

The effect of specimen temperature on the fretting wear behaviour of a non-nitrided against nitrided high strength alloy steel contact pair

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Abstract. The fretting wear performance of the heterogeneous non-nitrided against nitrided contact pair of the high strength alloy steel, SCM440 was investigated in the gross slip regime at ambient and elevated temperatures (120 and 150 °C). The tests were performed with displacement amplitudes of 25 and 100 µm at an applied normal load of 250 N using a cylinder-on-flat configuration. As the fretting contact temperature increases, the energy dissipation and total wear volume decreases for the same applied normal load irrespective of the displacement amplitude. The energy dissipation increases with increase in displacement amplitude for the same applied normal load. During fretting at ambient temperature, a substantial loss of material as wear debris was observed in the contact, whereas the overall loss of material from the contact significantly reduces with an increase in temperature. The variation in the tangential force coefficient and the total wear volume at elevated temperatures may be attributed to the sintering of oxide particles in the contact to form a protective debris bed. The worn surface morphology of the fretted specimen investigated using a scanning electron microscope shows the presence of wear debris in the wear track, oxide patches, delamination cracks, delamination cavities and discontinuities, scale like topography and plate-like wear debris. The abrasive action of the particles in the contact interface promoted wear at ambient temperature whereas at elevated temperatures, the compaction of the oxide particles reduced the wear.

Keywords: Fretting wear, high strength steel, wear mechanism, temperature

1. Introduction

Fretting wear is a surface degradation phenomenon, predominant in quasi-static loaded assemblies of machine elements and engineering structures subjected to small amplitude relative oscillatory motion occurring between two normally loaded contacting solid surfaces as a result of cyclic loading [1]. The influence of elevated temperature on the friction and wear performance of different types of steels in an unlubricated environment under fretting loading conditions have been examined by previous researchers and it has been reported that the fretting wear decreases with an increase in temperature [2-5]. Researchers have observed an abrupt decrease in wear rate once the temperature is increased beyond 200 °C, commonly referred as the transition temperature for austenitic stainless steels [2] and mild steels [3, 4] which can be attributed to the difference in the properties of the oxide formed at the contact interface. In the fretting wear process, the adhesion wear mechanism becomes more effective with



increasing interface contact temperature [2-4]. Experimental investigations by Hurricks [3, 4] on mild steel showed that the decrease in the wear rate with temperature may be attributed to the transformation in oxide structure where a spinel Fe_3O_4 structure becomes more thermodynamically stable above 200°C than a rhombohedral Fe_2O_3 (α - Fe_2O_3) structure and that Fe_3O_4 is more effective in preventing wear compared to α - Fe_2O_3 ; as Fe_3O_4 adheres more strongly to the surface, then acts as a solid lubricant. The formation of oxide at the contact interface and its separation from the surface are the two main processes of oxidative wear. Oxidation is a time-dependent process that is accelerated at high temperature [2] and is also affected by the partial pressure of the oxygen. It is also described [5] that the properties of the oxide generated at the contact interface influences the fretting wear performance more significantly than the hardness of the material.

