University of Southern Queensland, Faculty of Engineering and Surveying

Adhesive Wear and Frictional Behaviour of Glass Fibre Reinforced Thermoset composites

A dissertation submitted by

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Abstract

Friction and dry wear behaviour of glass fibre reinforced epoxy (GFRE) and glass fibre reinforced polyester (GFRP) composites are studied in the current project. Three sliding orientations of fibre with respect to the sliding distance are considered in the investigation, i.e. parallel orientation (P-O), anti-parallel orientation (AP-O), and normal orientation (N-O). On the other hand, different sliding distances (0- 15) km are accounted. The adhesive wear experiments were carried out using block-on-ring (BOR) configuration at room temperature, applied load of (30N), and sliding velocity of (2.8 m/s). Interface temperature and frictional force were captured and recorded during the sliding. Worn surfaces were examined by using (SEM) to classify the damage. The results revealed that the highest wear rate is taken place in (AP-O) of GFRE. (P-O) is the highest wear rate of GFRP. On the other hand, the lowest wear rate is exhibited for (N-O) at longer sliding distance. The maximum friction coefficient is observed when sliding take place in (N-O and P-O) at higher speed level. Although, (AP-O) shows 0.25 which is the lowest friction coefficient value than other orientations. (P-O) orientation of GFRP gave higher wear rate at maximum speed test in comparing to normal orientation.

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Gabrel Ahmad,

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

As a result of the rapid development that the world witnesses and the challenge in using metal materials in tribological industrial applications, the tribological behaviour of polymeric composites has recently experienced a creative development, and attention by many researchers. Fibre reinforced polymeric composites have numerous advantages compared to the metal materials due to their competitive mechanical properties of high specific strength, low weight, low cost of raw materials, low processing cost…etc. Recently, composites materials are heavily used in many applications that have been determined for these materials. Furthermore, composites materials have been provided superlative solutions to produce structural materials of aerospace industries, (Pihtili, 2009).

Tribological properties of such materials have been a core of interest for many scholars and researchers. The friction and wear performance are the significance characteristics that have been taking place by several researches,(Yousif, 2013b, Bajpai et al., 2013) focusing on the composite application in brakes, clutches, bolts and nuts. On the other hand, Shalwan and Yousif (2013) have been expounded that friction is the value of energy which dissipated at the material contact surface. Wear, the resistance to remove of solid surface, has been defined in various aspects such as weight loss, wear resistance and specific wear rate, (Bajpai et al., 2013). Friction and wear are classified to become a main effect on the machinery in the field of industry as so to work efficiently. Such deficiencies are mainly related to lifetime of the machinery, (Holmberg et al., 2012). In other words, it is important to arouse many researches to study the tribological behaviour of polymeric composites.

Nowadays, friction and wear are the most common problems that are encountered in industrial engineering and machine parts which cause to the replacement of components and assemblies in engineering, (Unal et al., 2004). As a result, the uses of polymer materials have been increased by industrial countries. Therefore, the need to understand the tribological behaviour of polymer is clear of this fact of polymer science and engineering (Brostow et al., 2010). There have been several types of productive friction and wear such as brakes, clutches, bolts and nuts. Also the unproductive friction and wear is equally considerable such as gas turbine, cams and bearings, and external combustion engines, (Bhushan et al., 1995). Nevertheless, the influences of deformation and adhesion of friction are addressed. Friction on surface energy is affected by different factors which are sliding velocity, applied load, and temperature, (Myshkin et al., 2005). In addition, the authors have reported that friction comprises of three elements namely, interfacial bonds, strength, and shearing and rupture of rubbing around the contact area of materials. It may also lead to damage materials' surface and then change the mechanical properties of the composite. Finally, the results from friction are temperature during converting mechanical energy to heat, this heat is produced by friction and deformation of materials leads to generate heat. On the other hand, few beneficial applications are provided by the friction such as tyres and brakes friction.

There are several studies have been done to inspect the tribological performance of polymeric composites based on synthetic fibres such as glass, (Pihtili, 2009). Carbone fibres were investigated by (Suresha and Kumar, 2009). From the literature, there is a lack of understanding on the tribological behaviour of thermoset composites based on synthetic fibres such as glass. In the recent work by Shalwan and Yousif (2013), it is highly recommended further studies on the thermoset composites to identify the wear and frictional characteristics of thermoset composites based on glass fibres. This motivates the current study.

In the current report, the wear and frictional behaviour of two fibre thermoset composites are considered as epoxy and polyester. Three different orientations of fibre with respect to the sliding distance are accounted in the study and different sliding distance (0- 15) km.

1.2 OBJECTIVES OF THIS STUDY

1. To study the specific wear rate and friction behaviour of epoxy and polyester composite based on glass fibre.
2. To study the influence of fibre orientations on specific wear rate and friction coefficient.
3. To examine the worn surfaces of the composite after the test and categorize the wear mechanism.
4. To understand the influence of interface temperature on specific wear rate and friction behaviour
5. To investigate the influence of the rubbing process on the roughness profile of the composite.

1.3 CONTRIBUTIONS AND SIGNIFICANCES

1. Understanding the wear behaviour of new materials will assist the designers in materials selection since there is no much available date on such materials.
2. This research is going to be a base of new research at USQ.
3. The outcomes of the research will contribute to the tribological science and will become a base for the new researches in this area. Furthermore, the findings will be published in international journals.

1.4 DISSERTATION LAYOUT

This dissertation organized for six parts as shown in figure 1.1 bellow. Firstly, the introduction explains the objectives of this work in reasonable pattern. Moreover, it indicates the aims behind this project which substantially defines the activities undertaken and the direction to complete this project. Secondly, the literature review provides significant researches that have been reported in this area. These articles reach to the damage that materials surface is subjected by different sliding parameters; damage face in applicable materials is also focused such as epoxy and polyester. Thirdly, the methodology demonstrates the equipment's and the used materials that are processed so as to achieve this work. This methodology is involved materials such as glass fibre reinforced epoxy/polyester. Furthermore, tribology machine and thermo-imager camera are used. Fourthly, the experiments' results and discussion are obtained in this chapter. Fifthly, the comparison between the outcomes is presented. Finally, conclusion and recommendations are provided. Appendices show project specification, conference paper and further outcomes respectively.

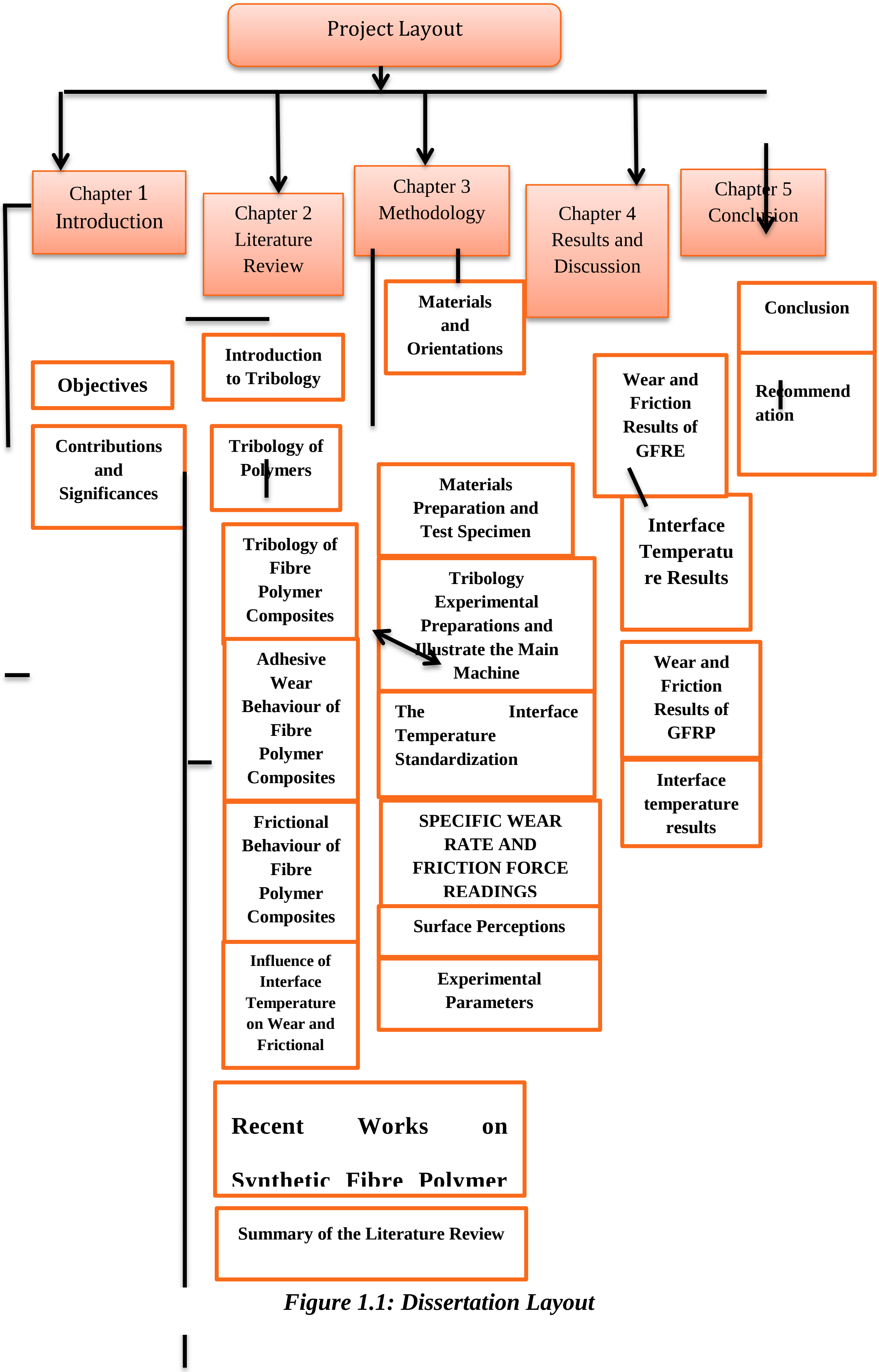


Figure 1.1: Dissertation Layout

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION TO TRIBOLOGY.

