

TRANSFER LAYER DYNAMICITY IN ROLL-SLIP OF POLYMER METAL PAIRS

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Abstract: Polymer-metal pairs are found in many engineering applications, especially in rolling/sliding conditions. Transfer layer formation is imperative in friction and wear investigations on using these tribo-pairs. In the existing literature quantitative description was given for the formation of protective layer from the post mortem analysis (preferentially for sliding configurations). Since there is a dynamicity involved in the transfer layer the straight forward answer from the quantitative postmortem responses is rather uncertain. In the current research, rolling/sliding tests were performed for polymer and its composite against metal to explore the underlying mechanisms using both qualitative and quantitative approaches. The tests were performed with intermediate pauses to observe the surface changes where characterization based on surface morphology and roughness (Ra) are used. The results show that the transfer layer deposition occurs in four stages which are explained from the view point of change in Surface roughness Ra in correspondence to its micrographs of the surface topography. The four stages can be categorized as 1. Scouring 2. Running-in 3. Transition and 4. Steady stage. Results show that in polymers the Ra increases during the scouring stage subsequently it decreases on reaching the steady stage. In steel counter parts the Ra does not change significantly during the scouring period. However, the Ra increases in the running-in period followed by a transition region leading to a steady state. Among the polymer and its composites the pure polymer shows significant change in roughness due to the difference in strength. The change in Ra for steel in the steady region also depends upon the contact materials, the mechanical and tribological properties of the polymer. Thus the stages can be used to study the transfer layer behaviour and understand the underlying mechanism in segregating the wear mechanisms both quantitatively and qualitatively.

Keywords: transfer layer; rolling/sliding; polymer-metal pairs; wear mechanisms

1 INTRODUCTION

Transfer layer phenomenon is often seen in many engineering applications where polymer-metals pairs are used. In which rolling-sliding conditions are critical for applications such as roller in sliding doors, automated racks, elevators guides etc. Tribological importance in these applications pertains to the accurate positioning dominated by the frictional characteristics. Moreover, the wear plays an important role in maintaining the life time operation of the components (Rollers, gears, cams) in these tribo-systems. One of the important factors in deciding the tribological characteristics is the transfer layer formation. Transfer layer is evident in both polymer-metal and polymer-polymer contacts. Already few researches were performed on identifying its characteristics and role on altering the tribological performance. [1-3].

Bahadur *et al* explains that the transfer film is a consequence of entrapment of polymer debris between the asperities of the counter material, and others also explain as the mechanical interlocking of particles. [3 & 4]. Rhee *et al* in his experiments on polymer-metal contacts explains the modification of wear property as a function of transfer film formation [5]. It is also a fact that the nature of transfer film is significantly affected by operating parameters and the tribo-system itself. The modification of frictional properties by means of transfer layer also depends upon the temperature involved in the process where solidification/free flow of transfer layer alters the tribological properties. Rhee *et al* reported a threshold temperature of 50 °C to change the frictional characteristics. Megler *et al* has observed modification in frictional characteristics due to the transfer layer formation [6]. Also the wear mechanism is affected by the thickness of the transfer film. In another research by Jain *et al* it was found that on polymer-polymer contacts the formation of protective layer is positively influenced by the sliding speed and affected on increasing loads [7].

In most of the investigations either a qualitative or a quantitative approach is used, however, in order to validate the quantitative approach justification should be made by qualitative techniques to completely understand the process.

Sviridyonok *et al* explains that the presence of transfer layer in the counterface is a dynamic process as a function of time [7]. The dynamicity of the transfer layer is highly dependent on the fillers used, materials, and operating parameters such as load, speed and temperature. Considering the dynamicity the initially formed transfer layer are found to be discontinuous in case of PA66 against quartz. All quantitative investigations were done on sliding systems and mostly in polymer-polymer contact. Since transfer layer is also process riven which differs from material to material and contact condition, the observed mechanisms in sliding does not represent the rolling condition. Even though research on polymer-metal rolling exists [8-11] the role of transfer layer and the evolution is not well described. Moreover, the role of transfer layer in modifying the tribological characteristics and the dynamicity involved in the transfer layer is unclear. Thus it is interesting to understand the evolution process and the sustainability of transfer layer.

