Journal of University of Science and Technology Beijing
1997, Vol.4, No.3: 18

Fretting corrosion of surgical 316L stainless steel in saline solutions *

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(Received 1997-05-01)

Abstract: A new simulation system for the laboratory investigation of fretting wear is developed. It consist of a mechanism device, a electrochemical cell and a datum acquisition and process software. Fretting of surgical 316L stainless steel in saline is studied. The results show that electrochemical corrosion is enhanced by fretting and anodic current density under fretting is 100 times than static condition. Fretting corrosion is a mechanic-electrochemical process.

Key words: fretting system, 316L stainless steel, saline solution

316L Stainless steel is now widely used as prosthetic devices (for the replacement of damaged parts of bone and joint that cannot be restored through treatment) or fixation devices (for holding bone parts in place until healing is established). As a self-passivating material, 316L SS is comparatively corrosion resistant because of the formation of a stable oxide film. However, 316L SS is subject to corrosive attack when the film is mechanically damaged. The fretting corrosion is a generally observed form of damage currently available alloy. Colangelo and Greene[1] had observed that more than 90% of implants of type 316 stainless steel showed corrosion attack when removed from the body and fretting corrosion was frequently found on these retrieved plates and screw implants.

Fretting is a wear phenomenon occurring when two contacting solids are subjected to a relative oscillatory tangential motion of small displacement amplitude[2] . This motion along the contact interface can result in the renewal of material by wear or in the initiation of cracks by cyclic contact stresses. Fretting can take place on all metal implants under relative motion between two components. Fretting corrosion can have significance for metallic surgical implants because it offers mechanisms of metal ion release in the body and of mechanical failure. It is therefore concluded that fretting corrosion is certainly a problem in orthopedic implants.

Someone had studied the fretting corrosion of implant alloys[3,4] , but they only evaluated the fretting corrosion resistance by weight loss, but the electrochemical behavior or frictional behavior of the 316L SS in fretting corrosion conditions is still unclear.

The purpose of the paper is to investigate the electrochemical, and friction process associated with fretting corrosion of 316L SS in bio-simulated solution.

1 Experimental

1.1 Fretting test system

The fretting corrosion tests were performed in an apparatus that was designed by authors. It consisted of 3 parts: an actuation mechanism for linear contact vibrations, electrochemical cell and a software terminal for acquiring mechanical data and electrochemical information on-line during fretting testing.

A small amplitude movement was produced by mechanical means, which translated rotational motion into linear displacement vibrations by eccentric flywheel. As shown in Fig. 1, the actuator is connected to shaft at which the long plate is attached. The fretting couple consisted of a ceramic (Si_3N_4) ball (ϕ6 mm) in contact with a flat round plate (radius 15 mm, 1 mm thick) which was mounted on the long horizontal plate. The upper ball specimen was fixed at the holder, which was placed at the end of the loading lever. The normal load was applied by weights. The frictional force was measured by strain gauges attached to the holder. The slip amplitude was detected by using a non-contact magnetic-resistance transducer. The machine can produce repeatable experimentation conditions. The displacement amplitude can be varied from 1 μm to 3 000 μm with a increment of 1 μm, and the normal force amplitude can be varied from 1 N to 100 N with a

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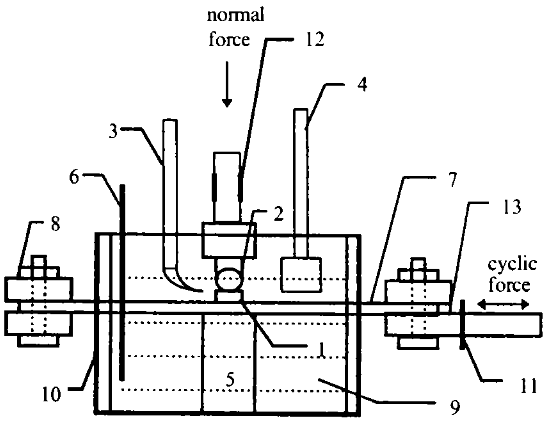
* Project Supported by the National Nature Science Foundation of China



1– specimen
2– rider
3– reference electrode
4– counter electrode
5– supporter
6– temperature controller
7– long plate
8– gripper
9– solution
10– perspex cell
11– displacement transducer
12– friction transducer
13– vibrating shaft

Fig.1 Schematic diagram of the fretting corrosion apparatus

minimum increment of 1 N. The possible fretting frequencies are in the range of 0.5 to 11 Hz.