Tribology is one of the important branches used in the mechanical engineer sectors(Nosonovsky and Bhushan, 2012). Tribology is the Greek word ' tribo' which verbatim indicates the science of rubbing, (Bhushan 2002). Tribology comprehends the science and technology that explore wear, lubrication, and friction of interacting surface in relative motion, (Friedrich et al., 1995). The principle of tribology is evidently the minimization of the deterioration of the surface resulting of friction and wear, (Khonsari and Booser 2008). The fundamental benefit in tribology exists in various fields involving lubrication, friction, wear, and other machine element such as piston rings, magnetic desk drives, and hydraulic lifts, (Khonsari and Booser, 2008).

Friction and wear, are the most common problems that encountered in industrial engineering and machine element which leads to the replacement of components and assemblies in engineering, (Unal et al., 2006). As a result, the use of polymer materials in dentistry continues to increase. Therefore, the need to understand the tribological behaviour of polymer is clear of this fact of polymer science and engineering, (Brostow et al., 2003). Bushan (1995) reported that tribology is greatly importance to modern machinery which applies sliding and rolling surfaces. The author mentioned that there have been several types of productive friction and wear such as brakes, clutches, bolts and nuts. Also the unproductive friction and wear is equally considerable such as gas turbine, cams and bearings, and external combustion engines. Moreover, Tooth wear studies have recently been appointed that dental tribology science is considerably since wear operations; exhaustion, corrosion and abrasion are particular to dental tribology, (Addy and Shellis, 2006).

Friction is defined as strength of contact surface in proportional motion and the coefficient of friction is (μ). the constant of friction is resolute by the magnitude of the real rubbing area, (van Kuilenburg et al., 2012). Other definition for friction is the magnitude of energy that squandered at the material surface, (Shalwan and Yousif, 2012). Based on the friction mechanisms which are namely severity deformation, adhesion and ploughing, (Shalwan and Yousif, 2012). Wear is a resistance of process of removal of solid surface, and it can be determined in various aspects such as weight loss, wear resistance and specific wear rate, (Hutchings, 1992). Bhushan (1995) highlighted that the energy resources in the world have markedly appeared as friction in one model or/and more. In order to overcome the importance of reducing the friction to some of the drawbacks of natural fibres experience such as hygroscopic and hydrophilic in nature as it tends to diminish the relationship strength between the natural fibre and polymer resin.

Yousif (2012) Notified that Friction, wear and lubrication are detected to tribological circumferences. In the previous industries, designers are not considered the tribological factors. Furthermore, mechanical engineering designers have recently been provided that tribological mechanism is an initial consideration in their works. It is an indisputable fact that tribological technique has become a core of advantage in mechanical studies areas so as to obtain typical product quality.

2.2 TRIBOLOGY OF POLYMERS

Tribology of polymers is a historical science which has been well-known in the area of design engineering. In the last decades, tribological behaviour of polymers is represented specifically the mid-20th century even today. New contact adhesion measurement has been defined with different coatings of surface energy,(Myshkin et al., 2005). Moreover, tribological researches have been executed under especial situations of dry sliding on the wear and friction behaviour of polymers, (Budinski and Budinski, 2009). Also Myshikin, Petrokovets (2005) have illustrated that the influences of deformation and adhesion of friction are addressed. Friction on surface energy is affected by different factors which are sliding velocity, applied load, and temperature.

Nowadays, applications of polymeric materials require sufficient knowledge of tribological properties. It is important that tribology of polymeric exists to be taken into consideration in material technology and engineering industries, (Brostow et al., 2010). There are several structural applications which are depended on polymer matrix. In addition, polymer and their composites have excessively used in order to offer advanced engineering applications in the aerospace, automotive, and improvement the metallic materials, (Basavarajappa and Ellangovan, 2012a).

Yousif (2008) highlighted that polymers and their composites are one of the important materials used in the machine elements which are designed to avoid tribological loading situations. Also the researcher has mentioned that the possibility understand of the wearing technique under appointed sliding circumstances. As a result, it is an essential that composite materials behaviour has known under operational conditions such as friction and wear resistance. On the other hand, tribological behaviour of polymeric composite has been paid attention to surface temperature as another imperative parameter, (Basavarajappa and Ellangovan 2012).

Blau (2010) has pointed out that the high-temperature; friction and wear are controlled in applications such as internal combustion engines, and aerospace propulsion systems. There have been two principal features that the polymers and their composites was made to ensure that its characteristics meet technical specification which are friction, wear resistance and surface temperature to minimize such issues in the future. Hence, these materials has become desirable compared to ordinary metallic performance,(Pihtili, 2009). In view of this, Yousif

(2008) has demonstrated that it also presupposes a preferable understanding of sliding wear mechanisms as so to design parts which have friction and wear resistance characteristics of the impacting loads on worn surfaces.

Numerous studies of friction are shown that the main non-interacting components of friction are considered which are adhesion and deformation,(Myshkin et al., 2005), Fig. 2.1. Friction comprises of three elements namely, interfacial bonds, strength, and shearing and rupture of rubbing around the contact area of materials, (Myshkin et al., 2005). The wear resistance is considered as one of the significant mechanical characteristics when the part of machine is subjected to a form of slipping contact, (Ben Cheikh Larbi et al., 2005). Also Cheikh Larbi, Cherif (2005) mentioned that Variation of the surface layer obtained from the chemical reaction , temperature and mechanical stresses. Polymers are sensitive to these factors because of that particular structure and mechanical behaviour are acquired.

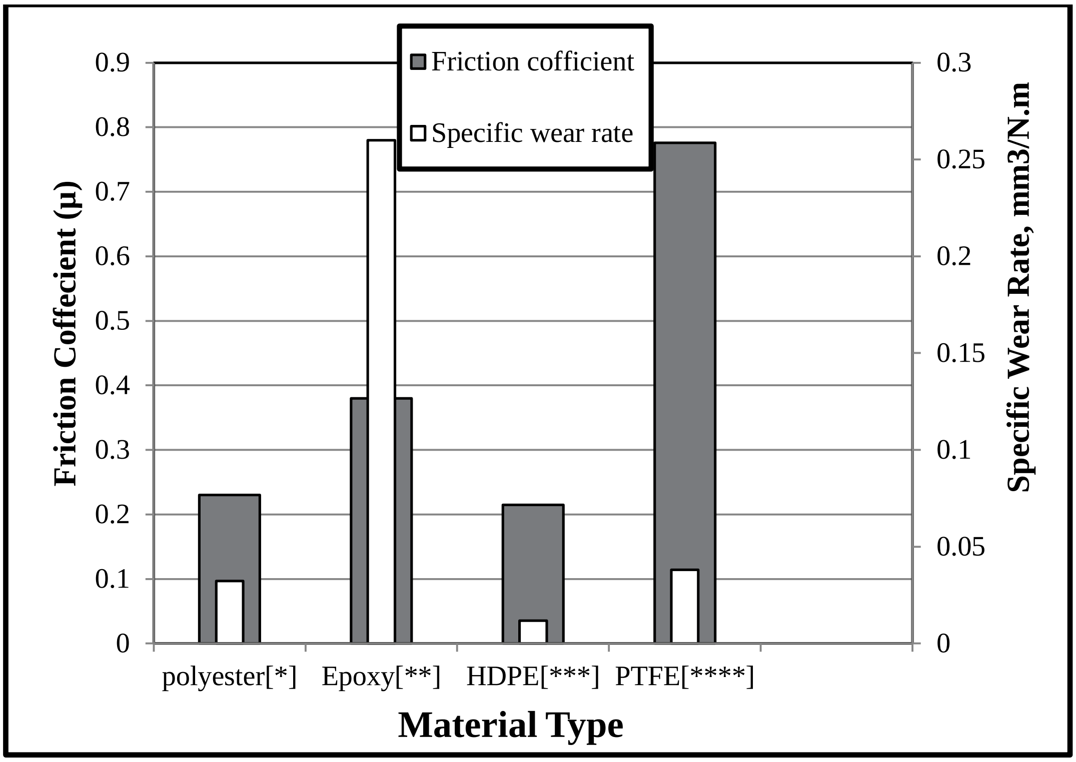


Fig. 2. 1: Friction coefficient and specific wear rate of common

[*](El-Tayeb et al., 2008), [**](Shi et al., 2003), [***](Cong et al., 2008),

[****](Unal et al., 2004).

Drawing on obtained views, the polymers and their composites are prestigious materials that provide the idealist mechanical properties of technical fields. Therefore, polymers were accepted by the designers to be used to minimize the frictional loss between the layers of material. Based on the previous studies, the required wear resistance and surface temperature were added to the technical considerations.

2.2.1 TRIBOLOGY OF FIBRE POLYMER COMPOSITES

Global warming is considered significant. As a result of certain comprehensive issues, some regulations are seriously taken to constrict environmentalist pollutions and contaminations have generally required for bio-composites materials, (Shalwan and Yousif, 2012). From tribological point of view, the application of polymer is usually used for tribological objectives which are increased and extending into even more new field. Many researches have been carried out on the tribology of polymer due to their usage in several applications and industries, (Brostow et al., 2010).

Nowadays, polymer matrix composites are became the most attractive for many applications which are aerospace, automotive, and chemical industries. Also polymer composites can be used in mechanical industrials such as wheels, impellers, brakes, clutches, conveyors, gears, cams, transmission belts, bushes and bearings, (Basavarajappa and Ellangovan, 2012b). furthermore, polymer matrix composites are investigated under special conditions in terms of sliding and abrasive wear by several studies, these results indicate that wear performance depends on applied load and sliding velocity, (Quintelier et al., 2006). Pihtili(2009) has reported that composites materials are widely used because of their properties such as low density and cost. For the few decades, glass fibre is kind of these materials; numerous studies have been allocated for these materials in terms of wear resistance, coefficient of frictional behaviour, and the effect of elevated temperature. For instance, the sliding wear is caused to reduce the wear resistance, for example in the case of adhesion and fatigue of wear. Moreover, this decreasing in wear performance is because of the pressure carrying capacity of the fibres. the results have provided that there is an existence remarkable characteristics on the worn contact surfaces, (Quintelier et al., 2006). El-Tayeb et al., (2006) Investigated that the wear resistance of glass fibre reinforced polyester composites have higher wear resistance compared to plain polyester. also there are three contact direction which are parallel(P), anti-parallel (AP), and normal direction (N), as a result the wear performance rises dramatically whereas increasing in the normal load for various orientations.