In the present study, the dynamic behaviour of the polymer transfer film on steel counterface under rolling sliding condition will be investigated. Qualitative and quantitative techniques were adopted to understand the underlying mechanisms in transfer layer formation. Stylus profilometry based observations through roughness measurement are done for quantitative information which is further validated by the micrographs obtained through optical microscopy on polymer and steel surfaces. To have precise information on monitoring the morphological changes a similar surface imaging methodology is followed using locating fixture.

2 MATERIALS AND METHODS

2.1 Materials

In literatures, sliding bearing being the focused application the used materials for most investigation was of bearing material. In our investigation, PA66 and PA66/GF which is extensively used in rolling application are chosen for testing. Commercially available polymers from Quattroplast (Hungary) with grades DOCAMID 66E for PA66 and DOCAMID 66-GF30 for its glass fibre composite is used. As a counter material commercially available alloy steel 40CrMnNiMo8; (Thyroplast 2738) of Thyssengrup, Belgium) was used. The properties of the used materials are summarized in table 1 .

Table 1 : Mechanical and thermal properties of test materials and counter material

Property	Unit	PA 66	GF/PA66	40CrMnNiMo8
Density	kg/m ³	1.15	1.35	-
Young's modulus	N/mm ²	3300	9500	210000
Yield strength	N/mm ²	85	180	826
Service temperature (Long term)	°C		120	-
Melting point	°C	260	220	-
Heat conductivity at 20°C	W/(mK)	0.23	0.28	34
Coefficient of linear thermal expansion between 20°C – 60°C	m/(mK)	80X10 ⁻⁶	80X10-6	-

2.2 Methodology

A twin disc setup is the appropriate configuration to experimentally simulate rolling sliding of polymer-metal pairs. For this purpose a modified FZG (Forschungsstelle fur Zahnrad und Getriebbau) twin-disc testrig at Laboratory Soete was used, more information of the testrig can be found in the literature [8 & 9]. A schematic representation of the test set-up is shown in Fig. 1.

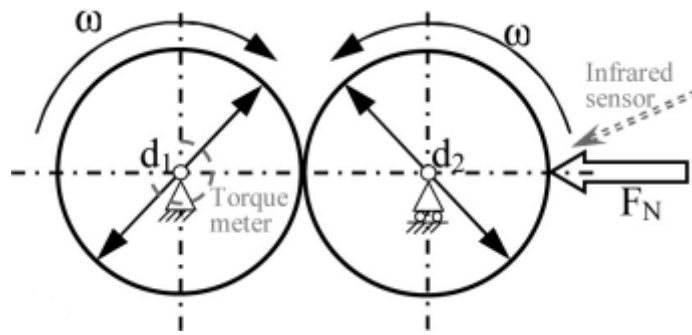


Figure 1. Shows the schematic representation of the twin-disc set up [9]

In general, the transfer layer interpretations were done based on the post-mortem analysis through microscopy techniques (SEM or optical microscopy). However, using such methodology (post-mortem) to interpret the result does not provide the evolution and the mechanism undergone during the course of wear. Since the transfer layer formation is a dynamic process the occurrence is random during the course of testing. To overcome such misinterpretation, tests were performed in interrupted mode with intermediate pauses. During the intermediate pauses the micrographs of the specimen were acquired using a 10 bit QICAM colour CCD camera in conjunction with an Olympus SZX optical microscope. The micrograph was acquired at specific intervals based on the preliminary testing. Moreover, in conventional investigation a random segment of the worn surface were used to analyse which does have limitation in representing the modification undergone as a consequence of wear. Such a challenge has been overcome by means of a locating fixture where a field of view (FOV) of 1300 μm (using 10X lens) can be located with a variation of $\pm 150 \mu\text{m}$ by which the evolution of transfer layer in the same region has to be investigated. To decide the total test duration and for identifying the steady stage a preliminary test was conducted. Moreover, the preliminary test helps to understand the temperature profile in steady stage and to maintain it within the maximum operational service temperature (95 $^{\circ}\text{C}$) Fig. 2 shows the temperature profile of the preliminary test conducted on PA66 against steel counter material (at room temperature of 25 $^{\circ}\text{C}$) with 30% slip ratio resulting in a running-in time of 2 hours, thus test were sequenced with 30 minutes interval until the completion of running-in period. Further to which during the steady state an interval of 2.5 hours was used as test duration for intermediate pause.

