under study. The degree to which a material expands or contracts during exposure to operating environments is an important factor to consider in any sealing application [16]. Operating fluids could be absorbed into a material causing its swelling. Operating fluids could also wash out ingredients within the material causing the decrease in volume. Sometimes both could happen with an initial swelling followed by shrinkage. High temperature and chemical environment could cause the cross-link structure to tighten causing a decrease in volume. Measurements of volume before and after exposure are expressed as a percent change. The low swelling of CNT/FE is due to the increased resistance to OBD and temperatures caused by using CNT in FE, and also barrier properties of CNT/FE-OBD toward permeation of drilling fluid components to nanocomposite. The reasons for increased resistance to OBD and also increasing barrier properties of FE by CNT will be explained at the end of the paper.

The influence of different types of drilling mud on size of rubber samples used as elastomer of mud motors are also reported [19]. It was proved that under long-term exposure, intensive change of rubber sample size takes place and was gradually stabilized for 200–250 hours. Total change of the sample size amounts 2–3 % relatively to the initial size. Oil drilling mud caused a decrease in the size of rubber. Besides, the influence of temperature on sample size of rubber put in hydrocarbon drilling mud has been analyzed. At room temperature decrease of a size in diesel fuel and oil was more intensive than under temperature equal to 50 °C. The reason for this was high evaporation degree of hydrocarbon volatile compounds and decrease in mud aggressiveness to the samples.

The swelling of polymer matrix by solvent depends on diffusivity as well as solubility of the solvent molecule, which are rate-dependent processes [20]. The penetration of solvent into a stiff polymer sample is usually described as a result of two different processes: firstly, the diffusion of solvent into the swollen matrix, secondly, the advancement of the swollen-unswollen boundary as a consequence of the stress induced in the polymer. Because in our CNT/FE-OBD sample the swelling was very low it could be concluded that diffusivity as well as solubility of the OBD into nanocomposite CNT/FE were low, while for those of FE-OBD and CB/FE-OBD they were not.

The effect of temperature on the diffusion process of selective solvents in rubber blends containing FE was studied by carrying out swelling in different temperatures [20]. It was found that the diffusion coefficient increased slightly with increase in temperature. The molecular motion associated with the chain flexibility allowed the solvent molecules to penetrate the polymer. As the temperature was increased the segmental motion was also increased with the result of more diffusion of the solvent molecules. However, the molecular network prevented the free diffusion of solvent. The swelling of the cross-linked polymer was the result of compromise between the osmotic swelling pressure and the elastic force of the macromolecular chain of the network opposing it. The net result was the migration of the solvent molecule, which was temperature dependent. In our filled and unfilled FE-OBD samples, also the high temperature of OBD test affected the swelling of these samples. However, in CNT/FE-OBD even at high temperature the swelling was low as well. Besides, the same verifications that mentioned above could be mentioned for low weight gain of all samples under study. Furthermore, the filler particles were able to interact with the chains and chain mobility restrictions could cause reduced sorption (weight gain) ability. Decreasing chain mobility could decrease free volume in the matrix and provide less space for the solvent absorption in the sample. The addition of nanofiller reduced the availability of these free spaces and also restricted segmental mobility of the rubber matrix [21, 22]. Therefore, in our CNT/FE-OBD due to high interactions of CNT and FE these free space and segmental mobility of the FE were low and the weight gain of this nanocomposite in OBD was also low. However, in CB/FE-OBD the weight gain in OBD was higher compared to that of CNT/FE-OBD. This was due to lower interactions of CB and FE compared to that of CNT and FE.

Table 1 also shows that the changes percentage in dimensions of all samples under study. The changes in dimensions of CNT/FE are very low compared to others and acceptable for applications of O-rings in drilling fluid. The reasons for low dimensional changes of CNT/FE were the same as those mentioned for low swelling of samples.

Optical microscopy

Figures 7–9 show optical microscopy images of filled and unfilled FE and also filled and unfilled FE-OBD at different magnification. As could be seen in these figures original compound of FE, CB/FE and CNT/FE had no cracks, while after subjecting them into OBD test at the surface of FE-OBD and CB/FE-OBD lots of cracks appeared, but CNT/FE-OBD surface was free of cracks. The surface of CNT/FE-OBD was the same as surface of original compound of CNT/FE.

Again, the aforementioned results show that original pure rubber (FE) is not resistant to the OBD, also, CB cannot induce resistance of FE to OBD but introducing CNT into FE induces resistance of FE to OBD and optical microscopy results support AFM results.