Myshkin (2006) has presented that there have been other impacts on friction in terms of temperature, by converting mechanical energy to heat, temperature is generated from friction and the main source of this heat is deteriorated of surface. In addition, surface contact of various coating can be determined with adhesion parameter. The author studied the deformation and adhesion of friction. This research is shown the principles effects of applied load, sliding velocity, and temperature. Hence, In the light of this weight, the applied load specified increases. As a result, the friction coefficient is likely to increase.

2.2.2 Adhesive Wear Behaviour Of Fibre Polymer Composites

Adhesion can be defined as friction impact between two surfaces is applied, surface forces were formed of attraction and repulsion distribute between the molecules and atoms of two approaching surfaces. These forces equalize each other, (Myshkin et al., 2005), Fig. 2.2. Likewise, Myshkin, Petrokovets et (2005) have explained that measure adhesion can be determined by measuring the molecular forces, which are effectively between two solids with particular agents. Also, they have employed a set of procedures to measure molecular attractive forces based on validation of outcomes. However, molecular forces have been recently measured by using atomic for microscopy.

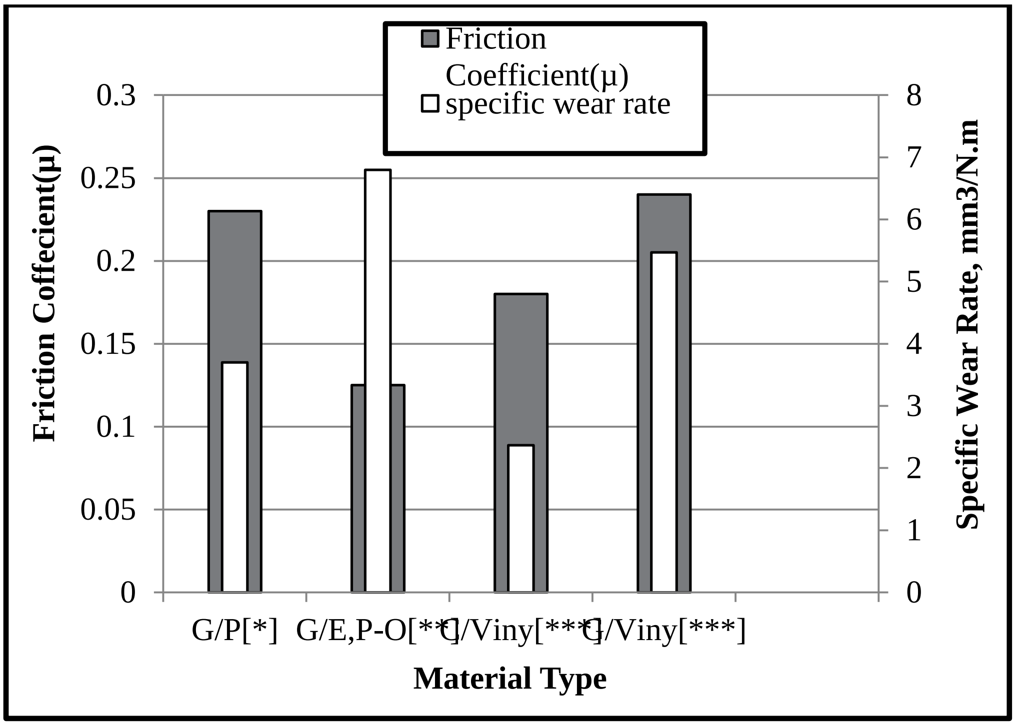


***Fig. 2. 2 Friction coefficient and Specific wear rate of common fibre polymer composites, [*](El-Tayeb et al., 2008), [**](Pihtili, 2009), [***](Suresha and Kumar, 2009)**.*

Adhesion and deformation are measured the source of frictional forces. Therefore, deformation appears while two slides surface contact to each other, such as plastic and elastic deformation, viscoelastic deformation, these may cause to mechanical energy dispersion, (Myshkin et al., 2005). There are several influences on friction in terms of load, velocity, and temperature. Firstly, coefficient of friction and applied load are proportional to friction force, at load between 10-100 Newton coefficient of friction stays constant. Secondly, friction force will minimize because of short period of contact, sliding velocity resistance will maximize and at high velocity. Finally, the results from friction are temperature during converting mechanical energy to heat, this heat is produced by friction and deformation of materials leads to generate this heat.

According to the tribological of view, there have been implemented several works on jute, cotton, oil, palm, sugarcane, coir, and bamboo fibres concerning their applications in tribo-polymeric composites. For example, oil palm fibre reinforced polyester composite is detected that oil palm fibres reinforced the wear performance of polyester by three to four compounds. In other study on cotton/polyester composite, the particular wear rate of polyester reduced markedly with the addendum of cotton fibre. Furthermore, sugarcane fibre has been influenced on tribo-characteristics of polyester composites. fibre mats oriented parallel to the sliding direction presented that wear performance of fibre mats oriented parallel to the sliding direction is lower than fibres oriented anti-parallel under the same test situations, (Nirmal et al., 2010b).

The influences of the coir fibres can be measured in terms of frictional and wear performance, block-on-disk (BOD) machine used in specific circumstances. As a result, experiments came up with worn surface, by use of scanning electron microscope wear rate and friction coefficient were studied in various aspects which are applied load between 10N to 100N, and sliding distance between 0km to 4.2km, (El-Tayeb et al., 2008).

It is generally accepted that the adhesive wear behaviour of polymers has been affected by several issues such as high friction of coefficient, stick slip behaviour, and high material removal. Therefore, many authors have reported that the most common mechanism is used to enhance the feathers of adhesive wear of polymers by providing carbon as synthetic fibres, (Friedrich et al., 2005), and glass, (Samuel et al., 2012). The tribological properties of the polymer depend on different thermoplastic and thermoset of synthetic fibres. In addition to that, interfacial adhesion of the fibre with the matrix is considered as one of several factors are controlled the performance of synthetic fibre/polymer composites, (Monteiro et al., 2012). For instance, the wear performance of polyester is enhanced by reducing the wear rate in glass fibres. Moreover, the performance of wear and frictional relies on some parameters which are applied load, sliding velocity, and fibre orientations. Hence, process parameters are effectively controlling the wear and the frictional behaviour of composites, (Chauhan et al., 2012). Adhesive wear applications of using betelnut fibres to reinforced polyester composites have been studied by Yousif and El-Tayeb (2010). Also the researcher has explained that high micro and macro crack diffusion on the interface of the composite surfaces. However, the shear force is resisted and managed by the end of the fibres to protect the polyester area. The large diameter is the main reason that it can be caused to disseminate of crack whether micro and/or macro on the rubbing surface.

Tribo-performance of polymeric composites is influenced by the contact conditions, which are wet and dry. From the previously reported, some of polymeric composites such as PA, UHMWPE, (Suresha et al., 2009), and betelnut fibres, (Nirmal et al., 2010a), have been enhanced during wet contact conditions compared to dry. Many researchers have been explored the effect of adhesion of elastic. Whereas, the elastic half-space comes in contact with a smooth sphere the Hertzian elastic theory is established the contact area. In addition, adhesive friction comprises strong long-range bulk forces, and weak short-range adhesive forces. To sum up, the adhesive friction includes the technicality of energy consumption, due to hysteresis and fracturing adhesive between the contacting areas, (Nosonovsky and Bhushan, 2007b).

2.2.3 Frictional Behaviour Of Fibre Polymer Composites

Throughout history, friction has been defiance for humanness. Hence, Myshkin and Petrokovets (2006) defined that friction is the resistance of motion contact between thin surface layers of bodies which the fundamental way for heat transfer between tribology is caused by friction and concept of convection. Friction is the magnitude of energy that consumed at the surface. Frictional behaviour has been an essence of interest for many scientists and researchers. Three mechanisms have been attributable to frictional behaviour which is adhesion and blouging, and cruelty deformation. Also, researchers have made attempts to determine that the total friction coefficient can be evaluated by quantitative treatment. In addition to that, the behaviour of these mechanisms depends on operating conditions and the type of material which are namely the contact surface topography, (Shalwan and Yousif, 2012).

Nosonovsky and Bhushan (2007a) Paid attention to the mechanisms of dry friction, the unique mechanisms of dry friction are deformation of severities, adhesion, fracture and third body mechanisms. Based on these studies, the theoretical rules to measure the coefficient of friction are the equal normal load to the ratio of the friction force. In the light of this weight, Suresha, and Shiva Kumar (2010) examined that the coefficient of friction of polymeric composites depends on applied load, and sliding velocity. Additionally, their experimental results shows that the coefficient of friction is directly proportional to applied load and/or sliding velocity. Shalwan and Yousif (2012) have applied an experiment to measure the friction behaviour of the natural fibres under dry sliding provisions; the authors reported that the frictional coefficient of epoxy is reduced by the existence of kenaf fibres in the composites. Also polyester with coir and betelnut and oil palm fibres achieve respectively reduction of the friction coefficient.

Diverse works have focused on volume friction behaviour of natural fibres. These researchers have investigated that frictional behaviour of polymeric composites can be strongly influenced by the volume friction, Yousif and El-Tayeb (2008a) have explored that the effort of replacing seed oil palm fibres(SOPF) with woven glass fibre(WGF) for tribo-polymeric composites. Moreover, many experiments have been done under dry sliding contact by using (BOD) with special conditions which are sliding distances up to 5 km, applied load 20N, and sliding velocity 2.8 m/s. In addition, Chin and Yousif (2009) have pointed out that kenaf fibres as reinforced with epoxy matrix have been used for bearing applications.

(BOD) machine is used to examine the frictional behaviour of fabricated composite at different conditions in terms of applied loads (10-100), sliding distances up to 5 km, sliding velocities (1.1-3.9 m/s). Kenaf fibres afford greater wear and friction coefficient as support to the matrix compared to oil palm, coir fibres, and sugarcane. Subsequently, set of results are exposed that the specific wear rate (w_s) of woven glass reinforced polyester (GRP) and 35% volume of seed oil palm reinforced polyester (SOPRP) were comparable, (Yousif and El-Tayeb, 2008a). The study also provided that the applied load and sliding velocity have sparse influence on the KFRE composites. However, the fibre orientation has obviously affected on the frictional behaviour and wear performance of the composites, (Chin and Yousif, 2009).