The quantitative modelling of fretting wear is difficult due to the complex relationship between fretting wear and slip regime (stick/partial/sliding), coupled with highly the nonlinear stress-strain relationship and the evolution and release of debris at the fretting interface. Finite element analysis of the fretting wear process has been studied by a number of authors to solve the evolution of stress and strain distribution for the gross sliding and partial slip regimes using various techniques [6 – 8]. Jin et al. [9] studied the effect of fretting frequency and the contact temperature due to the dissipation of frictional power in a stainless steel contact and a simple analytical model was developed to predict this behaviour. It was reported that at a fretting frequency of 200 Hz with a bulk specimen temperature of 150°C , due the frictional power dissipation the contact temperature at the interface was raised around 70°C and hence they suggested that there is a strong dependence of fretting behaviour upon fretting frequency at this temperature. Ding et al. [10] proposed a methodology to evaluate the fretting wear life of highly loaded assemblies based on the simple laboratory tests by developing a fretting wear simulation and predictive tool. Ding developed a fretting contact model using finite element analysis including the presence and evolution of the debris layer with increasing number of cycles and reported that with the introduction of the debris layer a smaller wear scar width and slightly greater wear depth was predicted when compared to the model without the debris layer. The model also predicts a shift in the maximum contact pressure from the centre of the contact to the contact edges and additionally predicts the retention and ejection rate of the wear debris as a function of number of cycles. Yue and Wahab [11] developed a two dimensional fretting wear model with a debris layer using the finite element method to study the effect of debris on fretting wear behaviour and reported, in contrast to Ding et al. [10], that the wear volume with debris layers was slightly higher compared to the model without the debris layer. Ding et al. [10] modelled the debris accumulation on the fretting contact interface as a layer structure, by defining the mechanical properties using an anisotropic elastic-plastic material model, whereas Yue and Wahab [11] described the material behaviour of the debris layer as elastic and homogeneous. The contact interface between the cylindrical pad and debris layer was assumed as a rigid connection by Ding et al. [10] whereas Yue and Wahab [11] assumed both the top and bottom contact interface as implemented contacts. The assumption and the material model considered by Ding et al. [10] and Yue and Wahab [11] are different which may be attributed to difference in the predicted wear volume value by these two approaches. Yue and Wahab [12] developed a two dimensional contact model by FE simulations using the ABAQUS commercial finite element software to study the effect of variable coefficient of friction with different fretting contact regimes. It is reported that the variable coefficient of friction in gross sliding conditions had a marginal influence in the prediction of wear volume at the end of the steady state condition, however in the partial slip regime or the running in stages of the gross sliding condition, the predicted wear volume by FE models with variable coefficient of friction are closer to the experimental results reported by McColl et al. [13]. Yue and Wahab [14] also studied the effect of the stress singularity in the simulation of the fretting wear using cylinder on flat contact using a two-dimensional FE contact model based on the fretting parameters such as applied displacement, coefficient of friction and number of cycles, and reported that the stress singularity has a close relationship to the fretting regime based on the stress singularity method. They also reported that the sensitivity of the element size at the contact interface is important and that the element size required for a converged solution should be determined.

In this work, the fretting wear behaviour of the high strength alloy steel, SCMV against nitrided SCMV (SCMVN) was investigated at ambient and, for the first time, elevated temperatures using a cylinder-on-flat configuration at 250 N applied normal load with displacement amplitudes of 25 and 100 μm under dry sliding conditions. The basis for this investigation is the need for high strength materials with enhanced mechanical and tribological properties in highly fatigue loaded components in order to achieve a longer service life at ambient and elevated temperatures. Creating an understanding of the fretting wear performance of SCMV-SCMVN material pair at the ambient and elevated temperatures will allow the development of the new materials with enhanced surface properties on the top surface layer, used in highly fatigue loaded components and it will provide a platform to better understanding the role of the contact conditions, surface hardening, temperature on the mechanisms controlling the fretting wear process.

2. Methodology

A series of fretting wear tests were performed on the high strength chromium–molybdenum–vanadium steel, SCMV and SCMVN at ambient and elevated temperatures using a crossed cylinder-on-flat configuration, as shown in Figure 1, which results in a 10 mm line contact. SCMV steel contains 3 – 3.5 Cr, 0.8 – 1.10 Mo, 0.15 – 0.25 V, 0.35 – 0.43 C, 0.1 – 0.35 Si, 0.4 – 0.7 Mn, < 0.007 P, < 0.002 S, < 0.3 Ni and balance Fe by weight percentage [15]. The ultimate tensile strength and yield strength of the SCMV material determined by tensile test was 1247 MPa and 1697 MPa respectively. The test material was initially cut into specimen blanks providing a machining allowance on all the sides. Once the heat treatment process was completed on the specimens, the raw material blanks were further machined into the required final dimensions of the flat and cylindrical specimens confirming that the decarburised layer formed by the heat treatment process had been completely removed from the specimen surface. The cylindrical fretting wear specimens were pulsed plasma gas nitrided in an atmosphere of 4 parts nitrogen and 1 part hydrogen for 30 hours with a nitriding temperature of $495 \pm 5^\circ\text{C}$. A minimum surface hardness of 7.85 GPa with a case depth of 0.2 to 0.4 mm at a hardness of +100 HV greater than the core was obtained in the nitrided specimen. The Vickers hardness of the heat treated SCMV material machined surface was $485 \pm 10 \text{ HV}_{30}$. The average surface hardness of the nitrided SCMV specimen was $1010 \pm 20 \text{ HV}_{0.5}$.

