Evolution of residual stress under fretting fatigue

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Fretting results from a small oscillatory relative displacement between two mating components in the presence of contact load. Under fatigue loading, this microscale slip induces surface damage and leads to an accelerated crack initiation which results in a shorter fatigue life as compared to conventional fatigue without fretting [1]. Residual stress at the surface region, which is often induced during manufacturing processes such as quenching, machining, and surface finishing, has been known to have an important effect on the fatigue behavior of materials. Normally, crack initiation and propagation are impeded by compressive residual stress under fatigue load, while tensile residual stress deteriorates fatigue strength by accelerating crack initiation and propagation. Therefore, techniques, such as shot peening [2], have been developed to intentionally induce compressive residual stress on the surface of the component to improve fatigue strength. There have been several investigations into the behavior of residual stress (i.e., evolution and/or relaxation of residual stress) on the surface of components under fatigue load [3–6]. The effects of residual stress on fretting fatigue behavior have also been demonstrated in previous studies [7, 8], in which compressive residual stress induced by shot peening led to longer fretting fatigue life of specimen as compared to unpeened specimen at a given stress level but this beneficial effect of residual stress was also reduced due to the relaxation of residual stress from fretting fatigue and/or exposure to elevated temperature environment. The present study is a continuation of previous studies to investigate into residual stress behavior during fretting fatigue. Unlike previous studies which focused on the relaxation of residual stress which was already present in titanium alloy, the present study investigated whether residual stress could develop on the surface of titanium alloy, Ti-6Al-4V under the fretting fatigue loading condition. Ti-6Al-4V is a common material used for aircraft turbine engine parts, such as blade/disk attachments, where fretting fatigue induced damage are often seen.

Specimens were machined from Ti-6Al-4V plate which was preheated and the solution treated at 935 °C for 105 min, cooled in air, vacuum annealed at 705 °C for 2 hrs, and then cooled in argon. Microstructure showed a nucleation of the α phase (HCP) in the β phase (BCC) matrix. The material had an elastic modulus of 119 GPa and a yield strength of 930 MPa. Specimens were machined to 17.8 cm long dog-bone shape with both width and thickness of reduced gage area of 6.4 mm. After machining, specimens were ground under low stress, and then polished by 600 grit silicone carbide. Residual stress on the surface of the specimen was completely removed by heat treatment at 704 °C for one hour in a vacuum. The complete relaxation of residual stress was confirmed by X-ray measurements after the heat treatment. Pads with a cylindrical end radius of 50.8 mm were also made of Ti-6Al-4V. Fig. 1 shows schematic drawings of both specimen and pad.

Constant amplitude fretting fatigue tests were conducted on a servo-hydraulic uniaxial test frame equipped with a rigid fretting fixture at a frequency of 10 Hz. The details of fretting fatigue test set-up and procedure can be found in previous studies [7, 8]. Two cylindrical pads were pressed against the width surface of specimen with a constant contact load of either 1335 or 4005 N via lateral springs which resulted in the peak Hertzian pressure of 292 or 506 MPa, respectively, in the contact region. The maximum and minimum applied cyclic stresses were 320 and 32 MPa,

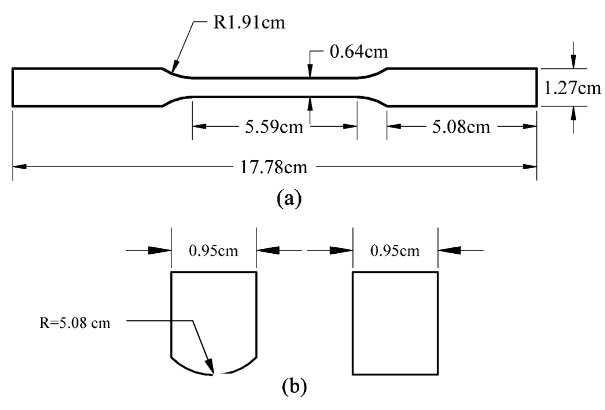

Figure 1 Schematic drawing of (a) specimen and (b) pad.