In summary, frictional behaviour is one of the important technologies used in tribology and materials sector. Yet, there remains an argument whether the frictional behaviour has brought positive and/or negative impacts of different applications. For instance, in the USA, reducing friction in engine parts has economized 120$ billion per year, (Yan et al., 2010). Advantageous, friction has used for everyday applications such as tyres, brakes friction. On the other hand, shear force and heat generation are occasionally caused by friction between sliding surfaces, which always lead to surface deterioration and deformation in changing degrees, (Yan et al., 2010). Likewise, Kenneth Holmberg (2012) employed a set of techniques to determinate the friction in the engine of passenger cars, tires, and breaks. Friction, lubrication, and wear have been respected to provide a great effect on the machinery in terms of efficiency and lifetime and then in the economy of the UK.

2.2.4 Influence of interface temperature on wear and frictional behaviour of fibre polymer composites

Interface temperature is a fundamental parameter in understanding tribological behaviour of polymeric composites, (Pihtili, 2009). Blau (2010) indicates that it is important to control of elevated-temperature friction and wear in several applications such as internal combustion engines, bearing of aerospace propulsion systems, and manufacturing equipment. Furthermore, higher interfacial temperatures can be produced by frictional contact and external sources. For instance, car brakes generate temperature enhancements due to frictional contact. Moreover, different properties are caused due to the increase of temperature such as mechanical and thermo-physical characteristics. Metals and alloys yield strength is decreased so as to keeping temperature in enhancements. For example, alloys yield strength has progressively decreased after critical point of yield strength such as nickel alloys, (Blau, 2010). Also, the researcher has studied the relationship between modulus of elasticity and temperature; he employed a set of experiments to determine maximum elastic stress for 8 mm long and 9.53 mm diameter. From the experiment's results the author has proved that high temperature lead to decrease elastic contact stress.

There are many influences of interface temperature on the wear and frictional behaviour. Pihtili (2009) has investigated that the wear of glass-woven reinforced composites is influenced due to two thermosetting resins epoxy and polyester under dry conditions. The previous works focus on the polymeric composite material in terms of the wear and friction properties. low thermal conductivity and high stiffness have been specified under particular conditions which are high temperature at the sliding surfaces meanwhile friction and after a specific critical temperature, wear performance were discovered to be increased very markedly, (Pihtili, 2009).

Several experimental have been done by Yousif and El-Tayeb (2008b) to investigate interface temperature and frictional behaviour of chopped strand mat fiberglass reinforced polyester (CGRP). The researchers have used three various orientations, namely parallel (P), anti-parallel (AP) and normal orientation (N). Also they are several parameters, namely normal load (30, 60&90), sliding velocity (2.8, 3.52 & 3.9 m/s), and sliding distance (0-2.51km). Experimental results show that friction and interface temperature properties of the CGRP/stainless steel based on principal roles which are pattern's orientations, and the tested parameters. The result from measurements, which proposed by the researchers, were exhibited that the interface temperature of (AP & P) orientation respectively is clearly similar. It will reduce due to lower sliding velocity, maximum interface temperature is obtained while the CGPR was examined in AP-orientation during higher friction rates, and however, the interface temperature was likely to decrease comparing with P-orientation as so to the rubbing operation mechanism.

According to Blau (2010), there have been immense mechanical properties of metals and their wear resistance which are connected to oxidation, sulfidation, and other chemistry operation of tribo-contact. Therefore, the researchers have paid attention to the effects of elevated temperature on thermodynamics and reaction kinetics. As a result, the Ellingham diagrams are used to measure the change of the Gibbes free energy (G) by comparing with function of temperature which is various oxidation reactions. Based on the previous discussion chemical reaction rates are inclined to increase while temperature increases. Furthermore, Blau investigate that the role of tribo-layers “glazes" is described as formula on sliding layers during frictional contact. Temperature resulting can be specified as the sum of the temperature of the associated plus.

From the tribological point of view, polymer composites are considered significant, central benefits in using these materials in tribological applications such as bearings, bushings and sliding surfaces. However, these materials are subjected to deterioration due to heat generated by the friction and/or shear force are generated by tribological loading. Moreover, the researchers have discussed the tribological behaviour of polymer composites reinforced by natural fibres such as Jute, Cotton, Oil palm, Sisal, and Kenaf. Eventually, the interface temperature and frictional behaviour have a major impact on the tribological performance of polymeric composites. However, the case of synthetic fibre enhanced epoxy composites investigated that the interface temperature has more influence compared to the frictional force. Furthermore, the friction and wear behaviour of the polymeric composites are controlled by equal operating parameters and fibre orientations, (Yousif, 2013c).

2.3 Recent works on synthetic fibre polymer composites

Synthetic fibres have brought more sufficient as advanced composites and applications have been heavily studied. The petroleum issues have made bio composites markedly important. However, these materials are continuously under pressure from the international market, which in turn, presupposes continuous research, (Faruk et al., 2012). Synthetic fibres have several features compared to inorganic fibres, i.e. anisotropic, non-abrasive, compostable, and recyclable, (Sena Neto et al., 2013).

There are immense works on Synthetic fibres polymer composites focusing on the mechanical properties of the composites. In the recent decade, there is high attention paid to use the Synthetic fibre as reinforcements for polymeric composites in tribological applications. In the coming sections, literatures on the previous works are addressed covering the mechanical and tribological researches on such composites.

2.4 SUMMARY OF THE LITERATURE REVIEW

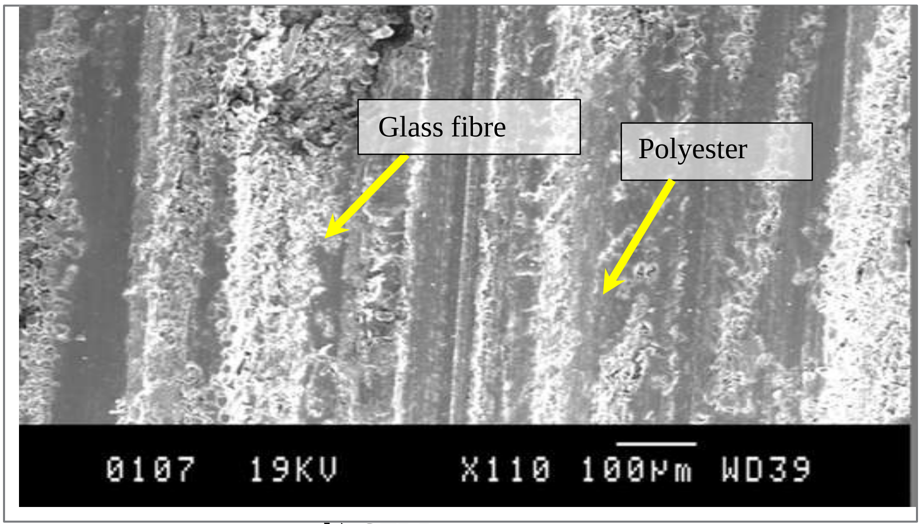
There have been many articles that have been done in materials science and they clarify different studies under different sliding parameters. The literature review can publicize obvious explanations of previous researches or/and studies that have been published to determine surface damage control under different sliding parameters. For example, (Yousif et al., 2006), have studied interface temperature and friction coefficient of glass fibre/polyester under different applied loads and different sliding distance. They found the interface temperature approximately 24-48 ºC and the increase of friction coefficient is discovered between the glass fibre and the polyester. According to these previous works different surface damage features are resulted from experiments under different sliding conditions. No much researches concentrated on the study between the friction force and wear resistance with surface observations. This research will study the influences of friction force, specific wear rate, and interface temperature on the surface damage by tribological loading.

CHAPTER 3: METHODOLOG

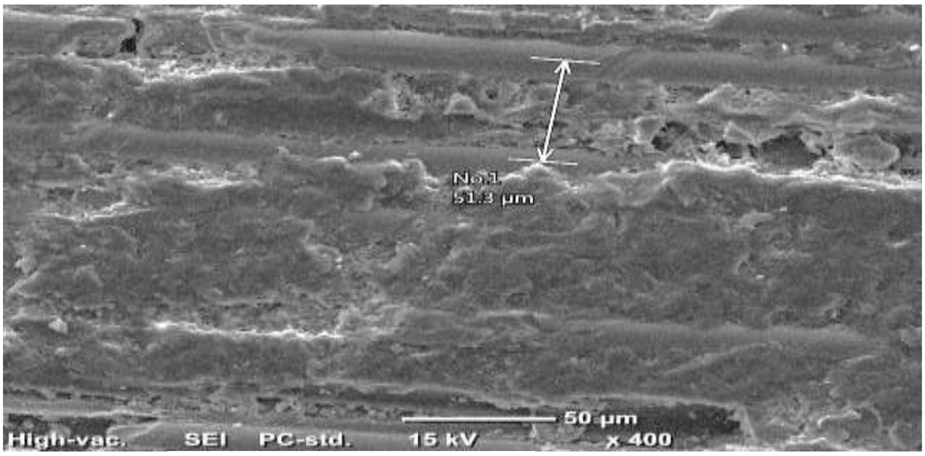
3.1 MATERIALS PREPARATION

This study proposed to use these materials in terms of their surface damage characteristics meanwhile they were experimented under diverse sliding conditions. Hence these materials have to be used in these experiments easier than other materials which may appear no surface damage. This project has used well known materials such as Neat Epoxy (NE), Glass Fibre Reinforced Epoxy (GFRE).