In addition to image acquisition, the roughness of the polymer and the steel was monitored at every interval. As discussed in the introduction, the transfer layer being the entrapment of polymer in the asperities their deposit on the counterface material tends to modify the Ra as a function of time. Thus during the intermediate pauses the corresponding roughness (average of five measurements) at the specific interval was also measured using SURFASCAN 3D stylus profilometer with DIN 1548 standard.

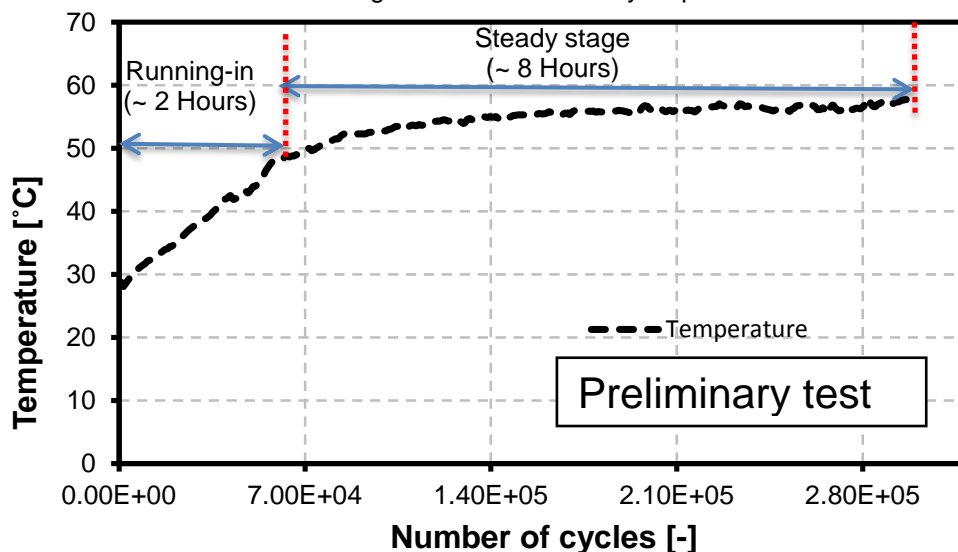


Figure 2 shows preliminary testing of PA66 against steel counter face at 500 rpm for 3×10^5 cycles

3 RESULT AND DISCUSSION

Wear test for 3×10^5 cycles which is approximately 10 hours of testing resulted in clear indication of the dynamic behaviour of the transfer layer. Since the main objective is to investigate the dynamic behaviour of the transfer layer, the friction and wear data are not discussed in the current paper. Among the polymer and its composites, PA66 transfer layer has correlating results. For GF/PA66 the micrograph from steel counter material are discussed in detail. The current investigation also aided to look for other height parameters such as change in the peak to valley values from the roughness profile.

From the interrupted testing the peak temperature at all intervals were recorded. The recorded temperature was plotted against the total number of cycles combining all the intervals. Fig. 3 shows both the comparison between the temperature profile of the preliminary test and the interrupted test showing similar trend in both cases. This means the frictional heating controlled by the surface in both the cases are similar. Thus, the interrupted test has similar temperature profile of the continuous testing to control the transfer layer behaviour.

