AN UNCONVENTIONAL APPROACH IN POLYMER WEAR: ONLINE VISION SYSTEM

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ABSTRACT

Tribology which deals with interaction of materials has robust link with surface morphology of contacting bodies. Adequate information on surface state during the interaction is essential for understanding the constructive/destructive nature of wear, especially for polymer composites. Such information can be acquired using recently developed advanced electronic imaging systems to study the morphological changes of moving surface. In the present research, polymer composite is tested against steel counterface under combined rolling/sliding condition. A high speed camera system in conjunction with a reflected light bright field optical microscope is used to acquire contact surface micrographs during testing. The acquired real-time micrographs are post processed in order to quantitatively estimate the area occupied by specific surface scars. Image processing techniques such as blur estimation, segmentation by local thresholding and grey scale granulometry were used to have a quantitative estimate of the surface state. The area of segmented regions from the values of grey scale granulometry validates the self-healing mechanism complemented by resin back transfer phenomena. It is also evident from this study that a substantial contact area should be investigated in wear analysis. The present research clearly points out that a combination of quantitative and qualitative analysis of real-time micrographs is indispensable for wear surface investigations.

Keywords: Online vision system, polymer wear, quantitative micrography

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INTRODUCTION

The rapid growth in material development has led to increased use of polymer composites in light and heavy duty applications. Despite of its extensive use as rolling components (eg. gears, cams and rollers) their wear response are scarcely studied [1-2]. In rolling contact of polymer it is evident that the dimensional change caused by wear is at a micron scale [3]. Measuring wear in such a system has high chance of producing uncertainty due to tolerances and also from the significant scale difference between the test specimen and wear. Beside the global volumetric damage, the micron scale surface scars also elucidates the wear characteristics. The micron scale wear is the surface morphological modification as a consequence of plastic deformation or local yielding at an asperity level. Such change can be studied either from the roughness profiles or micrographs of the worn surface. The conventional techniques and methodology used for wear analysis by post-mortem analysis do not completely explain the relative change suffered by material during the wear process. This is also due to the random segment investigation from the contact surface for comparative studies. Yet, most existing studies on polymers in rolling contact adopts traditional post-mortem analysis based on micrographs (qualitative), and roughness (quantitative) changes for validating the wear process. In rolling contacts, the relative change or even the evolution of damage can be precisely monitored using interferometry [4]. However this may be time consuming in case of 3D measurement or inadequate information with the 2D data.

The current research attempts to study the wear process from the real-time micrographs of the moving contact surface of polymer composite. The two dimensional (spatial) information from the acquired micrographs were studied for its changes as a function of time. Also the evolution of these surfaces were studied both qualitatively and quantitatively. Image processing techniques were used to understand the effectiveness of these surface scars in altering the global surface morphological characteristic.

METHODOLOGY AND MATERIALS

The current research uses the newly developed online vision system (OVS) for acquiring the real-time micrographs of polymer composite. The OVS is a combination of a high speed camera in conjunction with a reflected light bright field optical microscope. More details about the test rig and its capabilities are mentioned elsewhere [5]. A digital image of the online vision system is given in Fig.1.

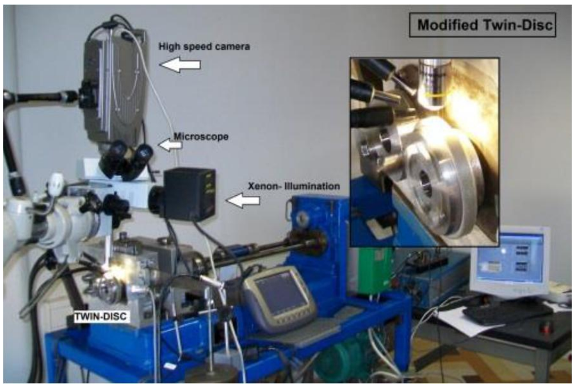

Figure 1. Online vision system incorporated in the modified twin disc test rig.

