitate the preparation of the different surfaces and to impart a high sensitivity to surface finish. The long edges were bevelled to enable the samples to be held for the purpose of electrochemically machining and grinding. (During this process the sides of the neck of the sample were insulated with a stopping-off lacquer to avoid rounding and hence dimensional uncertainties in the test pieces.) The rounded end was clamped

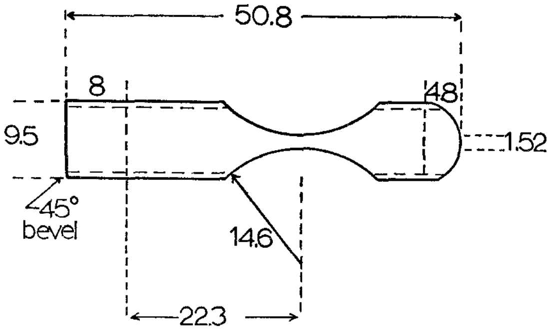

Fig. 2. The fatigue test specimen (dimensions in mm).

to the mark shown and the other end was pivoted at the mark between knife-edges. Fretting at this point was avoided by inserting slim rubber pads. The stress at the neck minimum, l (22·3 mm), was given by

$$\sigma = \frac{6lw}{bh^2} \quad (1)$$

where w is the applied load, b the width of the neck and h the height (thickness) of the sample. During development of the technique, specimens with a much wider neck width were contemplated such that the top and bottom surfaces to be stressed were very much the major surfaces. However, because of the high strength of the titanium alloys, the narrower section sample was used which introduced possible side-wall effects.

Samples were taken from the rolled bar by sawing and reduced to size and shape by milling followed by peripheral grinding. The surfaces were then finished mechanically with abrasive paper down to 600 grit. This treatment imparted a certain amount of surface stress to the sample, the degree of the surface work depending of course on the history of the material and thus producing considerable scatter in the fatigue results. A number of the mechanically-prepared samples were stress-relieved by heat treating in an argon atmosphere as follows. IMI 130 for 8 h at 425°C, 230 for $\frac{1}{2}$ h at 600°C, 550 for 4 h at 500°C, and 685 for 4 h at 550°C. Some of the mechanically prepared samples were heated in air at 900°C for an hour. This produced a good deal of oxidation, particularly at the grain boundaries, and produced a V-notching effect on the surface, the depth of which was found by electron microscopy to be 0·01–0·02 mm.

A number of samples were electrochemically machined on the upper surface for a few seconds in order to remove 0·1 mm of material. The electrolyte used was 2M KBr/1M NaCl [8] flowing through an initial gap of 0·5±0·05 mm at a current density of 50 A cm^{-2} and a cell voltage of 20±4 V. A variety of surface finishes were obtained for the different alloys. With an electrolyte flow of ~20 m s^{-1} the 130 and 230 alloys had a fairly bright, undulating surface of the type shown in Fig. 3a. (The undulations were about equivalent to the size of the grains). The 550 alloy gave the surface shown in Fig 3b and an increase in the electrolyte concentrations to 4M KBr/1M NaCl produced only a slight improvement. This surface is reminiscent of the microstructure of a longitudinal sample taken from 550 bar and indicates that extensive grain etching (differential dissolution) is taking place. This was checked by electrochemically machining a sample which had been heated through the martensitic transformation when a typical acicular α structure was observed. Electrochemically machined IMI 685 gave the surface finish shown in Fig. 3c, again similar to the microstructure. The surfaces exhibited in Fig. 3 can be related, therefore, with the active dissolution region of Fig. 1.

A batch of stress-relieved 550 samples were electrochemically ground on one face at 8 V (cell voltage) using the 2M KBr/1M NaCl electrolyte. This material proved to be difficult to EC grind due to sparking and minimum spark damage appeared to occur at ~8 V.

The fatiguing machine [9] shown in Fig. 4

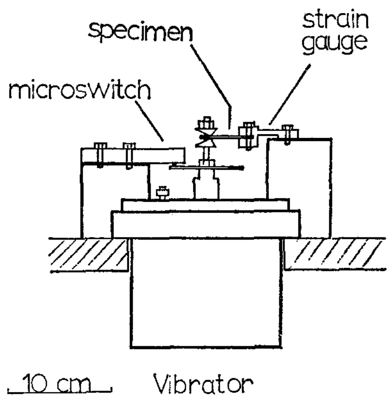

Fig. 4. The fatigue machine.