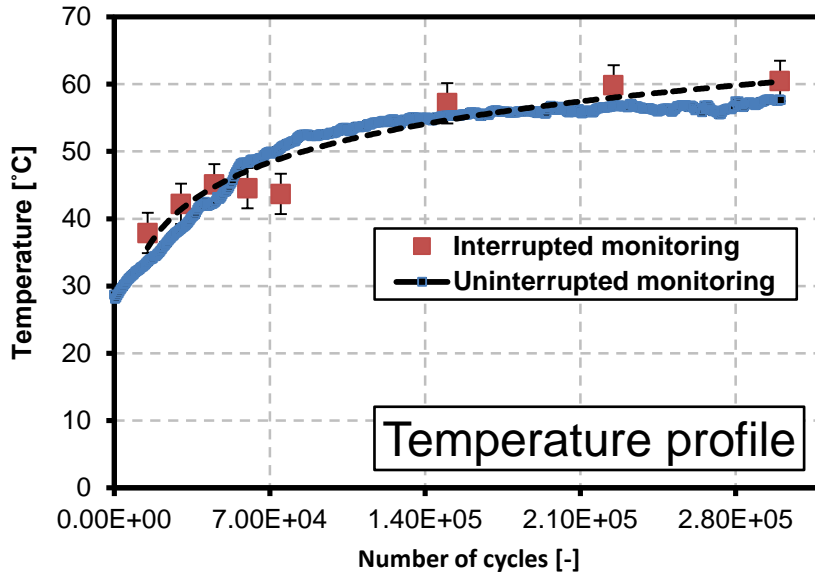


Figure 3 Comparison between the temperature profiles of continuous testing and interrupted testing.

3.1.1 Surface roughness (Ra) as a quantitative measurement

From the interrupted test of 10 hours test duration the roughness measurement showed clear segregation of run-in period and steady stage. There is an increase in Ra until 7×10^4 cycles (approximately 2 hours) which is considered to be the running-in period required for achieving a steady state (having constant temperature profile). There is a significant increase in roughness of steel surface until the running-in period. The initial decrease in the roughness can be due to the filling of micro/nano particle to fill the valley of the roughness profile.

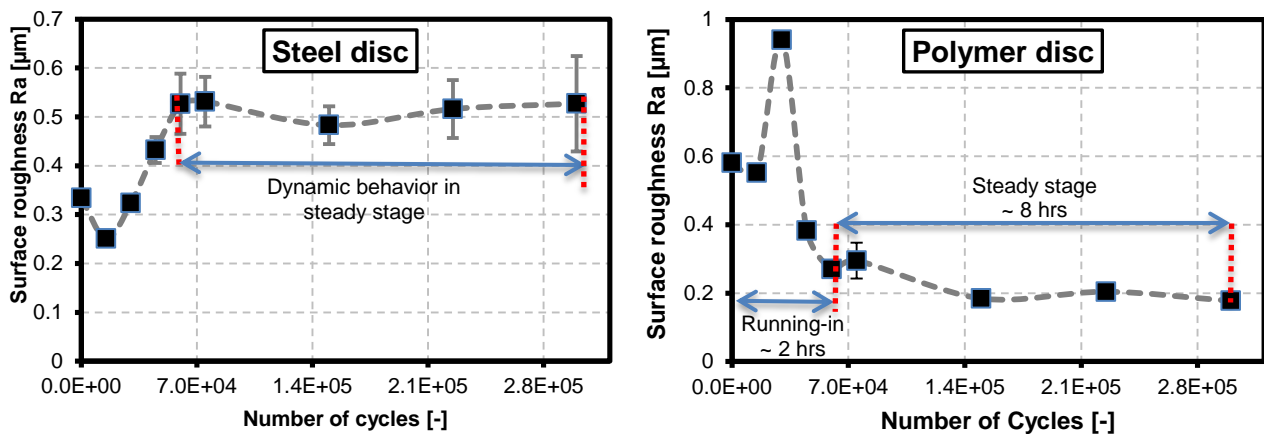


Figure 4 shows change in Ra as a function of cycles for (a) steel surface (b) polymer surface (PA66)

Further increase in roughness of steel surface is possibly due to surface modification made by polymer on the steel surface. Likewise, the Ra of the polymer surface changes rapidly in the running-in stage and then becomes constant on reaching the steady stage

3.1.2 Micrographs as a qualitative evaluator

Micrographs of the PA66 are shown in Fig. 5, traces of transfer layer are seen at 1.5×10^4 cycles. In figure 5 the arrow marked area in 1.5×10^4 cycles and 3.0×10^4 cycles showed increase in dark coloration and its intensity continued increasing until the end of testing. However, the deposition of PA66 during the initial running-in period (Fig. 5b) is not well observed which can be attributed to the less scattering of light from the valley in the roughness profile. Moreover the steel being a material with high light reflecting property than the polymer its visibility at these stages are less pronounced and also due to the limited deposits of polymer on steel surface. Once when the valley is filled, the conformal contact has been achieved completing the running-in process.