In regards to the material, commercially available polymer composite (Orkot, Trelleborg, Belgium) is tested against steel counterface (non alloy structural steel S355J2 according to the standards EN10025-2:2004). The used composite is a woven fabric impregnated with polyester resin. This material was chosen for its microstructural details which reveals individual phases. A photomacrograph of the unworn polymer composite is given in Fig. 2, where the fibers and the resin are clearly visible as bright and dark phase respectively. It is also observed that the axis of the fiber bundles were oriented along the rolling direction.

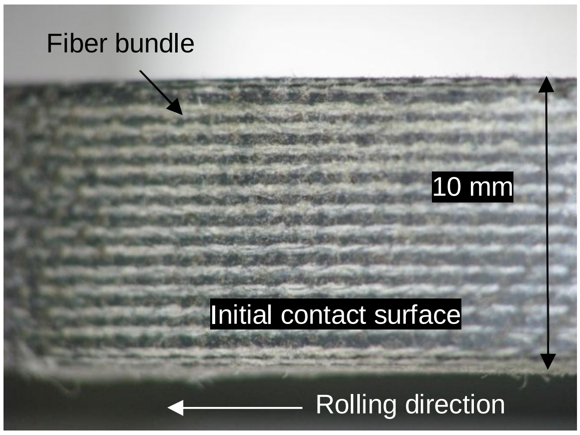

Figure 2. Photomacrograph of the initial contact surface of polymer composite.

To experimentally simulate the rolling/sliding contact a twin-disc model was used. This disc on disc configuration with Hertzian line contact was established between the composite and steel surface using the modified Forschungsstelle für Zahnräder und Getriebebau (FZG) tester (see Fig.1). The partial sliding accelerates the wear and induces additional mechanism (abrasion). Having both discs running at same rotational speed, the partial sliding is established by varying the diameter between polymer (d_1) and steel (d_2) discs. The slip ratio referring to partial sliding is calculated from the below function.

$$\boldsymbol{Slip\ ratio}\ [\%] = 2\,\frac{(v1-v2)}{(v1+v2)} * 100 \qquad \text{(Eq 1)}$$

Where, υ_1 and υ_2 are the surface velocities from the discs d_1 and d_2. The tests were performed at 200 rpm with 19% slip ratio and a normal force of 257 N.

Sequential imaging of the contact surface were made to study the wear process of polymer composite. Real-time images of contact surfaces are acquired at a specific interval of time (every two hours). The calculation for frame rate, exposure time and illumination strategy is given elsewhere [5]. The micrographs are post processed for understanding the quantitative estimate of surface modification. Techniques such as blur estimation, segmentation by local thresholding and grey-scale granulometry were used for post-processing.

RESULT AND DISCUSSION

In any tribological study it is essential to validate the wear process by quantitative means. Thus, change in diameter of the composite specimen was monitored online using a linear variable differential transformer (LVDT). Fig. 3 shows the online data (average of 1000 points sampled at 1 kHz) of the diameter change as a function of time and the dots represents the time of image acquisition.

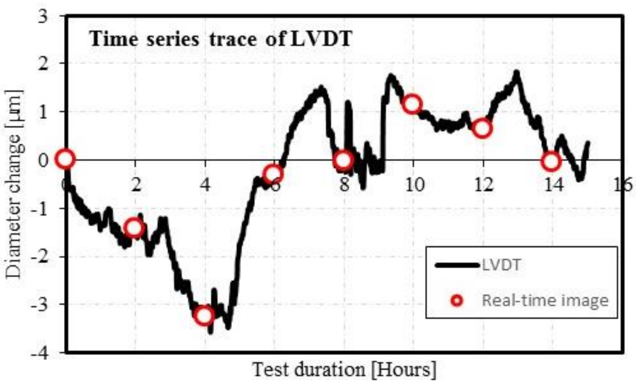

Figure 3. Diameter change as a function of time.