In electrochemical study, flat round plate was as a working electrode. The reference electrode was a saturated calomel electrode (SCE), which was connected electrolytically through a Luggin capillary and placed very near to the ceramic-metal contact surface in the cell containing an electrolyte. A bright platinum was used as counter electrode.

The present fretting apparatus permits on-line monitoring of the mechanical and electrochemical response of a material contact subjected to fretting vibrations. The displacement, the normal contact force, the friction force and potential, current were measured as a function of time over the duration of one fretting cycle and over the total test time. The output voltage signals from the respective probes were sampled by a 12 bit analogue-to-digital converter and was conditioned by low pass filtering with a cut-off frequency of 15Hz before digitizing to eliminate the interfere of high frequency noise. The sampling was performed with a multiplex smoothing technique, resulting in synchronous acquisition of the 6 (or less) measured signals. The sampling frequency was varied from 1 to 1000 Hz.

1.2 Materials and method

The chemical compositions and its mechanical properties of the 316L stainless steel (ultimate tensile strength, 588 MPa; elongation, 46%) used in this investigation are give in Table 1. Prior to testing, the specimens were given a final polishing with 900 grit emery paper, then washed in running water, degreased in alcohol, rinsed thoroughly with deionized water and dried with cool air. A physiological saline solution (0.9%NaCl) was chosen as the test medium, all of the experiments were carried out at 37℃, pH7.2.

The experiment was carried out under the conditions of normal loads at 13 N, slip amplitude at 50 μm and a frequency of 10 Hz.

By fretting study at free potential, a specimen was placed in the electrolyte and allowed to stabilize for 10min. The rest potential was recorded. By other electro chemical study, the polarization potential was set at a pre-selected anodic value (e.g. rest potential) for 5 min, and then had a step change (30 mV) in the anodic direction. While at the set potential, the anodic current was measured every 5min. During the fretting test, the friction force and displacement were recorded for every cycle.

2 Results

2.1 Rest potential

When fretting began, the rest potential of 316L SS rapid falls towards negative direction and the potential change is about 100 mV. While as soon as fretting end, the potential changed towards noble direction. Fig. 2 shows the result.

2.2 Anodic polarization test

Fig. 3 shows the anodic polarization curve of 316L SS in static and fretting conditions. It is seen that the