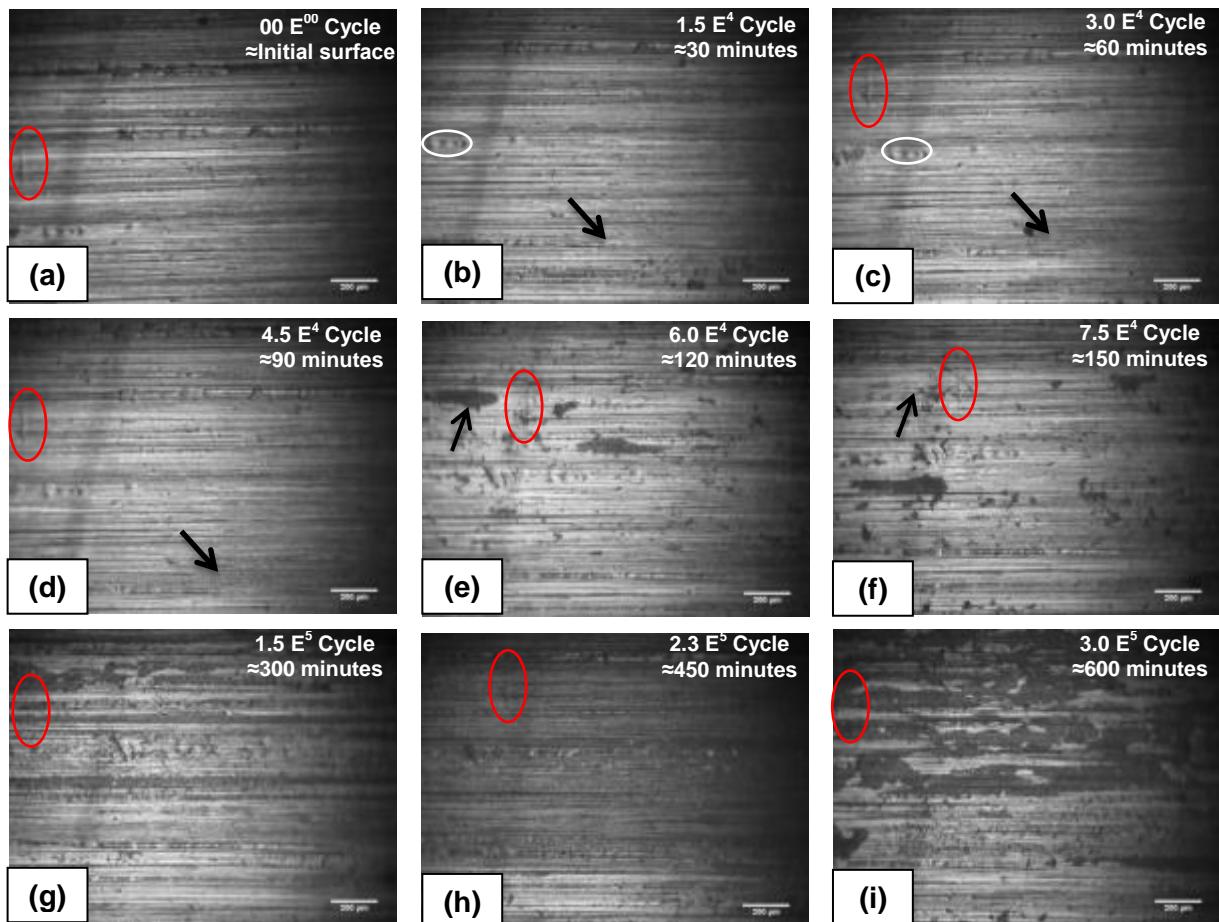


Figure 5 shows the deposition of PA66 transfer layer in the steel surface from running-in until the steady stage.