In the first four hours of testing the diameter of the composite increases gradually. However, after hour 04 there is a sharp decrease in the diameter further to which the diameter of the specimen does not change significantly. An overall change in diameter of 5 µm is observed from contact point measurement using LVDT. Such small change is not sufficient to indicate the diametric change for wear characterization. Apart from the LVDT, the dimensional changes at micron scale was investigated using the 3D stylus profilometry. Fig. 4 shows the roughness profile of unworn and worn composite surface. It is evident from the 3D profile that cavities as a part of surface texture are present even in the initial contact surface. In the conventional approach (post-mortem analysis) this can be considered as a reference for wear analysis. On comparing topography of cavities between unworn and the worn surface, there is a reduction in the depth profile of these cavities from worn surface which can be assumed as the height loss caused by wear. The groove marks running parallel to the rolling direction can be attributed to abrasion as a consequence of partial sliding. This also complements the hypothesis of "reduction in depth profile of the cavities" by means of material removal. The roughness parameters of unworn and worn specimen also show significant difference in pointing out reduction in the depth of the valley and smoothening of surface (See Fig. 4). However, having significantly large area of contact, it is impractical to generate reference topographic measurement at the same location to monitor the relative change.

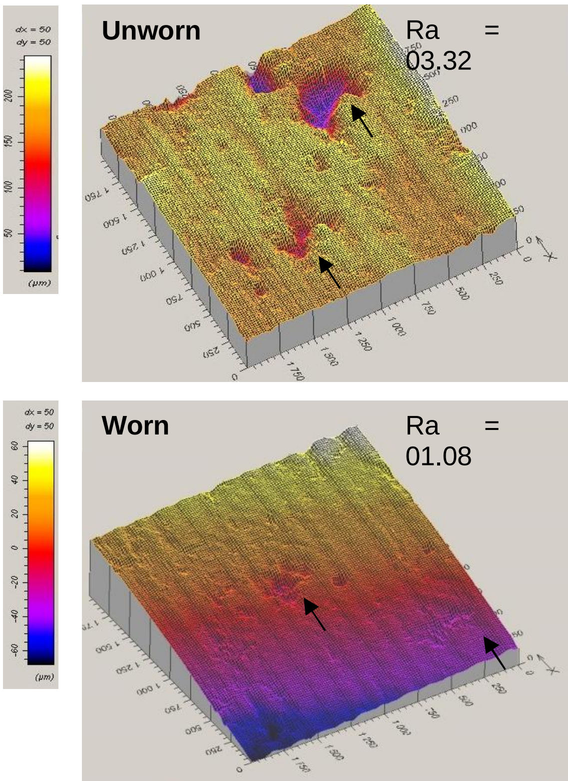

Figure 4. 3D topography of contact surface using stylus profilometer (Somicronic® EMS Surfascan 3D) with cut-off (0.8 µm) and trance length of 5.6mm.

<u>Qualitative micrography of high speed online images</u>

The high speed online micrographs covering the complete circumference of the contact surface were acquired. The real-time images within a single cycle is stitched and compared with images from different cycles to understand the wear process. The images are acquired at a specific frame rate (3000 fps) with an overlap (50%) between consecutive images. The overlap stands as a reference to identify the same sectors (location) between two frames for enabling the stitching procedure. Fig. 5 shows the real-time micrograph of composite contact surface acquired during the initial period of testing (at 2 hours). Image registration is done to match the overlap between subsequent images and also to compare the surface modification between two different cycles. Fig. 5 shows image of 10 frames stitched together which is approximately more than 2250 µm field of view for a resolution of 1.16 µm/pixel.

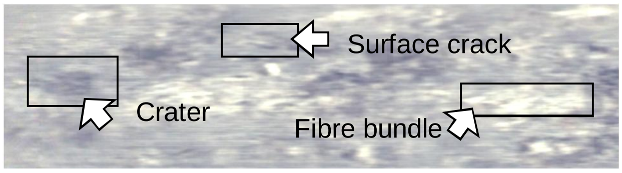

Figure 5. Stitched image after 2 hours of testing.