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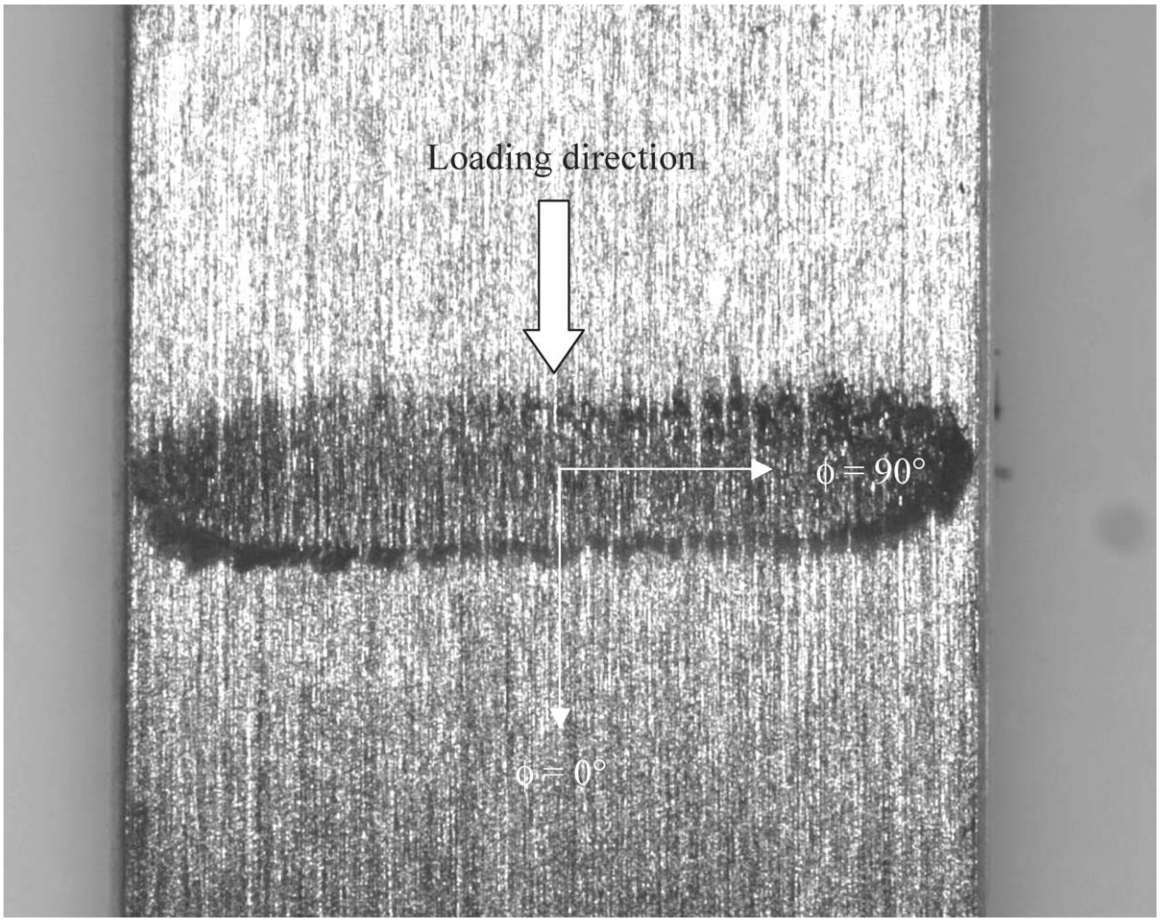

Figure 2 Typical contact region on the fretting fatigued specimen. Residual stress was measured along two orientations, $\phi = 0°$ and $90°$.

respectively. Several tests were conducted where specimen was subjected to a certain number of fretting fatigue cycles. After conducting fretting fatigue test up to a prescribed number of cycles, residual stress at the contact region was measured. Fig. 2 shows a typical contact region on the specimen surface after fretting fatigue. A commercial X-ray diffraction residual stress analyzer with two X-ray detectors covering both ψ_+ and ψ_- angles was used to measure the residual stress. X-rays from a copper K-α source, collimated to 2 mm diameter circular spot were used to examine the samples. Diffraction peak from (302) crystallographic planes of the alpha phase (HCP) of the Ti-6Al-4V alloy was utilized for all measurements. The changes in the d spacing were measured at seven ψ tilt angles and a plot of d vs. $\sin^2\psi$gas obtained. The slope of the curve determined from the least square fit to a line and the X-ray elastic constant of Ti-6Al-4V were used to compute the residual stress. Residual stress measurements were performed in two orientations, i.e., $\phi = 0°$ and $90°$ in Fig. 2, to investigate the directional dependency. The details of X-ray measurement can be found elsewhere [9].