Increase in Ra of the steel surface at the beginning of testing of 1.5×10^4 cycles demonstrates the polymer filling in-between asperities of the steel surface, This is a consequence of scouring of initial surface of the polymer. However it's not significant which can also be explained from the polymer micrograph. For the same cycle 1.5×10^4 (Fig. 6b) the material loss is not substantial as observed from the surface change. In the next intermediate pause at 3.0×10^4 cycles there is a significant change in polymer Ra showing a large volume of material removal also seen in the micrograph (Fig. 6c). As a consequence black coloration of steel surface indicated by the arrow mark shows a mild deposit of transfer layer. Further to which the running-in continues and the polymer surface shows behaviour with dark phase as a consequence of material removal. Similar situation has been explained by Sviridyonok *et al* that the formation of transfer layer is a consequence of detachment of micro particles from the parent material. In stage I the polymer surface with dark phase resembles micro pits resulting from the removal of micro particles.

Subsequently after 6.0×10^4 cycles (approximately 120 minutes) which is the expected running-in period from preliminary testing the trend begins to change by showing a negligible rate of change in Ra beyond this point for both the steel and polymer surface. Starting the steady stage from 6.0×10^4 cycles the steel surface shows black patches with size of $200 \mu\text{m}$ length and $50 \mu\text{m}$ width is seen in Fig. 5e as indicated in 6×10^4 cycles. Even with no significant change in Ra in the steady stage the micrographs of the steel surface shows a large variation in the deposit of transfer layer elucidating the dynamic behaviour of the protective film. Once when the transfer layer is formed the contact condition changes from polymer-metal to polymer-polymer where mechanism undergoes a change to match the contact condition. In the development of polymer wear, surface (Fig. 6g,6h,6i) shows the cumulative plastic deformation in the steady stage is dominant. Moreover mild grooves indicating abrasion from partial sliding is also observed from the micrograph of polymer surface.