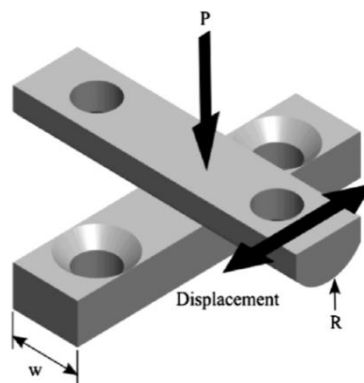


Figure 1. Cylinder-on-flat specimen configuration used in the fretting experiments, where $W = 10 \text{ mm}$, $R = 6 \text{ mm}$, P is the applied normal load.

The flat specimens were manufactured with a width of 10 mm while the cylindrical specimens had a radius of 6 mm. A brief description of the fretting wear test rig is presented here for ease of understanding although the full details of the setup is given elsewhere [16]. All fretting specimens were demagnetised, thoroughly degreased using detergent, rinsed with industrial methylated spirit (IMS) and acetone and finally dried using a hot air dryer prior to the experiment. The flat specimen was attached on a stationary lower specimen mounting block (LSMB) while the cylindrical specimen was fixed on a moving upper specimen mounting block (USMB). Fretting wear tests were conducted at an applied normal load of 250 N with displacement amplitudes of 25 and 100 μm at ambient and elevated

temperatures (120 and 150 °C) with a relative humidity of 35 ± 5 % under a constant frequency of 20 Hz. Cartridge heaters were used to heat the specimen to the required temperature and independent control loops exist for the heaters in the USMB and LSMB. In order to monitor the temperature near the fretting contact, additional thermocouples were spot welded to the surface of the flat and cylindrical specimens. The deviation between the surface temperature and the heater block temperature was relatively small, within ± 5 °C for all the fretting experiments. Table 1 presents the fretting wear test conditions used in the present work. A linear variable differential transformer (LVDT) was used to measure the relative displacements between the upper and lower specimen mounting blocks and the tangential force at the contact interface was measured using piezoelectric load cell. The normal loads were applied by dead weights using the lever arm acting on the USMB. The control and data acquisition system programmed in LabVIEW was used to log the tangential force (Q) and relative displacement (δ), continuously. To evaluate the surface topography, the wear scar on both the flat and cylindrical specimens were scanned individually using an ALICONA G5 “Infinite Focus” non-contact measuring instrument which has a vertical resolution of ~ 10 nm and a lateral resolution of 4.4 μm . Prior to scanning, the specimens were rinsed with acetone to remove the loose wear debris that was not adhered to the surface. A Philips XL 30 SEM scanning electron microscope was used to characterize the worn surface morphology of the fretted surfaces.

Table 1. Summary of the fretting wear test conditions.

Material combination (Flat/Round)	SCMV-SCMVN
Normal load, P (N)	250
Displacement amplitude, δ (μm)	25 and 100
Number of cycles, N	100×10^3
Radius of the cylindrical specimen, R (mm)	6
Frequency, f (Hz)	20
Temperature, T (°C)	Ambient, 120 and 150