Wear patterns such as surface crack and craters are observed from the high-speed micrograph. Both phases (resin and fiber) are differentiated from the grey scale intensity, where fiber bundle appears brighter and resin appear as a dark phase (see Fig 5).

An important phenomenon as understood from the morphological evolution is the repairing (patching) of cracks. Fig. 6 shows crack located at the root of the craters (pointed out with white circle) at hour zero which tends to partially close at the end of testing. Cracks which are critical factor for damage evolution are being repaired by means of back transfer of resin. Craters as a dark phase seen in the micrograph of initial contact surface (hour 00) is also observed in the 3D topography of the unworn specimen (see Fig. 4). From the sequential images (see Fig. 6) it is evident that these craters disappear and reappear as a function of time. Craters present in hour 00 (indicated by arrow) disappear in the image acquired at the beginning of hour 04 to 06, but reappear later at hour 08. Likewise, it is clear that the dark region within the square at hour 00 becomes partially bright in the subsequent images (see Fig. 6). With a relatively large surface for investigation, a reference segment is compared from subsequent cycles. From the image analysis based on reference segment it is evident that the initial contact surface is still partially visible which indicates that wear is merely at an asperity level. Thus, the disappearance of cavities can be attributed to the readhesion of polymer to the initial contact surface from the transfer film and loose debris. Similar phenomenon was also earlier reported in the literature but without online evidences on the chain of events [6]. In our case, real-time sequential imaging of contact surface validates the hypothesis of resin back transfer. This also indicates the dynamic nature of transfer film adherence on the counterface. The question of transfer layer playing a positive role in polymer tribology is partially answered. However, these visual observations are still subjective. Thus to precisely validate, a quantitative estimate was made from the real-time micrographs.

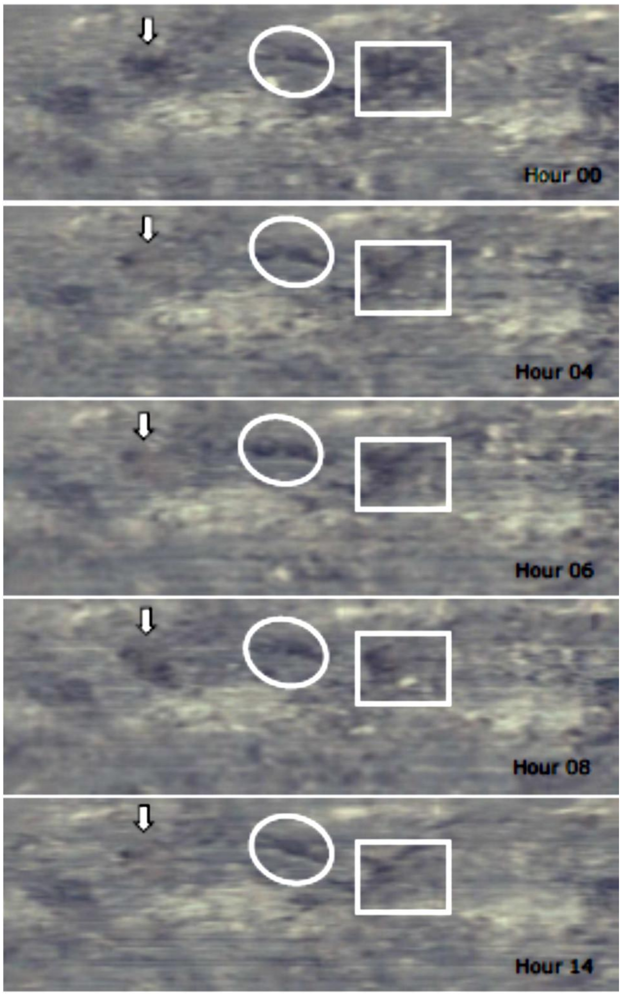

Figure 6. Online images acquired at 200 rpm (1 m/s).