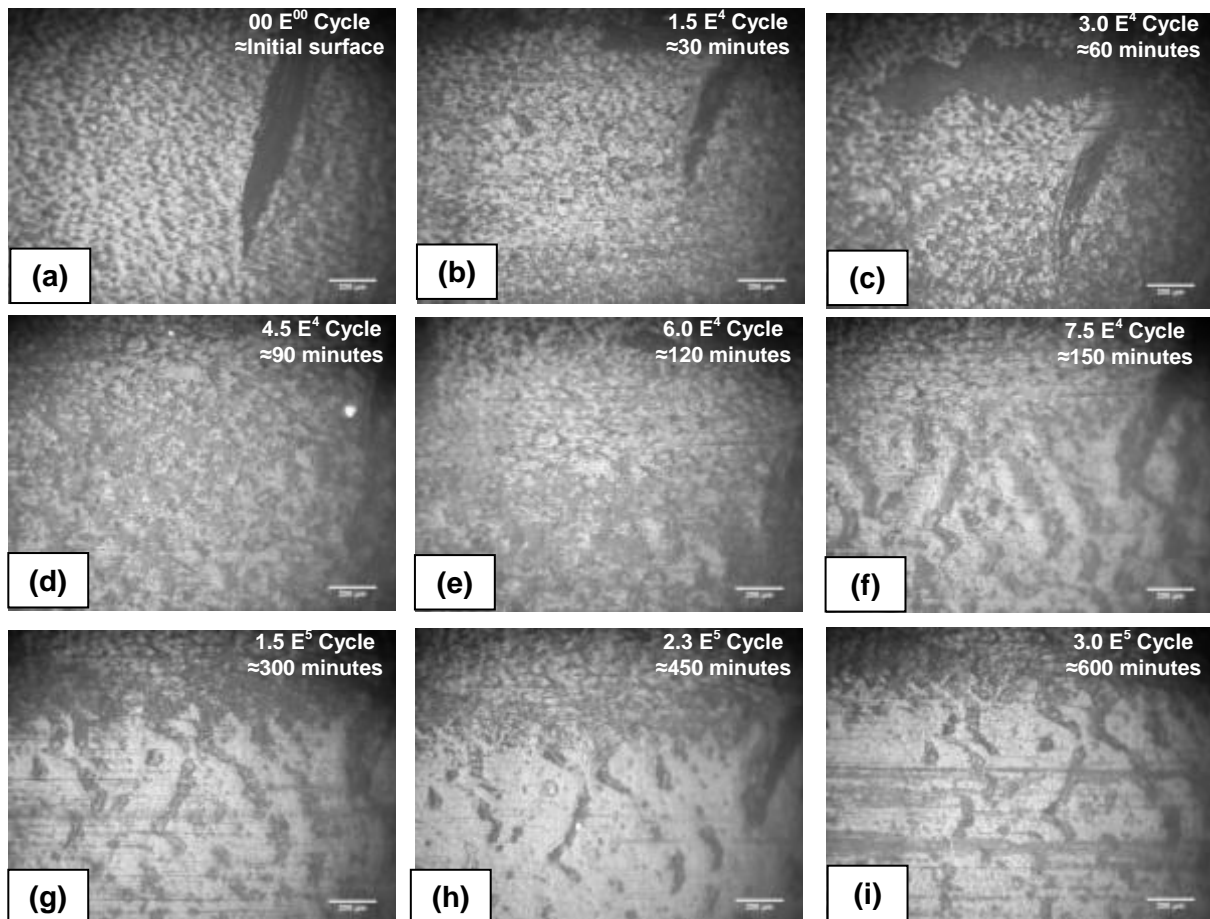


Fig 6 showing stage by stage change in polymer wear surface from 0 until 3×10^5 cycles.

Comparing the three images from the steady stage micrograph acquired at 3×10^5 and 1.5×10^5 cycles (Fig. 5g & 5i) are 50% identical considering the black deposits on steel surface. The black deposit at cycle 2.3×10^5 (Fig. 5h) is significantly larger than the earlier stage. Moreover, the deposited transfer layer has been removed in the forthcoming stage (3×10^5 cycles, Fig. 5i) showing a dynamic behaviour. Mergler et al in his sliding configuration of POM against steel explains that adhesion is not the factor for large transfer. The formation of polymer layer on the counter surface continues until a significant thickness of transfer film is formed. Further to which it depends upon the adhesiveness of the transfer layer to the counterface material. Sviridyonok et al has similar behaviour for polymer on polymer contact

Fig. 6 of the polymer surface confirms the dynamicity involved in the transfer layer formation. On comparing image acquired at 1.5×10^5 and 3×10^5 cycles (Fig 6g & 6i) with the image acquired at 2.3×10^5 cycles (Fig. 6h) abrasion is clearly visible with scratch pattern in both the images (Fig 6g & 6i) from the polymer surface. However image from 2.3×10^5 cycles (Fig. 6h) shows a relatively lesser intensity of scratches in the polymer surface which is due to the significant deposit of transfer layer in the steel surface as seen in Fig. 5h from the same cycle. Beyond 7.5×10^4 cycles the dynamic behaviour contributes to the tribological behaviour as the asperity interaction will be less effective and the tribological performance is contributed by the polymer on polymer contact rather than polymer on steel.

The dynamicity is even highly pronounced in the composite material as shown in Fig 7. Since the currently used composite material GF/PA66 is black in colour the deposit of polymer in the steel surface is well seen even at the initial stage of wear (Fig. 7b,7c &7d). Similar to PA66 the composite at the steady stage follows a trend with deposit of transfer layer in cycle 1.5×10^5 (Fig 7g) which then forms a uniform protective film over the steel surface (Fig 7h) covering 80% of the micrograph. Further to which the deposited composite transfer layer is then partially removed in the subsequent stage (3×10^5 , Fig 7i).