3. Results and discussion

The ratio of tangential force amplitude to the applied normal load is defined as the tangential force coefficient under sliding fretting conditions. The variation of tangential force coefficient with cycles elapsed for SCMV fretted against SCMVN at 250 N applied normal load with displacement amplitudes of 25 and 100 μm under the ambient and elevated temperatures is shown in Figure 2. At the fretting contact area, the tangential force is considered to be formed either by means of direct interlocking of surface asperities or through entrapment of wear debris in between the surface asperities. The tangential force coefficient is low at the beginning of the fretting action and after the completion of a few hundred cycles, the tangential force coefficient increases rapidly and reaches a more steady state value for the ambient conditions investigated. During the fretting process at elevated temperatures, the tangential force coefficient increases for few thousand cycles and then decreases and reaches a more steady state value with increasing fretting cycles. The initial increase in tangential force coefficient for all the conditions investigated under ambient and elevated temperatures is attributed to the strong adhesion at the contact interface after the removal of the natural lubricant layer by spalling and micro fragmentation, which is a weak oxide and provides minimal protection to wear; this initial case is a two-body wear system [17]. Once the preliminary oxide layer is removed, there is no creation/formation of the oxide layer and the metal surface remains reactive, resulting in high adhesion at the contact interface. This phenomenon not only results in high tangential frictional forces, but in some conditions (displacement amplitudes) it can also lead to seizure [18]. In the ambient temperature condition, as the fretting cycles advance, more and more wear debris is produced at the mating interface due to the repeated sliding action. This debris may remain stuck between the two mating interface thereby forming a three-body

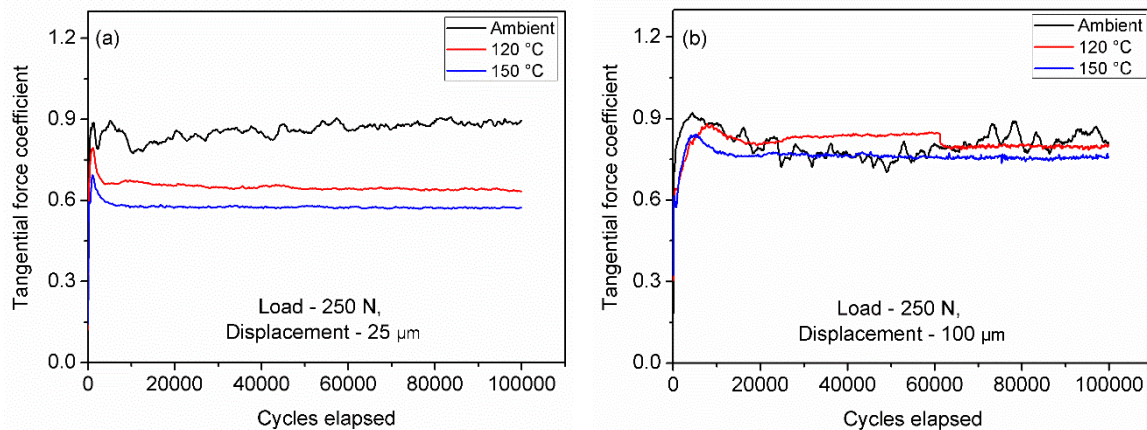


Figure 2. Variation of tangential force coefficient with cycles elapsed for the SCMV-SCMVN material pair at different displacement amplitudes with temperature, (a) 250 N, 25 μm and (b) 250 N, 100 μm.

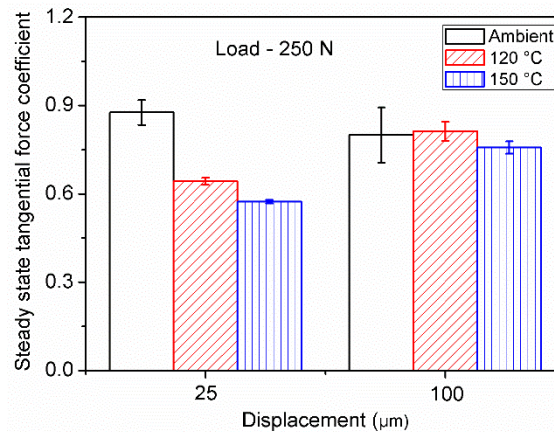


Figure 3. Variation of steady state tangential force coefficient with cycles elapsed for SCMV-SCMVN material pair at different displacement amplitudes with temperature.