Mechanical properties of filled and unfilled FE

Hardness

Table 2 shows the hardness changes of filled and unfilled FE due to OBD test. It is also shown that the hardness of the original compound of elastomers and OBD-aged elastomers have the following order: CNT/FE > CNT/FE-OBD > CB/FE and CB/FE-OBD > FE > FE-OBD.

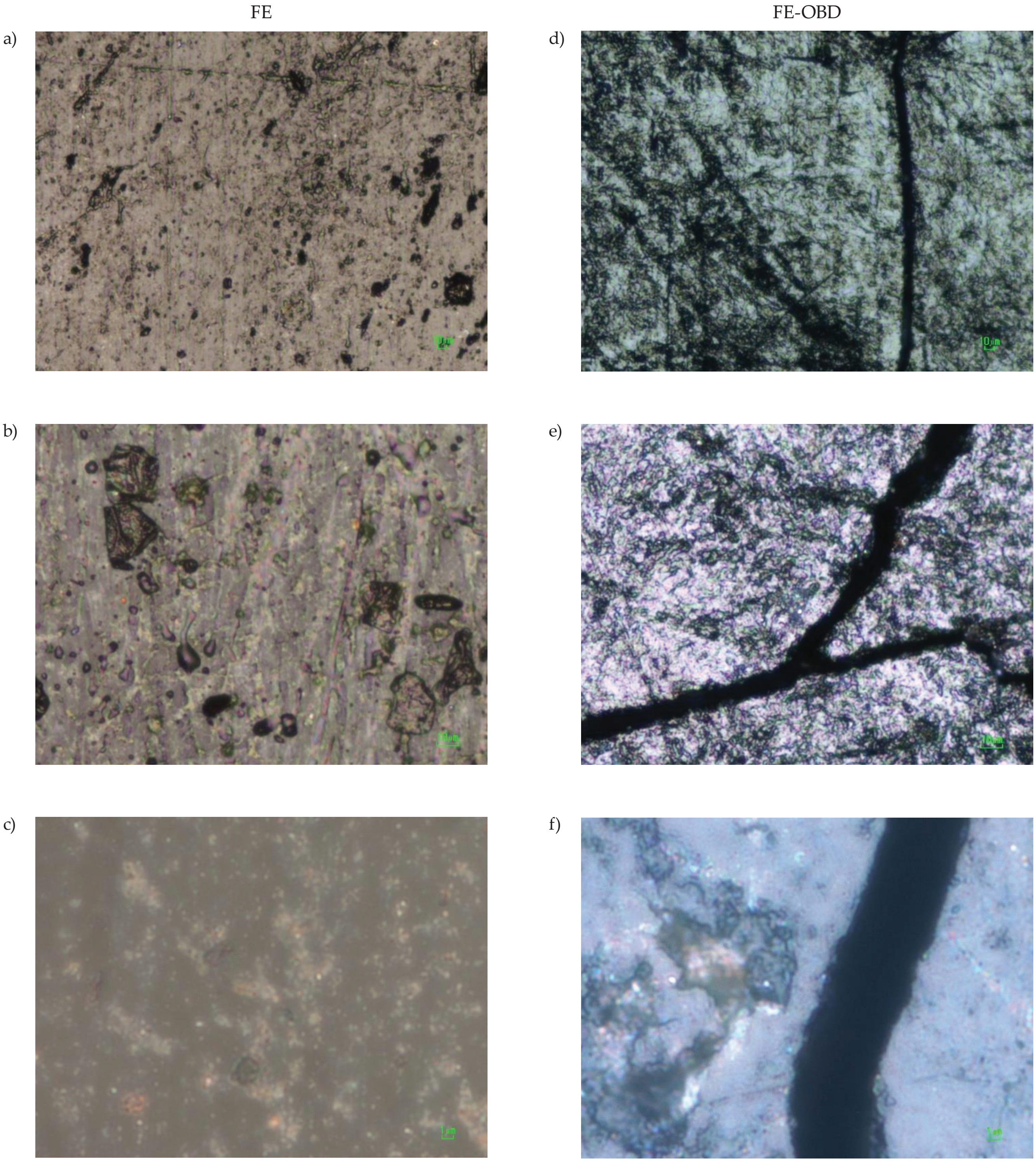

Fig. 7. Optical microscopy images of: a, b, c) FE, d, e, f) FE-OBD at different magnifications; a) and d), b) and e), c) and f) have the same magnifications