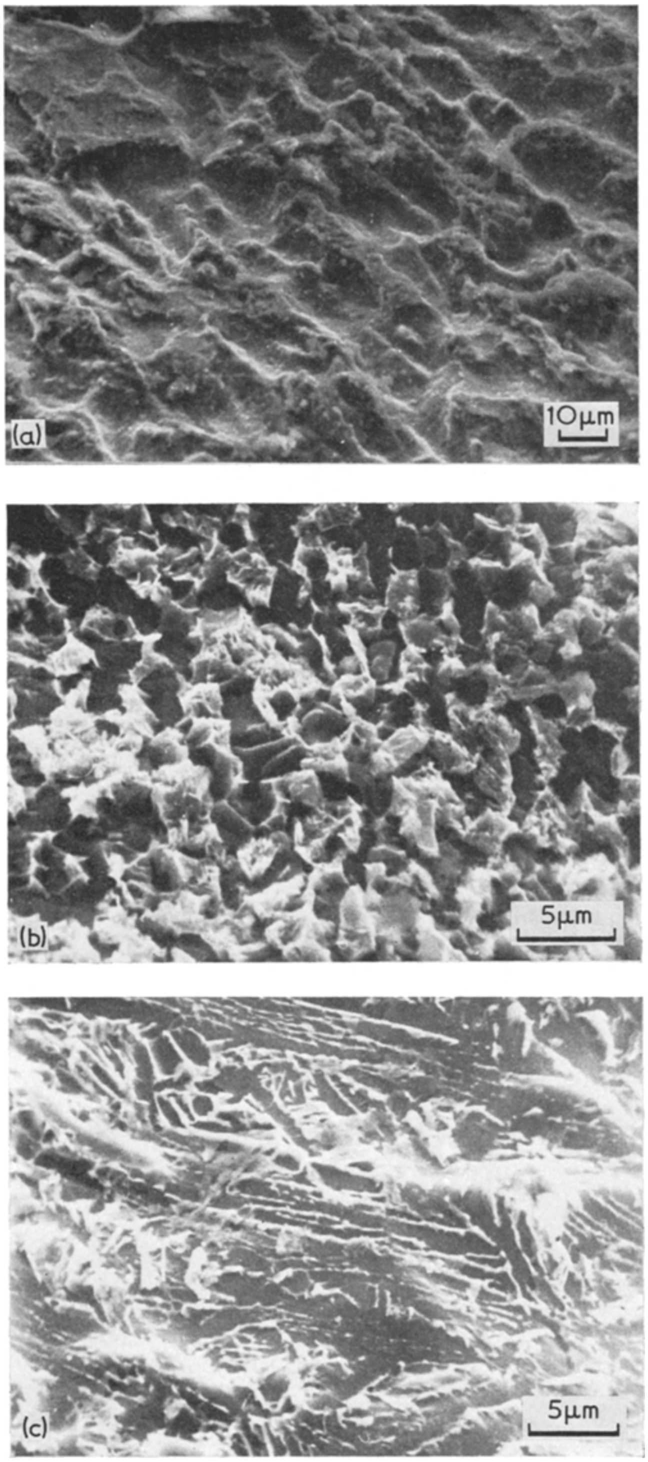

Fig. 3. Scanning electron micrographs of some electrochemically machined surfaces:
(a) Undulated surface of IMI 130
(b) 'Honeycombed' surface of IMI 550
(c) Etched surface of IMI 685

was an electromagnetic, mains frequency, vibrator. The sample was clamped at one end and bent between knife-edges at stresses measured with a strain gauge fixed to the clamp. Determinations with micro-strain gauges fixed to the neck of the specimen showed the surface stresses to be in good agreement with those calculated (within 20%). The strain gauge was first standardized against load and the factor, k used to relate stress, σ to micro-strain μe.

$$\mu e = \frac{2kbh^2\sigma}{6l}$$

The factor 2 arises because the measured μe is a peak-to-peak value and we are here interested in reporting the $\pm$ stress about a zero mean.

To count the number of cycles an electric clock was used which stopped automatically when the sample broke.

3. Results

The applied stress against number of cycles required to break the sample (S-N curve) for a selection of alloys following different surface treatments is shown in Fig. 5. For reasons of clarity most of the experimental points are excluded; the lines represent a best fit of at least twelve experimental points. The experimental scatter was such that it could not be determined if the plots should display 'knees' or if they should be continuous curves as shown.

4. Discussion

4.1 *Comparison with previous work*

Fuller [10] in 1949 recognized the fact that the fatigue life of titanium was sensitive to surface finish. The material was shown to display a far greater lowering of fatigue strength when notched than, for example, the steels. These findings were confirmed on slightly purer specimens [11]. Hanink [12] showed that shot-peening, a treatment administered to many steels in order to improve their fatigue resistance, affected some Fe-Cr-titanium alloys detrimentally. However, he noticed that fatigue strengths of notched specimens could be increased slightly by a stress relieve heat treatment.