The effect of residual stress on fretting fatigue life is shown in Fig. 3. Also the initial residual stress (i.e., before fretting fatigue test) is shown in this figure. The specimen which was prepared through machining followed by low stress grinding and polishing, but not subjected to any stress relief procedure before testing had initial compressive residual stress of 186 MPa on the

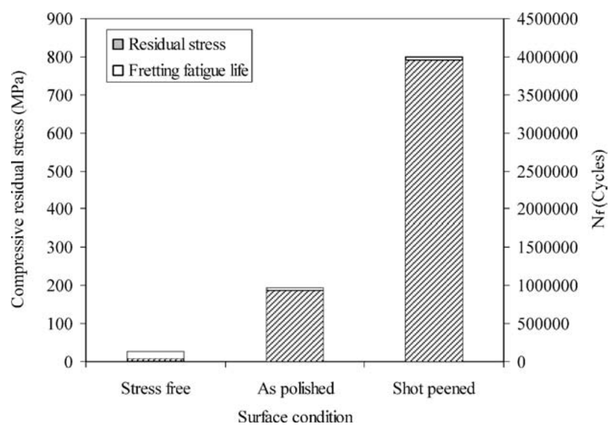

Figure 3 Fretting fatigue life dependency on residual stress.

surface. This is represented "As polished" in Fig. 3. Shot peened specimen in Fig. 3 was subjected to shot peening treatment after machining as per SAE Aerospace Material Specification (AMS) 2432 standard with 7 intensity Almen, using ASR 110 cast steel shots with 100% surface coverage. Shot peening induced compressive residual stress of 790 MPa on the surface. Several specimens, after machining, were subjected to simple heat treatment to relieve the residual stress from machining. These "stress-free" specimens had practically no residual stress on the surface, i.e., it was about 5 MPa. It can be clearly seen in Fig. 3 that specimens with higher initial compressive residual stress on the surface

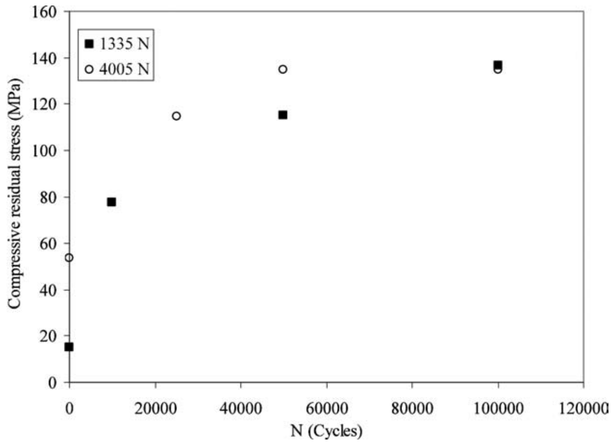

Figure 4 Compressive residual stress along the loading direction ($\phi = 0^\circ$) as a function of number of fretting fatigue cycles. Contact load was either 1335 or 4005 N.

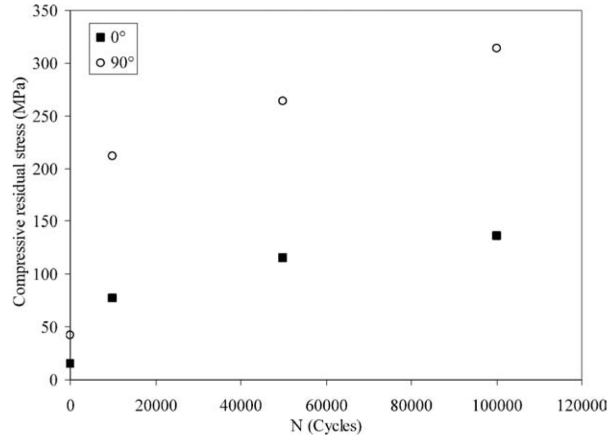

Figure 5 The evolution of compressive residual stress along $\phi = 0^\circ$ and 90° with cycling. The applied contact load was 1335 N.

had longer fretting fatigue lives. This clearly shows the beneficial effect of the compressive residual stress on the fretting fatigue life.

