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Fretting wear behaviour of surface mechanical attrition treated alloy 718

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ABSTRACT

Alloy 718 was subjected to surface mechanical attrition treatment (SMAT) using SAE 52100 steel balls of a 5 mm diameter for four different treatment durations (15, 30, 45 and 60 min). Fretting wear tests were conducted at different normal loads on untreated and treated samples for 25,000 cycles using alumina as a counterbody material. Microstructural features of the surface layer of samples treated by SMAT were characterized by cross-sectional optical microscopy and transmission electron microscopy. Hardness, surface roughness and residual stress were determined using a nano-indenter, surface roughness tester and X-ray residual stress analyzer respectively. SMAT resulted in the formation of nanocrystallites on the surface and near surface regions, increased hardness, increased surface roughness and compressive residual stress at the surface. Treated samples exhibited lower tangential force coefficient (TFC) compared to untreated samples. Samples treated for 60 min exhibited higher grain refinement, higher hardness, lower surface roughness and higher TFC compared to the samples treated for 30 min. The wear volume and wear rate of samples treated for 30 min were lower compared to those of the untreated samples, which may be attributed to an optimum combination of hardness and toughness and a low work hardening rate of the nanocrystalline structure at the surface of the treated samples. In contrast, the wear volume and wear rate of the samples treated for 60 min were higher than those of untreated samples, presumably due to the higher hardness and reduced toughness of the samples treated for 60 min.

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1. Introduction

Nickel-based superalloys exhibit an excellent mechanical strength and creep resistance at high temperatures, and corrosion/oxidation resistance. These alloys have been used extensively in aircraft gas engines, rocket engines, nuclear power plants, petrochemical equipment and offshore industries [1].

Alloy 718 is a nickel based precipitation hardenable superalloy, particularly developed for medium temperature range aerospace applications. The major industrial applications of alloy 718 include aircraft/industrial gas turbine components such as discs, bolts, shafts, cases, blades, vanes, combustors, afterburners, thrust reversers etc., steam turbine power plant components such as bolts, blades, stack-gas reheaters etc. and nuclear power system components such as control rod drive mechanisms, valve stems, springs, ducting etc. [1]. It is well established that the introduction of compressive residual stresses and strain hardening in the surface layer of these components could significantly increase their fatigue resistance and wear resistance. The essential surface layer properties can be obtained by surface treatment processes.

Fretting is described as the oscillatory relative tangential movement which contacting surfaces may experience as a result of vibration or cyclic stressing of one of the surfaces. It is often the origin of catastrophic failures or loss of functionality in many industrial applications [2]. Lee and Kim [3] studied the fretting wear behaviour of steam generator tube materials such as alloys 600MA and 690TT against ferritic stainless steels in room temperature water environment. The results indicated that the fretting wear rate of alloy 600MA was higher than that of alloy 690TT with increasing normal loads and sliding amplitudes. Kim and Kim [4] studied the fretting wear behaviour of Zircaloy 4 against alloy 600. The results indicated that wear damage increased with load, slip amplitude and number of cycles but was affected mainly by the slip amplitude. Lim et al. [5] studied the fretting wear behaviour of alloys 690 and 600 against AISI 304 stainless steel in room temperature water environment. This study showed that alloy 690 exhibited lower friction forces and lower wear resistance compared to alloy 600 in room temperature water.

In recent decades, improving the fretting wear resistance of materials has always been a major challenge for material scientists due to its importance in industrial application. Surface modification is expected to be a good way to improve tribological properties, especially the fretting wear resistance of conventional materials. Some surface modification techniques including ion-implantation [6–8], laser beam quenching [9] and plasma electrolytic oxidation [10] have been studied experimentally and identified as the promising methods to improve the ability of materials resisting the fretting damage. In recent years, a new

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surface modification process based on severe plastic deformation (SPD) technique, surface mechanical attrition treatment (SMAT) has been developed, by means of which a nanocrystalline surface layer on bulk metals can be achieved. This technique has been proven to enhance the tribological properties of materials such as AISI 52100 steel [11], copper [12], AZ91D Mg alloy [13], etc.

Sanda et al. [14] studied the effect of ultrasonic shot peening parameters (treatment time, material and quantity of shot balls and distance between radiating surface and sample) on residual stress induced in alloy 718. They reported that with increasing treatment time and reducing the distance, compressive residual stress of higher magnitude was induced in alloy 718. However, the compressive residual stress reached a saturated value after a certain treatment time. Use of higher quantity of balls resulted in lower compressive residual stress. Hessert et al. [15] reported that deeper compressive residual stress can be achieved in ultrasonic impact treatment compared to conventional shot peening, with lower level of surface roughness. Mukhtarov et al. [16] processed bulk nanostructured alloy 718 through multi-axis forging and high pressure torsion SPD processes and reported enhancement in the hardness and thermal stability of the nanostructured alloy.

The studies pertaining to fretting wear performance of Nickel-based alloys have been carried out either without surface modification to the alloys, or they are applicable to a very specific engineering application. An in depth understanding of the fretting wear characteristics of these materials with surface modification is very much required. In this paper the effect of SMAT duration on alloy 718, in terms of its microstructure and its response to fretting wear behaviour under dry condition, a situation more frequently encountered in many practical engineering applications is examined.