wear system. This third-body (wear debris) acts as a natural barrier by splitting the direct interaction between the two mating interface, consequently the local stress field is lowered, which prevents further crack nucleation and propagation and thereby the tangential force coefficient reaches a steady state value. The experimental investigation by Kayaba and Iwabuchi [2] reported that, during the initial period of testing, the contact interface suffers plastic deformation and subsequently oxidation is facilitated causing the formation of an oxide layer. Fretting wear decreases with increasing temperature and there exists a transition temperature for all the materials in fretting contact, which influences the oxidation characteristics of the material. At low displacement amplitude (25 μm) with increasing temperature, the tangential force coefficient decreases drastically, which may be attributed to the formation of the surface oxides which adhere strongly to the substrate without being easily removed from the contact interface, thereby able to agglomerate and compact and thus reducing metal to metal contact. It is also evident from the wear scar depth profile that material transfer takes places during fretting at high temperature at low displacement amplitude, which is not the case at a displacement amplitude of 100 μm. At high displacement amplitude, the retention of the wear debris formed at the contact interface is minimal as it is easily ejected from the contact surface due to the large displacement, this free movement of the debris in the contact region increases the adhesion and the tangential force coefficient. To enable further comparison between the different fretting conditions and temperatures, the average values of the tangential force coefficient between 40×10^3 to 100×10^3 cycles was calculated and is presented in

Figure 3. At elevated temperatures, the tangential force coefficient reaches a stabilized value (i.e. steady state) more quickly compared to at ambient temperature. The steady state tangential force coefficient was highest at ambient temperature and decreases monotonically with increasing temperature at low displacement amplitude, whereas at high displacement amplitude, there is little variation in the value of the steady state tangential force coefficient with temperature. Figure 4 (a) shows the influence of applied normal load and displacement amplitude on total energy dissipated, which increases with increasing displacement amplitude for the same applied normal load at both ambient and elevated temperatures, as a gross slip condition exists for the material combinations investigated. The higher value of total energy dissipated at ambient and elevated temperature may be due to the following reasons: at ambient temperature, due to shearing of asperities, the maximum frictional energy is needed for the removal of the material and at high temperature maximum frictional energy is needed due to the delamination of the tribo-oxide layer. Figure 4(b) shows the influence of applied normal load and displacement amplitude on the total wear volume of the material pair examined at ambient and elevated temperatures. At ambient and elevated temperature, irrespective of the displacement amplitude, the total wear volume decreases with increasing temperature. Figure 5 shows the wear depth profile of the fretting wear scar of the flat SCMV specimen tested at 250 N load with temperature and displacement amplitudes of (a) 25 μm and (b) 100 μm . At 25 μm displacement amplitude, the wear volume of the fretted specimens are very small as the applied displacement is accommodated by elastic deformation of the asperities. As the displacement amplitude increases, the damage mechanism is governed by abrasive wear which causes both the depth and width of the wear scars to grow monotonically as illustrated in Figures 5 (a and b). A similar wear behaviour was observed during the fretting of annealed 304 stainless steel against itself [2] and AISI 301 stainless steel fretted against AISI 52100 steel [19]. Figure 6 shows the worn surface morphology of the SCMV fretted against SCMVN at 250 N, 100 μm at ambient and