Quantitative micrography high speed online images

Despite the overall changes in surface morphology, the initial contact surface has not been completely transformed. This indicates that the diametric change might be a consequence of plastic deformation or squeezing of fiber bundles accompanied with the material removal at local level due to partial sliding.

The diametric changes as seen in Fig. 3 should also cause a focus blur. This "focus blur" serves as a variable in validating the dimensional change of the specimen. The images from specific cycles (every two hours) were processed further to estimate its blur. On comparing the curves of estimated blur (Fig. 7) from the image gradient and diameter change, both follows a similar trend which agrees for the change in dimension. Out of fifteen different blur estimation methods used only three (gradient, variance and Reimannian tensor) have good correlation with the online signals from LVDT [7]. However, it is noteworthy that the surface morphology has also changed in the course of testing which might be reflected as noise in the estimated blur.

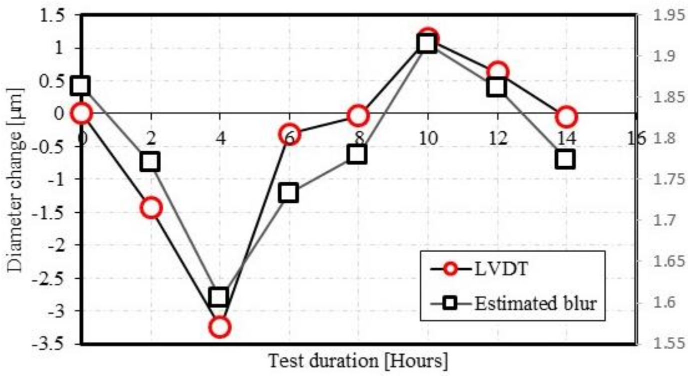

Figure 7. Online wear trend from the estimated blur and displacement measurements.

A more suitable comparison for the surface modification is quantitatively estimating the surface change from the texture itself. The morphological modification in case of image is merely a change detection based on pixel values. The change detection are regularly used at a tectonic scale for monitoring the landscape changes from aerial images [8]. We have adopted a similar approach at a micron scale. In the first place segmentation by local thresholding was applied to the images and subsequently the images are complemented for segregating the craters and cracks. The raw image from real-time micrographs shows difference between initial contact surface and the image acquired after 14 hours of testing (Fig. 8a and b). The results of binarised images from segmentation by local thresholding presented in Fig. 8c and d reflects the changes observed in binary image. A mathematical morphology technique with the operation of granulometry by binary opening is used to analyze the size distribution of surface scars. The change in size of the cavities and crack was estimated by filtering the surface scars by using structuring elements (SE). A square shaped SE is used for filtering the cavities. Though surface modification are revealed by the segmentation using local thresholding, it does not precisely represent the change in quantitative area of the texture. This is because the binary image does not clearly define the edges and the boundaries of the cavities. Having understood that the binary granulometry is inaccurate, another technique called grey-scale granulometry by closing was used. The closing operation has specific geometric interpretations, where the volume occupied within the surface scars can be estimated mathematically using SE from the intensity profiles of grey-scale values. A one dimensional representation is given by Gonzalez for easy understanding [9]. Among the three image processing methods, the grey-scale granulometry which is effective in representing the surface change is discussed in detail.