Table 1 Chemical composition of 316L stainless steel (mass fraction) %

C	S	P	Cr	Ni	Mo	Si	Mn	Fe
0.021	0.002	0.031	17.61	12.45	2.29	0.69	1.05	balance

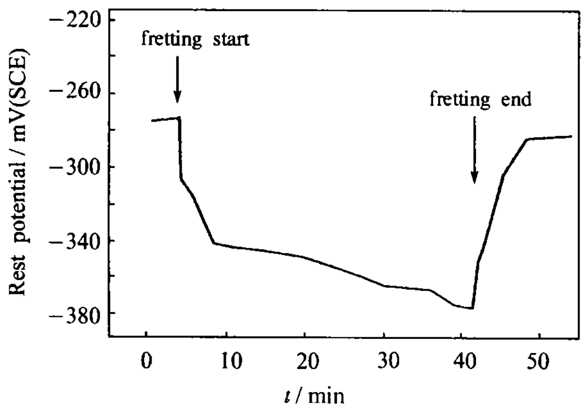


Fig.2 A typical rest potential-time plot for 316L SS in saline solution

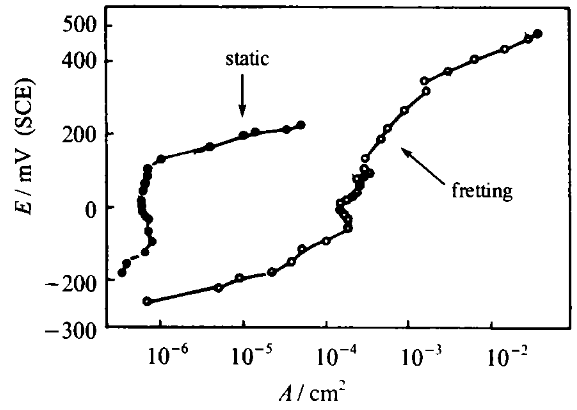


Fig.3 Anodic polarization curve for 316L SS in saline solution

passive region of polarization becomes narrow under fretting condition and corrosion current is 100 times than under static conditions.

2.3 Friction test

Fig. 4 shows the friction coefficient vs. displacement curve at varied cycles 1) $N=$ 10 cycles, 2) $N=10^4$ cycles, 3) $N=10^5$cycles. Fig. 5 shows the variation of the friction factor (Maximum friction force vs. normal force) with the cycles (N). From the Fig. 4, we can see that all the plots of friction factor vs. displacement is a elliptical cycle. The friction factor remains a constant values in initial stage of fretting process, and increase in $N=10^4$ cycles, then decrease (Fig. 5).

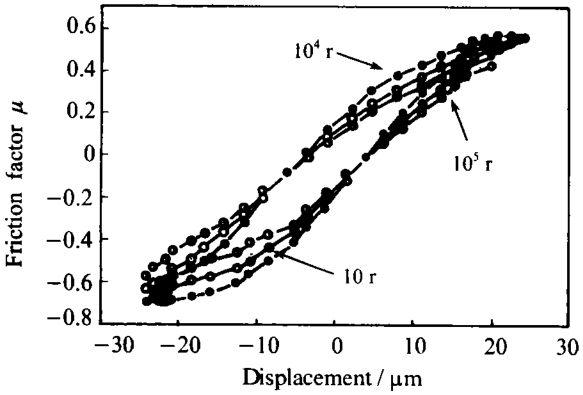


Fig.4 Fretting maps of 316L SS in saline solution (frequency, 10 Hz; displacement, 50 μm; normal force, 13 N)

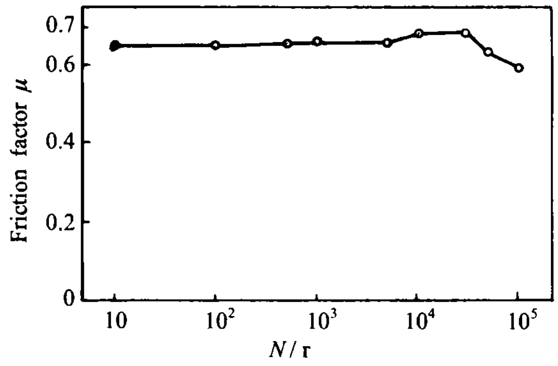


Fig.5 Friction factor of 316L SS in saline solution (frequency, 10 Hz; displacement, 50 μm; normal force, 13 N)

3 Discussion

The rest potential test shows that in the initial stage of fretting the friction between the ceramic ball and metal surface cause disruption of metal surface film giving rise to true metallic contact and possible metal deformation, rest potential immediate fall, metal more active, and the rest potential risen while the fretting finished. So it indicates the fretting is a corrosion process where film formation and disruption are in some kind of dynamic equilibrium. As we known, 316L SS is a inherently reactive metal and has notable protective oxide films, in normal aqueous environments (e.g. saline solution) the clean metal surface is sites of intense anodic activity. In fretting, the area of anodic activity is very small in comparison with the very large cathodic surroundings (the area ratio is about 1: 150 in this study), so severe corrosion in the anodic (fretting worn) regions is given rise to. Furthermore the fretting contact itself is similar to the crevice corrosion situation, fretting processes will be influenced by electrochemical reactions occurring at the metal surface, and conversely the electrochemical reactions will be profoundly influenced by fretting processes. As Fig. 3 showed, comparing with static conditions, the breakdown potential of 316L SS becomes more negative and there is an extreme narrow polarization zone under fretting. In another word, 316LSS is very susceptible to crevice corrosion. Obviously, 316L SS is extremely reactive, and if oxide film is removed or partial removed, very large corrosion rate will be produced.