2. Experimental procedures

The chemical composition (wt.%) of the material alloy 718 used in the present study was Ni 53, Cr 18.2, Nb 5.08, Mo 3.13, Ti 0.97, Al 0.51, Si 0.12, C 0.02, B 0.003, S 0.002, P 0.005 and Fe balance. Alloy 718 was subjected to solutionising followed by a double ageing treatment (i.e. solutionising at 1095 °C for 1 h and then air cooling, followed by holding at 720 °C for 8 h and furnace cooling to 620 °C, subsequently holding at 620 °C for 8 h and then air cooling). The material had the following properties: elastic modulus = 208 GPa, Poisson's ratio = 0.29. Alloy 718 plates ($80 \times 10 \times 6$ mm^3) were subjected to SMAT using surface nanocrystalization equipment (Model: SNC1, Chengdu SNC Advanced Technology Co., Ltd., China). The schematic and methodology of SMAT were given elsewhere [17,18]. Before carrying out SMAT, all samples were polished by using four grades of silicon carbide abrasive papers followed by alumina polishing and then finally cleaned with acetone. The SMAT process was carried in vacuum (−0.1 MPa) with SAE 52100 steel balls of a 5 mm diameter for four different durations (15, 30, 45 and 60 min) at a vibrating frequency of 50 Hz.

Cross sections were polished by using silicon carbide abrasive papers (grit sizes of 400, 600, 800 and 1000) and diamond paste of 0.25 μm. Finally etching was done at room temperature with Kalling's reagent. The cross sectional structure was examined using an optical microscopy (Laborlux 12 ME, Leitz, Germany). Surface roughness measurements on the treated and untreated samples were done using a surface profilometer (SJ 301, Mitutoyo, Japan). X-ray diffraction (XRD) was done on the surface of treated samples using an X-ray diffractometer (XD-D1, Shimadzu, Japan) with Cu K_α radiation. The average crystallite size and mean microstrain were calculated from the broadening of Bragg diffraction profiles by using pseudo-voigt function. The residual stresses in untreated and treated samples were measured by using an XRD residual stress analyzer (Xstress 3000, Stresstech, USA). Nanoindentation hardness was measured just below the treated surface using a nanoindenter (Triboscope, Hysitron Inc., USA) at a load of 10 mN. Microstructural studies were done using a transmission electron microscope (CM 12, Philips, USA) operating at 120 kV. Thin foils of the sample were cut along the direction parallel to the treated surface using a low speed diamond saw cutting machine. Foils were mechanically polished from the untreated surface side to a thickness of 100 μm (i.e. only the side opposite to the treated surface was polished) and followed by dimpling to a thickness of about 50 μm. Subsequently, final thinning was carried out on the untreated surface side to electron transparency by ion milling. Similar sample preparation techniques have been reported in case of SMAT treated samples such as pure copper [19] and Mg alloy AZ91D [20] to make observations on the top surface of the treated samples.

Fretting wear tests were carried out on samples of size of $10 \times 10 \times 6$ mm^3. These samples were cut from the plates subjected to SMAT for 30 and 60 min. For reference fretting wear tests were also done on untreated samples. Test rig works on scotch yoke mechanism and full details about the test rig were given elsewhere [21]. Dead weight loads were used to apply five normal loads (1.96, 4.9, 9.8, 14.7, 19.6 N). All tests were conducted at a constant frequency of 5 Hz, displacement of 50 μm and up to 25000 fretting cycles. Tests were conducted in ambient air (relative humidity of 80 ± 5% and temperature of 303 ± 5 K). The counter body was alumina ball of a 10 mm diameter to establish a ball on flat contact on the flat test samples. The properties of alumina ball are: hardness = 1950 HV, elastic modulus = 382 GPa, and Poisson's ratio = 0.24. The values of friction force (tangential force) and displacement were acquired continuously at regular time intervals and stored by a data acquisition system. Friction loops were plotted between tangential force and the imposed displacement. The value of tangential force coefficient (TFC) was calculated by dividing half of the difference between maximum and minimum tangential forces obtained in a friction loop by the corresponding normal load used. Fretting wear scars in the tested samples were observed under a scanning electron microscope (FEI Quanta 200, Philips, USA) and their dimensions were measured along the parallel and the perpendicular directions to the fretting direction. Fretting wear volume was calculated using equations derived by Kalin and Vizintin for a ball on flat contacts [22]. Wear rate was calculated by dividing the wear volume by the normal load and the displacement.

Initial maximum Hertzian contact pressure (P) and initial contact radius (a) were calculated using Eqs. (1) to (3) based on Hertz theory [23].

$$P = \sqrt[3]{\frac{6NE^{*2}}{\pi^3 r^2}} \tag{1}$$

where

$$\frac{1}{E^*} = \frac{\left(1-\gamma_1^2\right)}{E_1} + \frac{\left(1-\gamma_2^2\right)}{E_2} \tag{2}$$

$$a = \sqrt[3]{\frac{3Nr}{4E^*}}. \tag{3}$$

N is the normal load, E_1 and γ_1 are the elastic modulus and Poisson's ratio of flat specimen (untreated or SMAT treated sample), E_2 and γ_2 are the elastic modulus and Poisson's ratio of counterbody material (alumina), E^* is the composite elastic modulus and r is the radius of the ball (5 mm).

3. Results and discussions

3.1. Microstructure

Cross-sectional optical micrographs of samples after SMAT for two different durations (30 and 60 min) are shown in Fig. 1. Severe plastic deformation could be observed in the near surface layer. A similar

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