Fig. 4 shows the evolution of residual stress of initially residual stress-free specimens with increasing number of fatigue cycles. Residual stress was measured in a direction of $\phi = 0$, i.e., fatigue loading direction (Fig. 2). Zero number of cycles indicates a condition where only contact load was applied on the fretting pads before a fretting fatigue test, i.e., without any fretting fatigue cycle. The application of contact load is the first step in a fretting test. Applying contact load only induced compressive residual stress at the contact surface and higher contact load resulted in greater residual stress at the contact surface. As the number of fretting fatigue cycles increased, compressive residual stress increased and then stabilized at about 136 MPa for both applied contact loads after about 100, 000 cycles. However, specimens with a higher contact load (4005 N) showed higher residual stress at the earlier portion of fatigue cycles and they reached a stabilized value of residual stress faster, i.e., at about $N = 50,000$ cycles, than those with a lower contact load (1335 N), i.e., $N = 100,000$ cycles. It should be noted that the non-contact region of specimen did not show any change in the residual stress during test, i.e., residual stress on the surface remained at zero due to the plain fatigue condition only. Further, residual stress was not developed on the specimen surface when a plain fatigue test without fretting was conducted under exactly the same loading condition up to 100, 000 cycles. Considering that residual stress originates from misfits in the original shape between different regions and/or phases, it can be postulated that the evolution of compressive residual stress during fretting fatigue is primarily caused by the application of contact loads in the contact region, which caused non-uniform deformation in the contact region, and the degree of deformation increased as the higher contact load and more number of cycles were applied. However, this non-uniform deformation would not occur without the presence of contact load. Therefore, conventional fatigue without fretting did not show any residual stress evolution during plain fatigue cycling.

Fig. 5 compares the evolution of compressive residual stresses along two directions (i.e., longitudinal, $\phi = 0^\circ$ and transverse, $\phi = 90^\circ$, in Fig. 2) under the contact load of 1335 N. It can be seen that the measured residual stresses along the transverse direction of $\phi = 90^\circ$ were much higher than those in the longitudinal direction of $\phi = 0^\circ$ at a given number of fatigue cycles. Similar directional difference of residual stress was also observed when residual stress was intentionally induced by a low plasticity burnishing (LPB) surface treatment, in which a hard ball was pressed against the surface of the component with enough contact force to produce deformation and moved over the target area. This LPB also induced significantly higher or lower, depending on treatment variables, compressive residual stress along the normal to the moving direction than that along the moving direction [9]. Fretting action in the contact region can be regarded to have the same deformation mechanism as LPB since a pad moves to and fro on the specimen surface in the loading direction during fatigue. This relative movement of pad in the contact region would induce relatively more flow of material in a particular direction which could result in the directional difference in the compressive residual stress.

In summary, the evolution of residual stress from a stress free Ti-6Al-4V during fretting fatigue was observed. Fretting fatigue life was significantly reduced for the stress free specimen as compared to ‘as polished’ and ‘shot peened’ specimens. Compressive residual stress first appeared from the application of contact load only, increased with increasing number of fatigue cycles, and then reached a stabilized value at 50, 000 or 100, 000 cycles depending upon the applied contact load. Higher contact load induced faster increase in residual stress at the beginning but stabilized residual stress was the same as in the case of the lower applied contact load. Residual stress measurements in different directions showed that greater residual stress was developed along the normal than along the fatigue loading direction. Finally, it should be mentioned that residual stress from shot peening also relaxes during fretting fatigue [7, 8]. Thus, it appears that fretting action has an interesting role on residual stress. It can develop or relax the residual stress. Further studies are needed to look into the conditions which cause these conflicting phenomena.

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