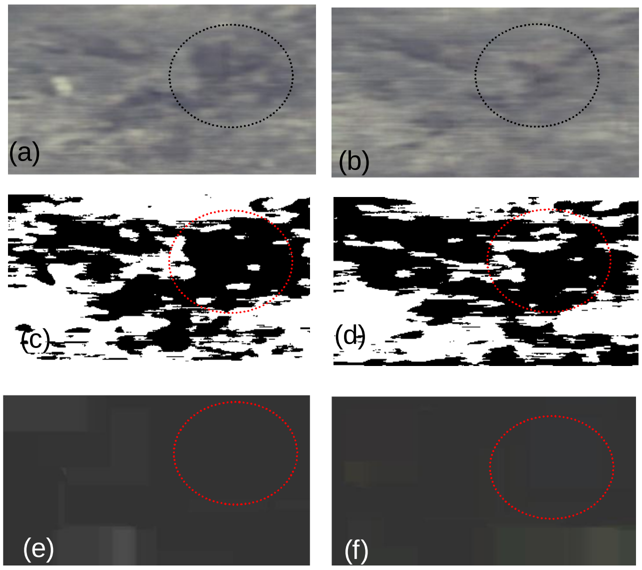

Figure 8. Polymer contact surface of initial surface and after 14 hours testing (a and b) grey scale image from of the contact surface (c and d) binary image after local thresholding (e and f) grey-scale granulometry.

In order to validate the representativeness of the different surface scars on the overall image the stitched regions were divided into several segments. The whole image of 1870 pixels full field of view (FOV) is divided into six regions. The schematics in Fig. 9 shows the sectors and its sizes in pixels. The size of the used SE side for crater evaluation is limited to 250 pixels starting from 50 pixels in steps of 25 pixel. The maximum limit is approximated from the size of the regions. It is assumed that the significant changes from surface scars are to be reflected in the grey-scale values resulted from granulometry by closing. The difference between these grey-scale values of sequential images for various SE sizes in six segments are shown in Fig. 10. It is evident from Fig. 10 that the smaller SE 50 and 75 pixels does not show significant difference between the regions. The substantial differences between the regions are seen for SE with element side 125 and 175 pixels. This corresponds to the sizes of the surface scars marked with arrow and circle in Fig. 6.

It is evident that even in the absence of substantial wear (in terms of material removal reflecting on the diametric change) in rolling contact condition, a considerable difference in surface morphology can be observed within a specific area and between the cycles. Nevertheless, most researches considers surface morphologies from post-mortem analysis of a narrow region to describe the wear process. Furthermore, the wear scar interpretation are based on few randomly selected contact points for which the wear mechanisms are generalized for the whole contact surface. Comparison of the FULL FOV with LHS FOV, crack and cavity 1, a substantial difference between the segments were observed for the trend on change in surface scars. However, the current research trend is to compare high resolution images with FOV less than one fifth of the LHS FOV. The results from quantitative analysis through grey-scale granulometry clearly indicates the local behaviour of wear scars. Thus, serious attention has to be brought to the conventional practice of generalizing the surface scars effects based on few local points or regions in studying the global wear characteristic of the material.

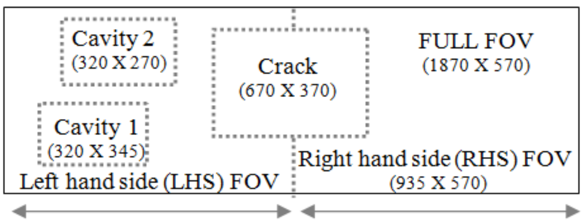

Figure 9. Schematics of the segmented regions.

It is evident that even with an overlap of 50% FOV, while comparing the FULL FOV with the LHS FOV there is a significant change in surface morphology from the grey-scale value of scars (see Fig. 11). Thus, it is suggested from the current research to have a significant area for investigation but at micrometer resolution. To have a significant area for investigation, manual image acquisition using the conventional techniques is rather tedious. The qualitative explanation given in the previous section for Fig. 6 on the reappearance of cavity 2 at hour 08 and the repairing of the crack is validated by the values from grey-scale granulometry (see Fig. 12). It is evident from the above research that an *in-situ* imaging technique is more appropriate which can have a reference for comparative studies. Moreover, while focusing on specific mechanism such as craters or cracks a size distribution can be made for wear analysis.