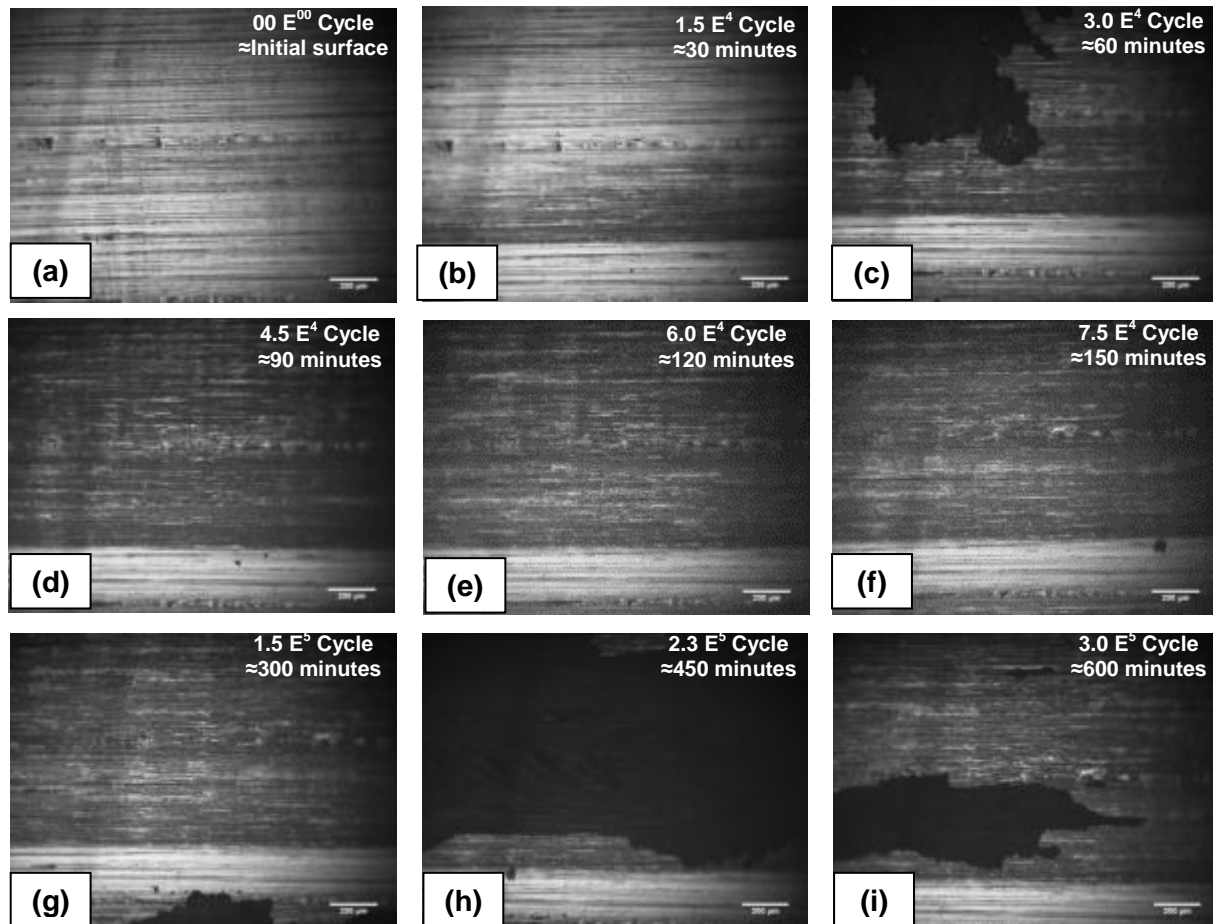


Figure 7 shows the deposition of composite (GF/PA66) transfer layer in the steel surface from running-in until the steady stage

The current methodology with a qualitative and quantitative approach gives an overall understanding of the dynamic behaviour of the transfer layer. However, with dismantling the test material causes disturbances in the equilibrium of the testing. Also the area under investigation is relatively small with a FOV of $1300 \mu\text{m}$. knowing that the imaging techniques works well on such small FOV, a system with larger capabilities such as online monitoring without stopping the test and investigations on a significant area can aid valuable information on the transfer layer dynamicity.

4 CONCLUSIONS

Tests with intermediate pauses on polymer and its composite against steel in rolling sliding contacts resulted in the following conclusion

- In polymer tribology of rolling/sliding contacts the wear mechanism based on the surface morphology can be segregated in four different stages such as 1. Scouring 2. Running-in, 3. Transition and 4. Steady stage
- Irrespective of the steady stage both the polymer and its counter material there is dynamicity involved in the transfer layer formation from the view point of micrograph. However, the roughness change does not show the dynamicity in the steady state.
- The roughness measurement at running-in and steady stages agrees well with the micrograph.
- Steel tested on PA66 has relatively less transfer layer compared to its composite (GF/PA66).

5 NOMENCLATURE (OPTIONAL)

Ra	Roughness average	μm
D1	Diameter of steel disc	m
D2	Diameter of polymer disc	m
Fn	Normal force	N

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