There are combinations of materials being used to meet technical procedures. Glass fibres based composites have been specified of a set of mechanical characteristic. In addition, this work has been used the liquid of epoxy resin (DER 331). It is occasionally used for several purposes such as automotive parts and casting. Epoxy resin supplies good resistance to adhesive and alkalis properties. The epoxy resin and hardener has been mixed with 2:1 of ratio. Also the mixture was systematically made, melted down in the mould and placed in the vacuum room (MCP 004PLC). In order to dispose of air bubbles between fibres in the mould at room temperature 24 hour. Glass fibre reinforced epoxy and glass fibre reinforced polyester were chosen as reinforcement materials. In order to provide prestigious properties for, this specimens were conducted with the specific volume of fibre is v_f =48%. Micrographs of the original composite surface for both materials selected are shown in **Fig.3.1**. Consequently, the orientations of fibre have been paid attention. GFRP were used as a reinforcement material that it provides a high chemical resistance and high resistance to environmental influences. Epoxy resins are preferred so as to commonly of available rates from high melting solids, and viscous liquids. They have numerous of mechanical properties, and chemical resistance. Furthermore, epoxy resin had approximately less than 2% of the shrinkage and high hardness. The provided composites were formed in size 30mm*20mm*20mm and different orientations of fibres were displayed in **Fig.3.2.**



b) GFRP



a) GFRE

Fig. 3. 1 Micrographs of the original composites surface for a) GFRP and b) GFRE

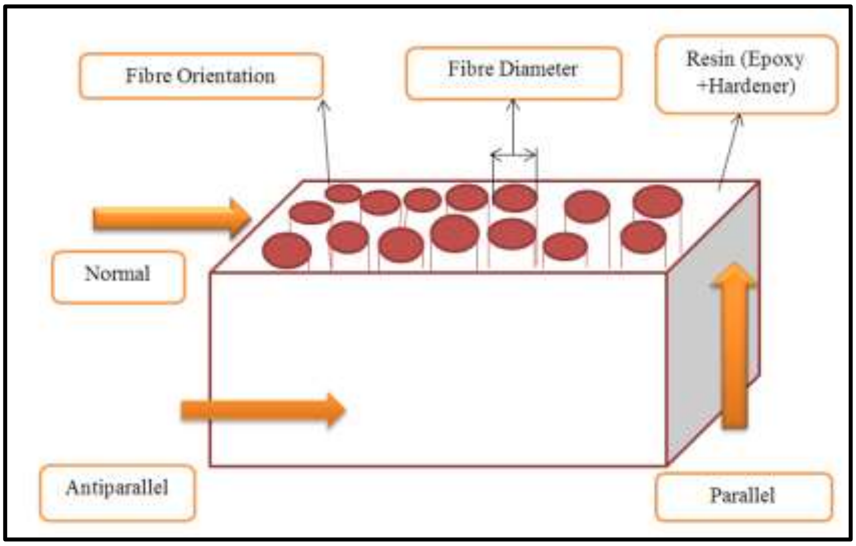


Fig. 3. 2 Schematic drawing showing the orientation of the fibre

Similar techniques are conducted in fabricating the synthetic specimen, three orientations have been considered in the tests. Polyester is a thermosetting resin that has been used a. Glass fibre reinforced polyester has been produced under a different of lengths, widths, and weights. 20-30mm, 450g/m^2 are used as measurements of current specimen of fibre lengths and mass of fibre respectively. (Revesol P9509) is an unsaturated and addition of Methyl Ethyl Ketone Peroxide (MEKP) which can be used for ambient the surrounding temperature. Kong Tat Company of fiberglass engineering (Malaysia) has been provided both reinforcement and polyester materials.

3.2 EXPERIMENTAL SET UP

Block-On-Ring (BOR) is the main machine that it has been used to conduct the experiments. The specimens surface (10mm*10mm*20mm) was tested against a counterface made of stainless steel (AISI 304, hardness =1250HB, Ra=0.1µm). Before each test, (Sic G2000) was utilized to smooth the counterface and thereafter a piece of wet cloth with acetone was used to clean the counterface. **Fig. 3** shows the block on ring step up showing the load cell, samples, counterface and the sample holder. The load cell is connected to the computer to capture the frictional force during the experiments.

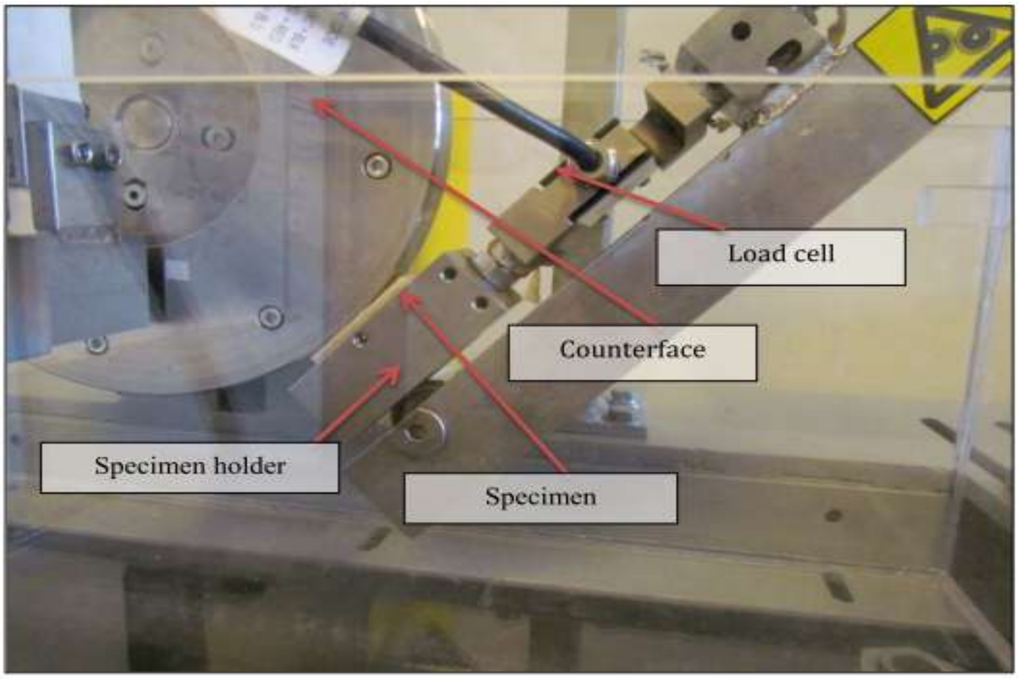


***Fig. 3. 3 Photo showing the Block-on-Ring configuration of multi-purpose machine**, (Yousif, 2013a).*

The roughness of the wear track was gauged before and after experiment by using Mahr Perthometer S2, As a result for higher close contact between the stainless steel and the specimen, abrasive paper (Sic G2000) and dry soft brush was used to polish and cleaned respectively the specimens contact surface. The composite surface varies in each orientation in terms of the roughness. For instance, in N-O, the composite roughness measures were in rate of the (0.70μm). While, in P-and AP-orientation were the average of (0.30μm).

3.2.1 EXPERIMENTAL PROCEDURE

The experiments were processed at appropriateness parameters which are constant applied load (30N), sliding velocity of 2.8 m/s, and sliding distance (0-15 km) at room temperature (28˚C). The used of a new specimen had to be done for each sliding distance. Before and after the test, the dry soft brush cleaned the prepared composite specimen continually. Serta weight balancer (±0.1mg) being used in this operation to determine and ensure the weights of the composite specimen before and after test and then weight loss was evaluated. In addition, thermo-imager camera was applied as so to determine the initial interface temperature. SEM (JEOL) was used to investigate the composite surface morphology. The composite specimen surface was coated before to use the SEM machine. Thus, each tribological test was repeatedly done several times and the average of the magnitudes was measured. The weights of the specimens before and after test using Sera balancer and then specific wear rate were determined for each test condition by using Eq1.

$$\boldsymbol{SWR} = \frac{\frac{\Delta \boldsymbol{W}}{\boldsymbol{\rho}}}{\boldsymbol{L}} \times \boldsymbol{D} \qquad \textbf{(1)}$$

In the light of this weight, during and after the experiment interface temperature was standardized. Using a thermo imager can be used while after the test, can also show the heat allocation during the materials sample. Moreover, the temperature was generated and the thermo imager camera has been used because of interface temperature was calibrated during periods of time. The specific wear performance is one of the expected results as so to explore the impact of the wear damage on the specimen surface. Therefore, theoretical rules were applied to measure the relationship between the sliding distance and the weight of the specimen before and after the test in order to investigate the specific wear rate. As a result the required friction force can be obtained by the tribology software which was connected with the Block-on-Ring machine. Hence, shear force readings were automatically registered according to the results data.

3.2.2 INTERFACE TEMPERATURE

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3.2.3 SPECIFIC WEAR RATE AND FRICTION FORCE READINGS

The specific wear performance is one of the expected results as so to explore the impact of the wear damage on the specimen surface. Therefore, theoretical rules were applied to measure the relationship between the sliding distance and the weight of the specimen before and after the test in order to investigate the specific wear rate. As a result the required friction force can be obtained by the tribology software which was connected with the Block-on-Ring machine. Hence, shear force readings were automatically registered according to the results data.

3.2.4 SURFACE PERCEPTIONS

There are different surface procedures in order to obtain the required outcomes and determine the surface damages being affected, which involving

1. Mahr Perthometer was supplied from the University of Southern Queensland (USQ).

2. (SEM) scanning electron microscopy was provided from University of Southern Queensland (USQ).

3. Thermo imager camera and thermometer.

Engineering and Surveying Faculty at University Of Southern Queensland has supplied the generality of this equipment. As a result, the valid and accurate outcomes were taken by using these techniques.

3.2.5 MAHR PERTHOMETER

The roughness of the surface is important parameters that can be measured before the test by using this tool. Moreover, Mahr Perthometer can be used in every single test for every specimen to avoid any possible error during the experiments.

3.2.6 (SEM) SCANNING ELECTRON MICROSCOPY

Demonstration of specimen surface is clearly shown by using this device after operation test with particular sliding conditions. Some of micrographs were provided in this study.

3.6.3 OPTICAL MICROSCOPY

Although, optical microscopy is an important instrument due to it is a procedure in which surface observation is collected systematically about a set of damage features; however, this equipment is not able to present results in micro. On the other hand, the micrographs from microscopy were considered significant compared to the outcomes from optical microscopy. Thus, SEM is provided to be the preferable surface observation procedure.

3.6.4 DEMONSTRATE THE THERMAL-IMAGER

Heat distributions were investigated by using this Thermal-Imager in terms of accurate results that might provide from infrared thermometer. Based on heat distribution in the specimen some of random samples of images has been attached in the appendix C especially results were collected as so to illustrate the generation of temperature through the sample.