The manufacturers of the alloys used in the present work, Imperial Metal Industries, Ltd., supply data sheets on their materials which give fatigue values for mechanically prepared specimens. However, the tests reported are for either a rotating-bending or for a direct stress, push-pull technique; the data cannot strictly be compared with the beam-bending technique used in the present work. The method was chosen because small specimens and flat surfaces were preferred for the ECM and EC grinding processes. At the same time the technique can be criticized because of the non-homogeneity across the sample of the applied stress (when one face is under compression the opposing face is under tension with a mean, zero, stress in the middle) and because of the possible uncertainty in crack propagation characteristics associated with the sidewalls. The order of the S-N curves obtained for the various alloys is, however, in agreement with that reported by IMI and in view of the difference in the techniques the numerical agreement

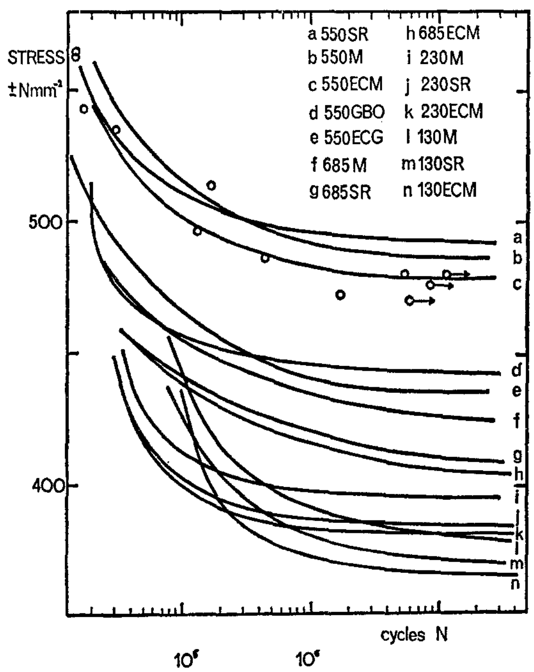

Fig. 5. S-N curves for some titanium alloys with various surface finishes:
M = Mechanical finish.
SR = Stress-relieved.
ECM = Electrochemically machined.
GBO = Grain boundary oxidation.
ECG = Electrochemically ground.
The experimental points relate to curve C.

of the fatigue limits for the 230 and 685 alloys is good (within 2%). The IMI data for the 550 alloy is poorly defined, i.e. the history of the material from which samples were taken is not given; the fatigue limit quoted by IMI is much higher than that found in the present work. The fatigue limit for IMI 130 presented here agrees with the upper limit of the range quoted by the manufacturers.

Other work on the alloys considered here includes a study of the effect of hydrogen dissolution on the fatigue behaviour of IMI 115 [13]. Hydrogen additions to this material (a commercially-pure Ti like IMI 130), which would be expected to have a detrimental effect on the tensile properties [14], were found to raise the S-N curve. Work on the effect of surface finish on fatigue life has been carried out on IMI 680 (Ti 11Sn 4Mo 2Al 0.2Si). This work [15] was concerned primarily with the effect of metallic coatings. Initial work, however, on the effect of mechanical finish emphasizes the importance to fatigue endurance limit of a finely machined or polished finish, but again the use of different techniques precludes comparison with the present work.

4.2 *Effect of surface finish*

A side effect of the mechanical treatment of metals: turning, grinding, polishing, etc. is to impart surface compressive stresses which usually increase the fatigue life of the metal. The stress-relieve heat treatment is seen to lower the S-N curve for the 130, 230 and 685 alloys. The S-N curve for IMI 550 is not lowered at all by the heat treatment; in fact it appears to be raised very slightly. This is probably because this alloy suffers surface micro-cracking in preparation; these defects are to some degree annealed out by the heat treatment. An increase in fatigue limit was found by Hanink [12] on stress-relieving a Ti-2.5Cr-1.4Fe alloy.

Electrochemical machining is a process for the removal of metal in which the surface remains stress free, and it is not surprising therefore to find the S-N curves very close to those of the stress-relieved samples. The slight lowering of the EC machined fatigue limit relative to the stress-relieved limit is probably brought about by the existence of pitting and etching, but it is seen that specimens prepared under normal ECM conditions give S-N curves essentially the same as those for the stress-free material. On the other hand samples (of IMI 550) which were deliberately oxidized to produce extensive grain-boundary notching, showed a much reduced S-N curve. A similar effect of extensive pitting is displayed in the curve for EC ground IMI 550 specimens. This material proved difficult to electrochemically grind and the spark damaged surface may be indicative of S-N curves expected from samples prepared by electro-discharge machining.

5. Conclusions

1. Surfaces obtained by ECM were etched at 'active dissolution' potentials, differential dissolution occurring in the case of the two-phase alloys. According to Hoar (Fig. 1), increase in anode potential may bring about brightening. As chloride solutions exhibit higher breakdown potentials on titanium than do bromides [8] further experiments with the two anions may produce better surfaces.
2. Mechanical preparation of specimens introduced compressive stresses into the surfaces which usually increased the fatigue life for a given stress.
3. Fatigue lives of electrochemically machined specimens were little different from the fatigue lives of those that were stress-relieved by heat treatment; EC machining merely acts as a surface stress relief treatment even though extensive differential dissolution may occur.
4. Deliberate over-exposure of IMI 550 to oxidizing conditions produced severe grain boundary attack which considerably reduced the fatigue life. Spark damage of this material also considerably reduced the fatigue life.

Acknowledgment

The author thanks the Ministry of Defence for financial support.

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