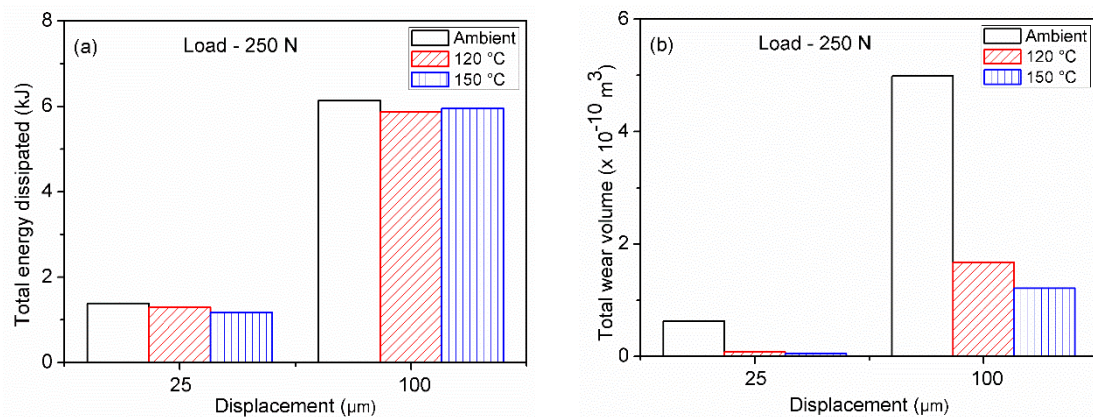


Figure 4. Influence of applied normal load and displacement amplitudes for SCMV-SCMVN material pair with temperature on (a) total energy dissipated and (b) total wear volume.

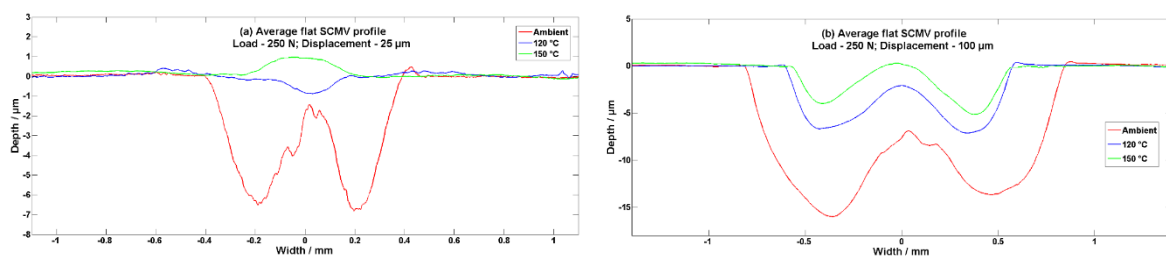


Figure 5. Wear depth profile of the flat SCMV specimen for the test conducted at 250 N with temperature (a) 25 μm and (b) 100 μm .