3.6.5 EXPERIMENTAL PARAMETERS

According to previous studies, sliding conditions have been chosen due to the surface damage was showed. Therefore, this study will attempt to use these experimental parameters which are: Applied load of 30 N, Sliding velocity = 2.8m/s, time from 0 to 90 min, and sliding distance 0 to 15 Km.

CHAPTER4: RESULTS AND DISCUSSION

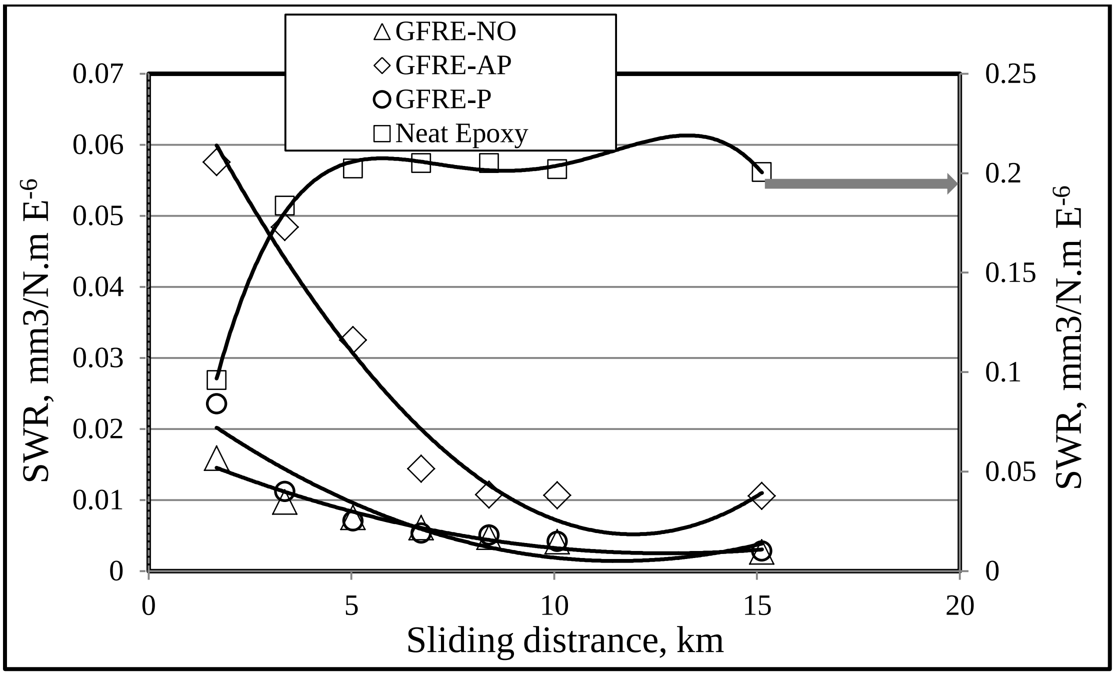
Tribological experimental results of glass fibre reinforced epoxy or polyester are presented in this chapter at various operating parameters. Frictional and wear behaviour of the composites and the thermoset are introduced in a form of friction coefficient, interface temperature, and specific wear rate. Surface morphology and roughness profile of the worn surfaces are given to assist in explaining the experimental wear and frictional results.

4.1 WEAR BEHAVIOUR

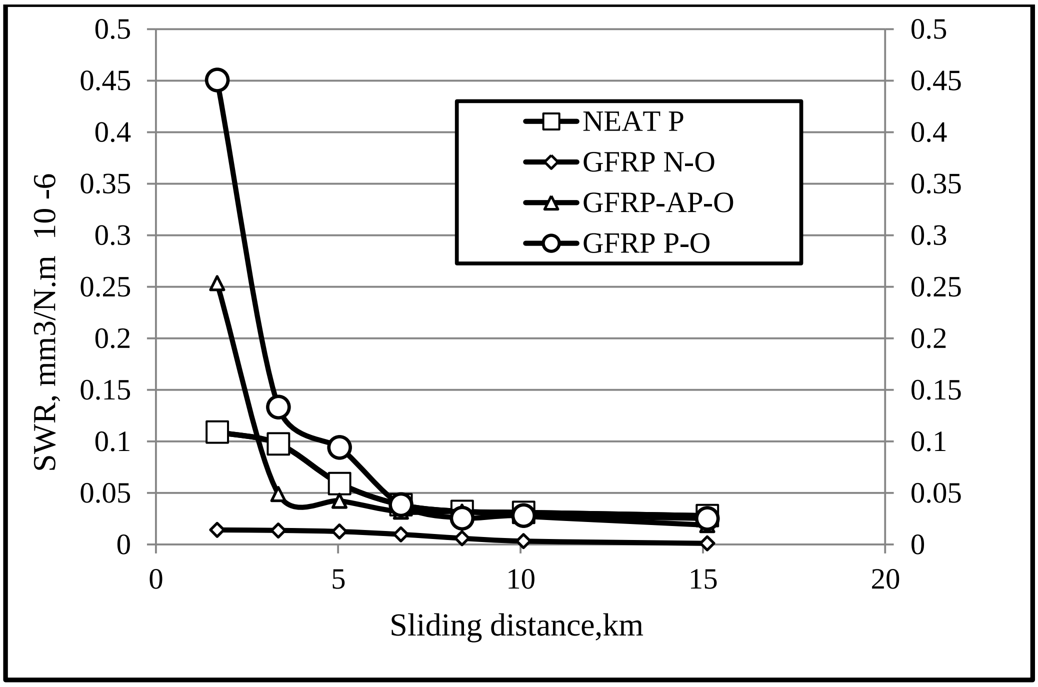
In order to study the wear behaviour of neat epoxy, (NE), neat polyester (NP), glass fibre reinforced epoxy (GFRE) and glass fibre reinforced polyester (GFRP), a series of experiments have been conducted at different operating parameters and orientations. The orientations are (N-O, P-O, and AP-O)

The specific wear rate of the GFRE and NE against the sliding distance of different orientations is given in **Fig. 4.1.a**. Since the specific wear rate (SWR) value of all the selected materials is very small, the presented values are multiplied by 1000000, and i.e. the values should be multiplied by E-6. Moreover, the specific wear rate of the epoxy is relatively high compared to its composites that are why its values are on the right vertical axis with different scale. From this figure, one can see that the neat epoxy exhibits very high specific wear rate and reached the steady state after about 5 km. on the other hand, the epoxy composites show lower specific wear rate compared to the neat epoxy for all the fibre orientations. The steady state of the composites reached after about 10 km since the interaction between the asperities took longer time to adopt. Further explanation will be given with the assist of the roughness profile in the next section.

Regarding to the composite, (AP-O) orientation indicates poorly wear rate compared to (P-O) and (N-O) orientations, the composite in (P-O) and (N-O) directions exhibit lower wear rate after sliding distance of 5 km. moreover, in comparison with Neat epoxy and three orientations found that AP- orientation has approximately 30% less than Neat epoxy while (P-O) and (N-O) orientations give about (20% less). The realization for this can be explained that the proportionally harder phase (CSM) is pulled out, broken, fractured of glass fibres and removed from CSM. It is generally accepted that the weight loss of the composite specimens have significantly increased with the effect of constant sliding velocity and sliding distance when applied load was about 30 N.



a) GFRE



a) GFRP

Fig. 4. 1 Specific wear rate against sliding distance of neat polyester, neat epoxy, and GFRP and GFRE composites

The result of specific wear rate of glass/polyester and neat polyester against the sliding distance of different orientations is represented in **Fig 4.1.b**. It shows the specific wear rate of glass/polyester at various orientations with the neat polyester. Since the highest wear rate value is registered for the (P-O) at sliding distance of about 3 km since the interaction between the hardness some time to adopt, the right vertical axis is presented the values of specific wear rate. Because the specific wear rate (SWR) is very small, the obtained values are multiplied by 1000000. It is generally seen that the polyester composites show the lowest specific wear rate for (AP-O and N-O) at approximately after 3 km. Likewise, the composites reached the steady state after 6 km. Concerning to the composite, the wear rate has significantly decreased with increasing the sliding distance for the orientations, i.e. (AP-O and N-O) This lowering is pronounced after about 3 km. After about 6 km all the composites have reach the steady state. Meanwhile, for (N-O) gives less wear rate compared to the others for all levels of sliding distances are tested. Furthermore, there is no markedly difference in wear rate for all the composites when they reached the steady state. Differently, in comparison with (N- O) exhibits less wear rate at lower sliding direction and slightly decrease in wear rate at higher sliding distance. It is accepted that glass fibre gives superior wear performance and through the sliding of the (N-O) orientation. (Ws) Values of the composites are obviously decreased as a result the better wear behaviour of the composite is achieved for (N-O). Therefore, it could be due to the reinforcement of the adhesion properties between the glass fibre and the polyester resin. From the mechanical point of view, the interface adhesion is enhanced the mechanical characteristics of the composite. Thus, the material's strengthens is another reason, which can cause to lower weight removal. However, Summary of the specific wear rate of the selected materials after reaching the steady state at 10 km is shown in **Fig.4.2.** It seems that there is general value of specific wear rate of GFRE and GFRP in which the best wear performance can be achieved, i.e. (N-O) for both fibre composites exhibited an optimum value. On the other hand, neat epoxy and neat polyester are reached the highest value for both composite. GFRP is shown the higher value compared to GFRE in the case of (AP-O). Moreover, there is markedly difference value between the composites in (P-O). However, the optimum wear value is produced in the (N-O) for both materials. Due to the lowering in the hardness of the film in the composite surface this can be related to the mechanical properties in term of interfacial adhesion and strength.

