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Anisotrpic friction behavior of charcoal and the influence of humidity

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ABSTRACT

Tribo-tests were carried out on pyrolyted wood derived charcoal specimen in the directions of "flat-face" and "curved-face". In former direction, an ultra-low friction coefficient 0.03 was measured in a high humid condition with 75% relative humidity. Eventually, the friction coefficient becomes 0.45 when the humidity level decreased to 10%. However, under similar tribo-test condition, the friction coefficient is high 0.1 in the "curved-face" of charcoal specimen at 75% humidity. This value further increased to 0.8 at humidity level of 10%. Large amount of polar functional groups, oxygen complexes and water molecules was observed on the "flat-face" due to the presence of microscopic pores which act as a reservoir to lubricate the sliding surfaces.

1. Introduction

Lamellar materials such as graphite [1], molybdenum disulphide [2], carbon fiber reinforced [3] and boric acid [4] along with several other materials characterizes low friction due to their layered lattice structure. However, the quantum of lubricity associated with these materials is anisotropic and low friction is exhibited only under certain specific conditions. Some of carbon allotropes and carbon-based advanced materials prepared by physical and chemical vapor deposition also signifies advanced tribological properties [5–8]. However, there are several limitations in realizing practical applications of thin film deposited by physical and chemical means. Friction behavior of these materials is sensitive to the atmosphere and only under certain test condition it yields low friction coefficient. The charcoal is traditionally cheaply available commodity and it is potential contributor for progress of human civilization as it is harnessed in energy resources [9]. It is constituted by activated carbon with large amount of pores which provides high internal surface area [10]. Therefore, it constitutes increased surface energy capable of adsorbing large amount of gases and liquids. Increased surface energy acts as a catalyst to generate chemical reaction which favors to assists interaction with several functional groups. Chemically activated carbons are versatile adsorbents which find wide spread industrial applications such as water and gas filtration, catalysis, biomedicine and pharmaceuticals [11,12]. In order to purify chemical constituents, the charcoal effectively removes undesired species due to the adsorption of liquid/gas molecules. Although, these material aspects have widely explained by chemical engineering point of view, the mechanical properties are still a subject matter of study due to its complex microstructure and texturing during coalification process [13–15]. As a further consequence, complex fracture behavior results due to inhomogeneous distribution of inorganic constituents in charcoal matrix. Mostly, magnitude of stress acting on the charcoal defines mechanical behavior that may be dominated by elastic and plastic deformations [16–20]. Such deformation largely depends on stability and physical characteristics of the pores under equilibrium/non-equilibrium conditions [21]. Moreover, deformation and fracture behavior in charcoal is by and large anisotropic. The in-built structural inhomogeneities and the role of interacting test atmosphere likely to render wear phenomenon mechanistically and chemically complex. This issue has not been investigated so far.

Therefore, in this article, friction behavior of charcoal specimen is investigated with change in humidity level in argon inert cover gas used during the tibo-test. The tests were conducted in both "flat-face" and "curved-face" directions of the charcoal specimen. Microstructure and chemical behavior of charcoal were investigated by the scanning electron microscope (SEM), X-ray diffraction (XRD) and Raman spectroscopy. In addition, surface functional groups were investigated by FTIR. Relationship among friction, microstructure, chemical behavior and surface functionalities has been established in both the directions. Wear track morphology

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was obtained to enable correlation with humidity and direction dependent deformation behavior.