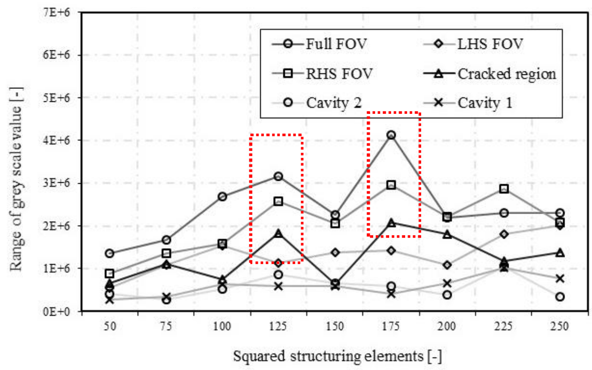

Figure 10. Range of grey-scale values from the sequential images for different size of structuring element size.

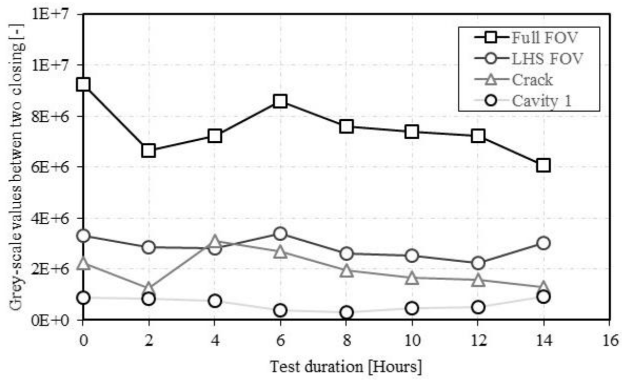

Figure 11. Trend on surface morphology using grey-scale values estimated using granulometry with 125 SE for the sequential images.

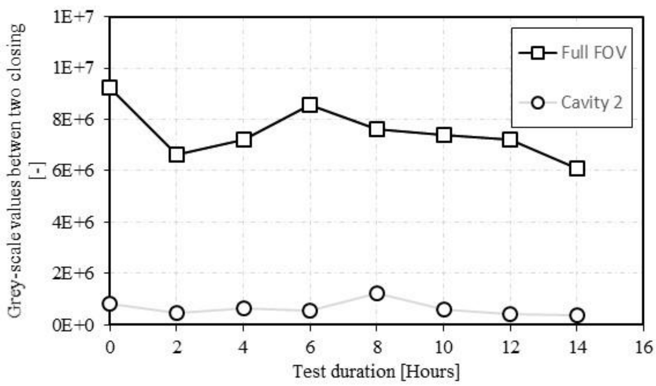

Figure 12: Trend in surface morphology modification from grey scale granulometry for two segments using 125 SE.

Apart from quantitative estimate of surface change, the intermediate wear mechanism of resin back-transfer from the steel counterface is validated using the approach followed in the present research. By combining the quantitative measurement from grey-scale intensity values with wear phenomenon, the material removal process is clearly understood. Here in our case even though polymer wear has detrimental effect, the dynamic behaviour of the transfer layer as understood from the online images repairs the cracks and fills the cavities to cover the surface defects. Thus, materials with properties owing to formation of transfer layer can be considered effective in a polymer-metal tribo pair. The current research strongly recommends the use of online vision system and grey-scale granulometry for understanding the wear process and damage mechanisms.

CONCLUSIONS

The high speed real-time micrographs acquired using online vision system stands effective in identifying the intermediate mechanisms in the wear testing of composite under rolling/sliding condition. This approach is efficient in tracking the positive wear characteristics such as the self-healing effect of composite surface by resin back-transfer. The dynamic characteristic of the transfer layer in complementing the resin-back transfer is understood from the refilling of cavities and closing of cracks in the intermediate sequences of the wear testing. Also among three different image processing techniques, the grey-scale granulometry stands effective in representing the surface defects such as cavities and cracks. Though the quantitative micrography is effective in representing the surface scars, they are validated manually from the visual interpretation of micrographs. Thus as a future work using an intelligent system should be adopted for efficient and automated image analysis.

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