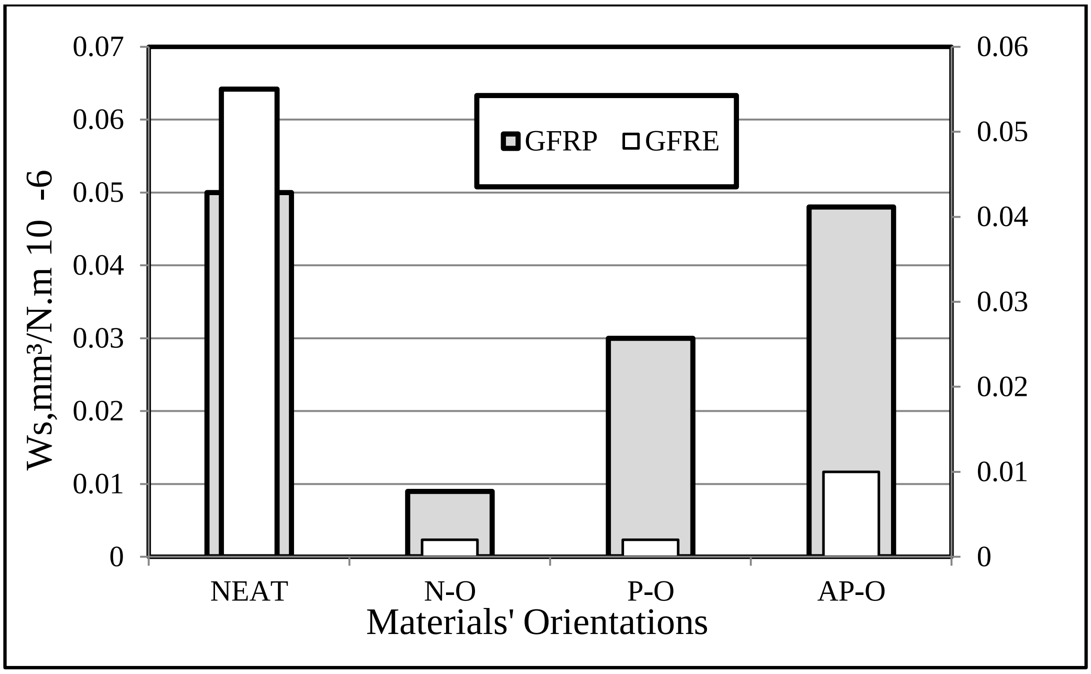


Fig. 4. 2 Summary of the specific wear rate of the selected materials after reaching the steady state.

4.2 FRICTION COEFFICIENT

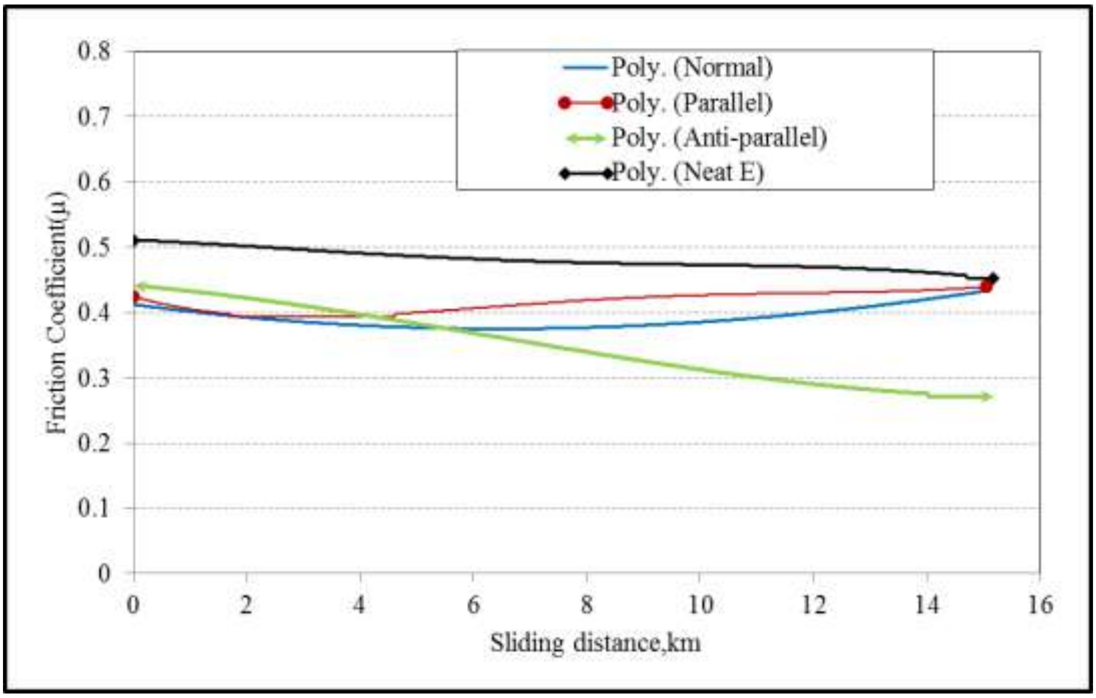
Fig 4.3.a shows the distinction of friction coefficient values for all materials with sliding distance for three orientations and applied load 30N, and sliding velocity 2.8m/s. It can be indicated that the trend of the friction coefficient is slightly decreased with increasing the sliding distance for the neat epoxy. Moreover, friction coefficient of the normal and parallel orientations is partially increased at about 6 km and starts to reach a steady state. Differently, anti-parallel orientation provides the lowest value of friction coefficient comparing to neat epoxy (about 29% lass). As a result, the values of friction coefficient have evidently increased for the most orientations. The glass fibre epoxy composite confirms that similar behaviour to three orientations. However, the friction coefficient of the composite with fibres is higher than the glass fibre where glass fibre demonstrates about the range of 0.29 to 0.45 while the neat epoxy gives above 0.49 of friction coefficient.

In the light of this, there is difference between the three orientations of the composite in terms of friction coefficient. It can be seen that there are close values for the friction coefficient between normal and parallel, however, the trend of the anti-parallel orientation exhibits the lowest value of (0.25-0.3) than the others.

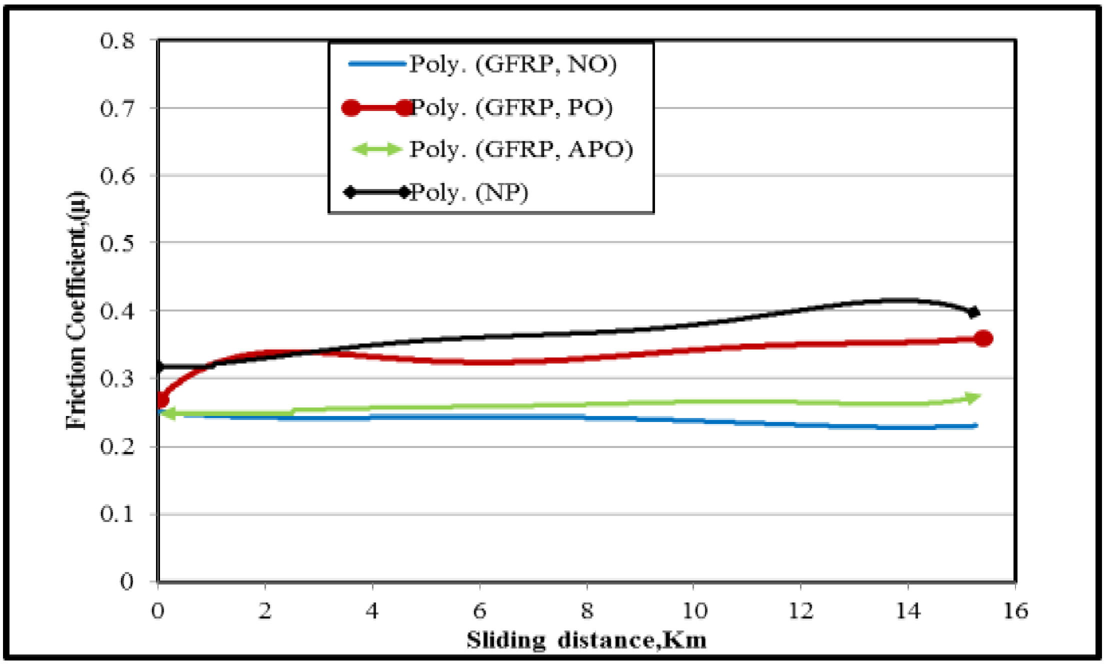
The effect of sliding distance and applied load on friction coefficient of GFRP is presented in **Fig 4.3.b**. In addition to that, the influence of glass fibres on the tribological behaviour of the neat polyester and the composite are clarified.

Regarding to the composite, the findings of friction coefficient are provided as a function of sliding distance at 30N applied load. Generally, it can be seen that the friction coefficient increases at the beginning and starts to reduce at approximately (5 km) sliding distance. However, it appears that normal and anti-parallel (N-O and AP-O) orientations have achieved the lowest friction coefficient at the applied load of 30N which are about 0.23 and 0.28 respectively. Consequently, the higher value of friction coefficient is evident for the neat polyester, which is about 0.42 while the glass fibre composite at different orientations exhibit 0.2 to 0.3 of friction coefficient. There is no significant effect on the friction coefficient at different sliding distance. It can be seen that friction coefficient does not reach steady state at all sliding distance. Nevertheless, the friction coefficient is minimized whilst the sliding distance increasing. This cause can be due to the strongly transfer film on the counterface and the existence of the fibres and polyester. During longer sliding may lead to impairs the adhesion between the two sliding surfaces and then associated interaction takes place between them. The influence of the friction coefficient and wear performance will be illustrated by the help of the micrographs of the composite's worn surface. With regards to the glass fibre polymer composite, the friction coefficient of both GFRP and GFRE are summarised in **Fig 4.4**. The highest friction coefficient during tribological conditions at 10 km is represented for neat composite. However, the friction coefficient is high for other direction of the composite. This can be noted that the deponding of fibre and the strong of interfacial adhesion are avoided breakage and bending. As a result, (AP-O) show the lowest friction value for both materials. Whereas, (N-O) in GFRE has a higher value than

(N-O) in GFRP. However, (AP-O) in GFRP is achieved the lowest value compared with all the orientations for both composite.



a) GFRE



b) GFRP

Fig. 4. 3 Friction coefficient against sliding distance of GFRP and GFRE composites