2. Experimental

The round shaped wood stick with diameter of 10 mm and length of 10 mm was burned at 800 °C in argon inert atmosphere. At this temperature, most of the non-carbon elements such as hydrogen and oxygen were removed in gaseous form by pyrolytic decomposition. After burning process, it was cooled in same inert atmosphere. Samples surface was mechanically well finished and polished. Flatness was excellent which was measured by mercury scale. Surface roughness of the sample was measured by a Dektak 6 M–stylus profiler where 5 mg load with a scanning speed of 30 μm/s was used. During the measurement, tip of the diamond stylus with a radius of curvature 12.5 μm was scanned across the charcoal specimen and the wear track to obtain the roughness value. Friction behavior of charcoal specimen across "flat-face" and "curved-face" was measured by a ball-on-disc micro-tribometer (CSM Instrument, Switzerland) operating in a linear reciprocating mode. 100Cr6 steel ball with 6 mm diameter was used as a sliding probe against the charcoal specimen. Normal load and sliding speed were kept constant at 1 N and 2 cm/s, respectively. A stroke length of 3 mm was fixed for each experiment. The tests were carried out in ambient environment and controlled argon gas atmosphere. Humidity level in tribometer test atmosphere was controlled by varying flow rate of argon gas which entrained certain fraction of moisture. Wear depth was measured by linear variable differential transformer (LVDT) coupled with microtribometer. The average value of wear depth measured in both the directions with error bar is used. In addition, the wear width is measured by optical microscope and the average value is reported. Morphology of the charcoal specimen was analyzed by field emission scanning electron microscope (FESEM, Zeiss Supra 55). XRD measurements were carried out with a Bragg-Brentano powder diffractometer using CuKα radiation. The diffraction pattern was recorded at room temperature in 2θ range from 10 to 80° with a resolution of 0.05°. Micro-Raman spectrometer (Model NVIA) was used to record spectra and decipher chemical structure of charcoal specimen. Laser radiation with a wavelength of 514.5 nm (Renishaw inVia, in the backscattering configuration) was used as an excitation source. The infrared absorbance spectra with 4 cm^{-1} resolution were obtained at normal incidence in an evacuated chamber of an IFS 66 V FTIR spectrometer (Bruker Optics). A KBr beam-splitter and a DTGS detector were used to allow the spectral frequency range 500–4500 cm^{-1}.

3. Results and discussion

3.1. Morphology of the charcoal

In the SEM micrograph, morphology of charcoal is constituted by well patterned large pores present in the "flat face" of the surface (Fig. 1a). High magnified image is shown where arrow points to large cavity. However, in "curved face" direction, the flakes are clearly visible and pores are less abundant and these posses small size (Fig. 1b). The burning of wood leads to carbonization process which involves thermal decomposition of carbonaceous materials. This process eliminates non-carbon species which produces a pore like structure [22]. The structure of pores and pore size distribution are largely dependent on nature of the raw materials and carbonization process [22,23]. Carbon atoms in charcoal differ from each other in their chemical reactivity which depends upon their spatial location. Chemical activation eliminates disorganized carbon, exposing aromatic sheets which act as an activation agents leading to the development of a microporous structure. Porosity facilitates easy adsorption as adsorbing species which interact with high surface energy of the pores.

3.2. X-ray diffraction

Structure of the charcoal specimen was investigated in both "flat-face" and "curved-face" as shown in Fig. 2. In both the directions, micro-structures are quite similar and mixed phase consisting of orthorhombic and hexagonal lattice is observed. Broad XRD peaks at 2θ values of 24.3° and 43.3° are observed which belongs to the (002) and (111) orientation of nanocrystalline graphite phase, respectively. The lattice spacing of (002) plane is calculated in both the directions and it is 0.334 nm which corresponds to *c*- axis of hexagonal graphite structure [24]. Debye-Scherrer formula was used to estimate the average size of graphite

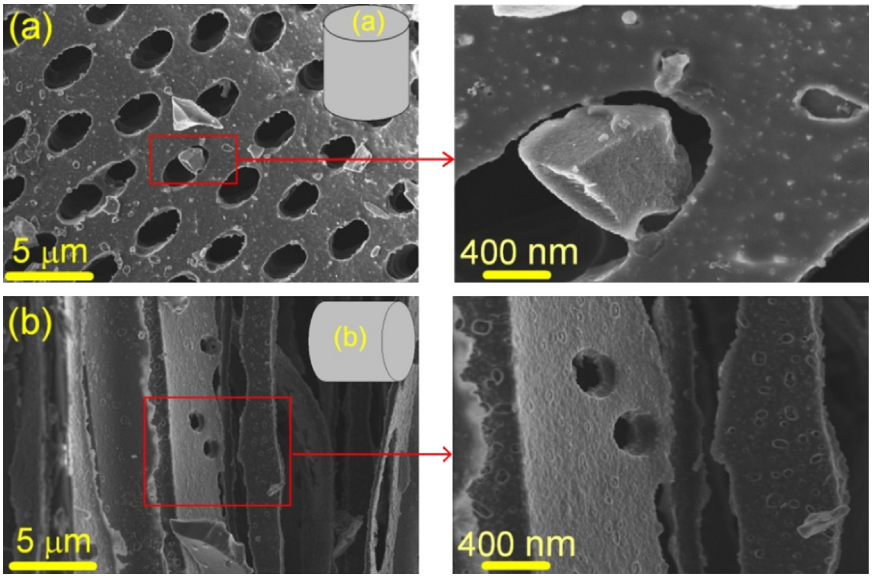

Fig. 1. SEM image of the charcoal in the direction of (a) "flat face" and (b) "curved face".