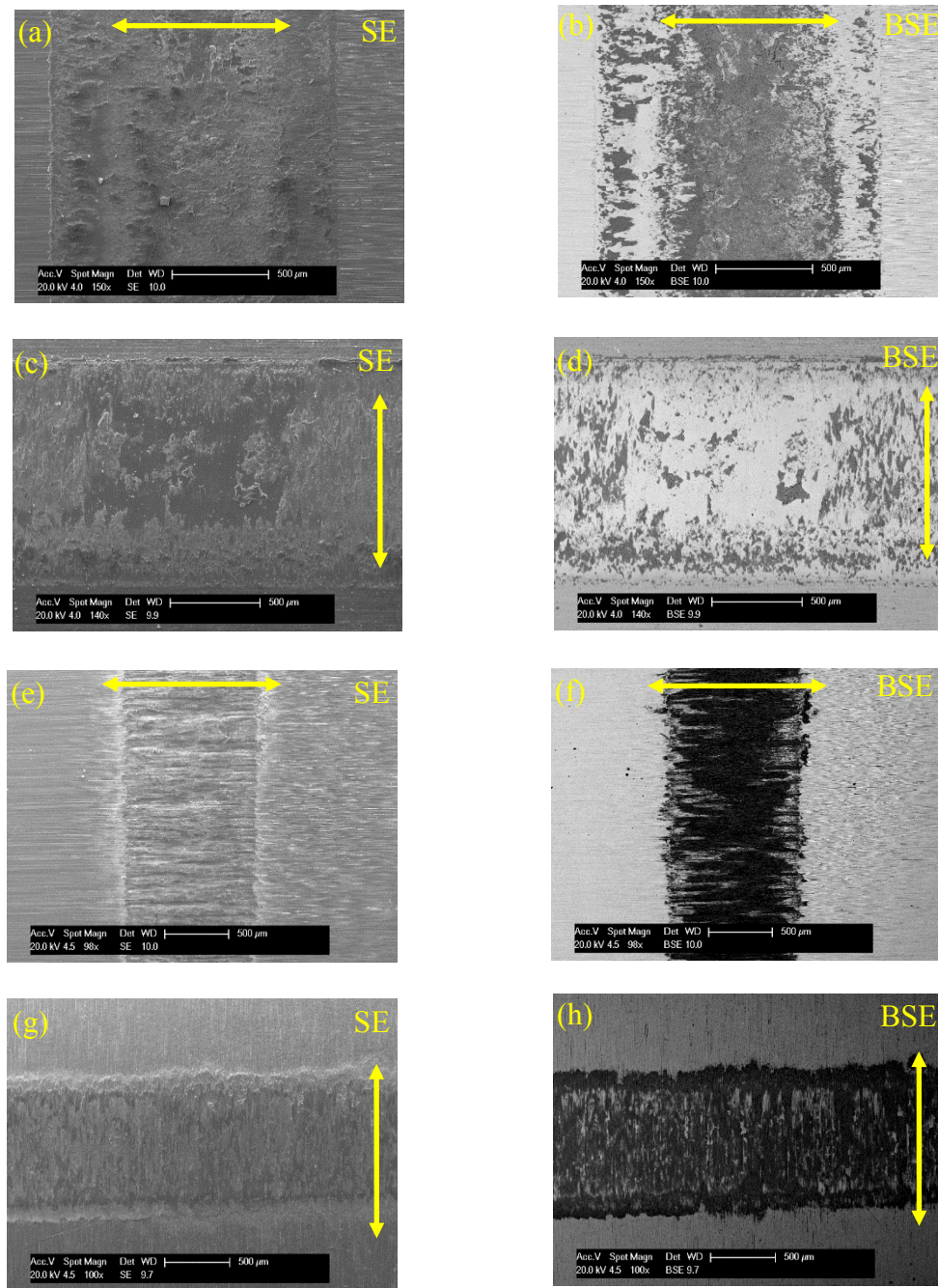


Figure 6. Worn surface morphology of the SCMV fretted against SCMVN specimen at 250 N, 100 μm (i) (a-d) – Ambient temperature; (ii) (e-h) –150 $^{\circ}\text{C}$. (a, b, e, f) – flat SCMV specimen and (c, d, g, h) – round SCMVN specimen.

150 $^{\circ}\text{C}$ temperature. From the BSE images, it is evident that at ambient temperature, patches of oxides debris are present; whereas at high temperature, the wear scar is fully covered by the oxide debris, illustrating the bed of compacted oxide debris on the wear surface. At ambient temperature, delamination, adhesive wear and abrasion were found to be the most predominant mechanisms of failure at the contact interface in the high strength alloy steel under the fretting conditions investigated. The oxidation of the wear particles is accelerated with the increase in temperature and ploughing by wear particles are observed with increasing temperature. The adhesive transfer layer seemed to protect the

surface with the increase in temperature due to the reduction in the interaction of the worn surface and the total wear volume decreases with increasing temperature. Ploughing, abrasion and abrasive wear are the most predominant wear mechanisms at high temperatures in the high strength alloy steel under the fretting conditions examined.

4. Conclusions

The influence of temperature on the fretting wear performance of SCMV against SCMVN was investigated using a cylinder-on-flat specimen configuration. Experiments were conducted in gross slip condition for all the fretting studies. The material response during fretting was examined by analysis of the friction force response, characterization of the wear debris and wear measurement. At 25 μm displacement amplitude, the steady state tangential force coefficient decreases monotonically with increasing temperature whereas at 100 μm displacement amplitude there is little variation between the temperatures examined. The total dissipated energy and the total wear volume decreases with increasing temperature irrespective of the displacement amplitude. The reduction in wear and tangential force coefficient with the increase in temperature is due to the retention of wear debris within the contact interface, leading to the formation of a stable loading bearing bed and progressive formation of a glaze oxide layer. At ambient temperature, the abrasive action of the particles promoted the wear at the contact interface whereas compaction of the oxide particles reduces the wear at elevated temperatures.

5. References

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