As in Fig. 4 and Fig. 5, the friction test result shows that fretting corrosion of 316L stainless steel in this study (displacement, 50 μm; Normal force, 13 N; frequency, 10 Hz) is in mixed fretting regime; Fig. 6(a) shows the worn zone of the surface degradation after 10^5 for 316L SS in saline solution at 37℃. The contact surface displays a clear subdivision in a central stick area and a surrounding, annular slip area. The contact surface edge is degraded and ejected oxide debris could be observed at the contact edge. The center of the contact is absence of the wear, contact surface is corrode. Particularly in partial slip zone, there are some pits. Fig. 6(b) is the enlargement view of right bottom crack which reveals a long narrow crevice, and some pits lie in bottom of the crevice. It is noted that pitting corrosion or crevice corrosion can initiated in fretting conditions. This is due to fretting contact supplied a severe "crevice condition" which associates oxygen depletion and pH fall. At the same time, corrosion (especially pitting and crevice corrosion) accelerates fretting wear process. From these observations, it is apparent that fretting process of 316L SS is a mechanic-electrochemical corrosion process.

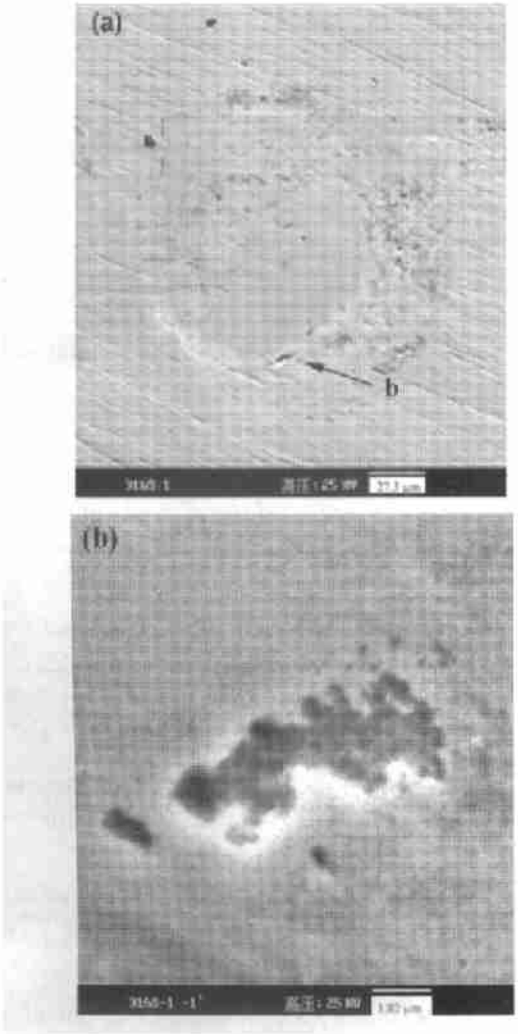


Fig.6 SEM view of the wear scar of 316L SS in saline (a) and the enlargement at the bottom b point (b) (experimental conditions as same as Fig.4)

4 Conclusion

(1) A new fretting corrosion machine is described and it is valid for investigation of fretting corrosion.

(2) 316L SS in saline solution shows substantial negative falls of free potential under fretting conditions. The corrosion current density increases 100 times due to fretting and fretting initiates the pitting corrosion.

(3) The fretting corrosion process of 316L SS in saline solution is a mechanic-electrochemical process.

References

1 Colangelo V, Green N. J Biomed Mat Res, 1969, 3: 247~265
2 Waterhouse R B. Int Mat Rev, 1992, 37: 77~97
3 Cook Stephen D, Gianoli Gerard J, Clemow A J T, etc. Biomat Med Dev Art Org, 1983~1984, 11(4): 281~292
4 Brown S, Merritt K. J Biomed Mat Res, 1981, 15: 479~488