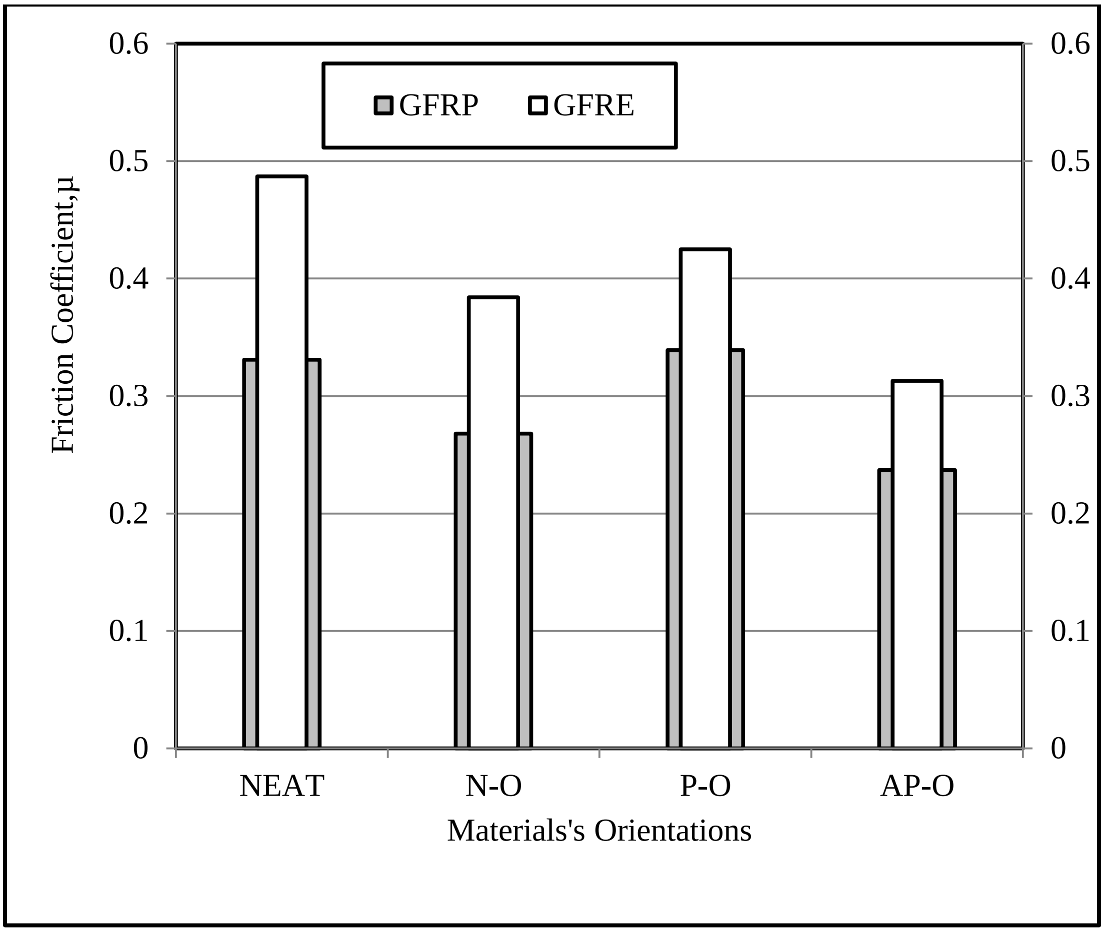
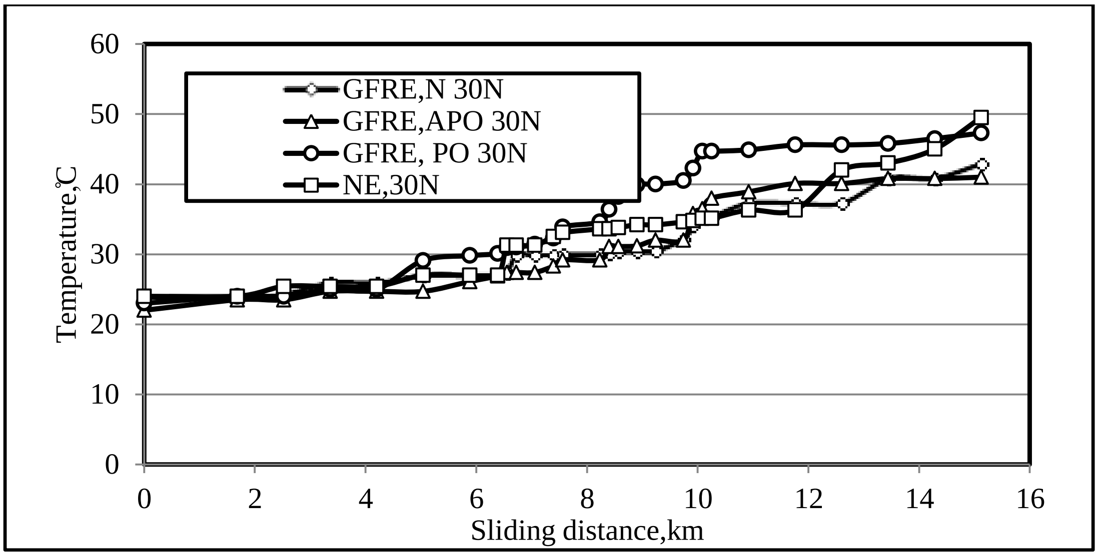


Fig. 4. 4 Summary of the friction coefficient of the selected materials after reaching the steady state after 10 km sliding distance

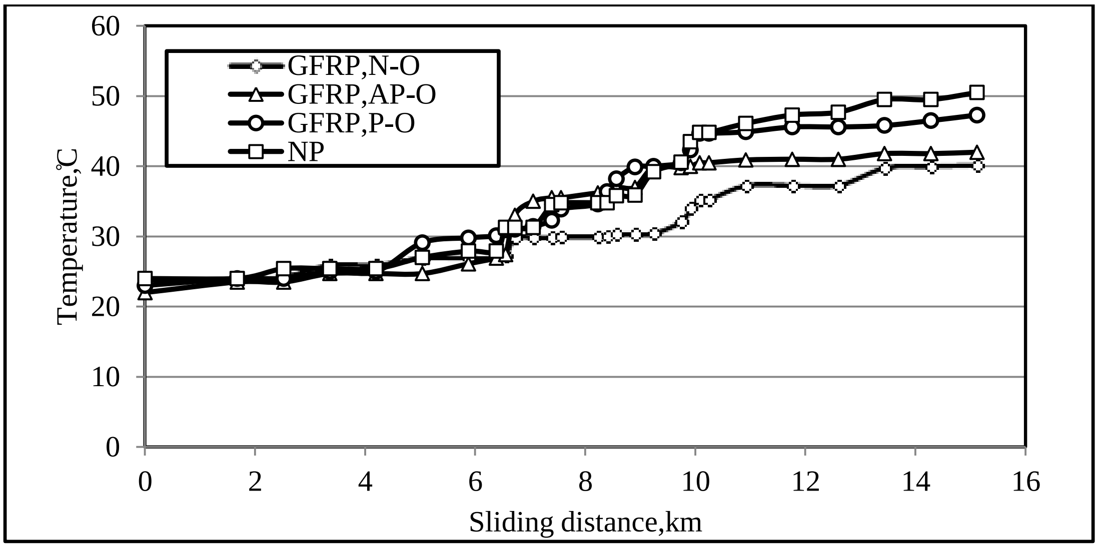
4.3 INTERFACE TEMPERATURE

Fig 4.5.a shows the influence of the applied load and different sliding distance on the interface temperature of GFRE composite in different orientations (N-O, P-O, and AP-O) and the comparison with the neat epoxy composite. The friction coefficient, applied load and sliding distance are maximised. As a result, interface temperature is expected that it is likely to increase. There is intimate relation between the interface temperatures and sliding distance, at applied load of 30N interface temperature reaches gradually the high temperature when the sliding distance increases. it can be noted that there is linear trend of temperature at the beginning of the sliding distance until approximately 5Km, the highest degree is about 50ºC, after 14 Km for (NE). Meanwhile, in the case of (AP-O) and (N-O), there is no severe effect on the temperature degrees compared with (P-O) which reached 47ºC after 12km. Several experiments have indicated that temperature trend is elevated gradually when the sliding distance has long term effect on the composite. However, these outcomes have been gained with the assist of thermo-imager camera which has been used for every separate experiment at 30 N applied load, 2.8 m/s sliding velocity. Meanwhile, the GFRE (N-orientation) is examined at 2.8 m/s, increasing in the sliding distance does not observe any change in the temperature from 10 km until 14km.

Fig 4.5.b shows the maximum interface temperature that is evaluated during the rubbing, i.e. at sliding distance 15km at 30N. The highest interface temperature is measured due to the high friction coefficient of NP and GFRP (in P-O); higher interface temperature is gauged in NP compared to NE composite. Since AP-O has the lower temperature value than GFRE (in AP-O). Generally, the sliding distance has close relation with the interface temperature, and friction coefficient of the entire composite are increased. Therefore, we can record that the temperature starts in increase after 10 km. Finally, thermo-image camera has been applied for every test and provided more results.



a) GFRE



b) GFRP

Fig. 4. 5 Interface temperature vs. sliding distance the selected materials under 30 N applied load

4.4 COMPOSITE SURFACE OBSERVATION

Further explanation will be exhibited with the assist of the roughness profile in the next dictation. The results from the test are recorded in the direction of the counterface and against the direction of the counterface. **Fig 4.6** shows some samples of the roughness profile of the selected materials GFRE/GFRP at different operating parameters. On the other hand, **Fig 4.7** summarises the roughness values of the selected materials after test under 30 N applied load for 15 km sliding distance. **Fig 4.7.a** shows the roughness value of GFRE. It seems that the highest value is recorded in the case of (AP-O) in the direction of the counterface while the lowest value is provided in (P-O). Compared to the GFRE, **Fig 4.7.b** shows significantly reduce the roughness value of the GFRP in (AP-O) for both directions; moreover, one can notice that (P-O) shows less effect value on the counterface in the direction of the counterface.

Regarding to the surface roughness profile of the neat polyester and GFRP in three orientations, it seems that the roughness profile of the (N-O) orientation has reached the highest value of roughness profile of 3.536m. However, the roughness profile of the AP-O is the lower value. **Fig 4.7.b** shows the relation between the roughness values of the GFRP after test under 30N applied load for 15 sliding distance. In addition to that, the roughness profile of the neat polyester is slightly decrease compared to the surface roughness profile of the neat epoxy in the previous section.

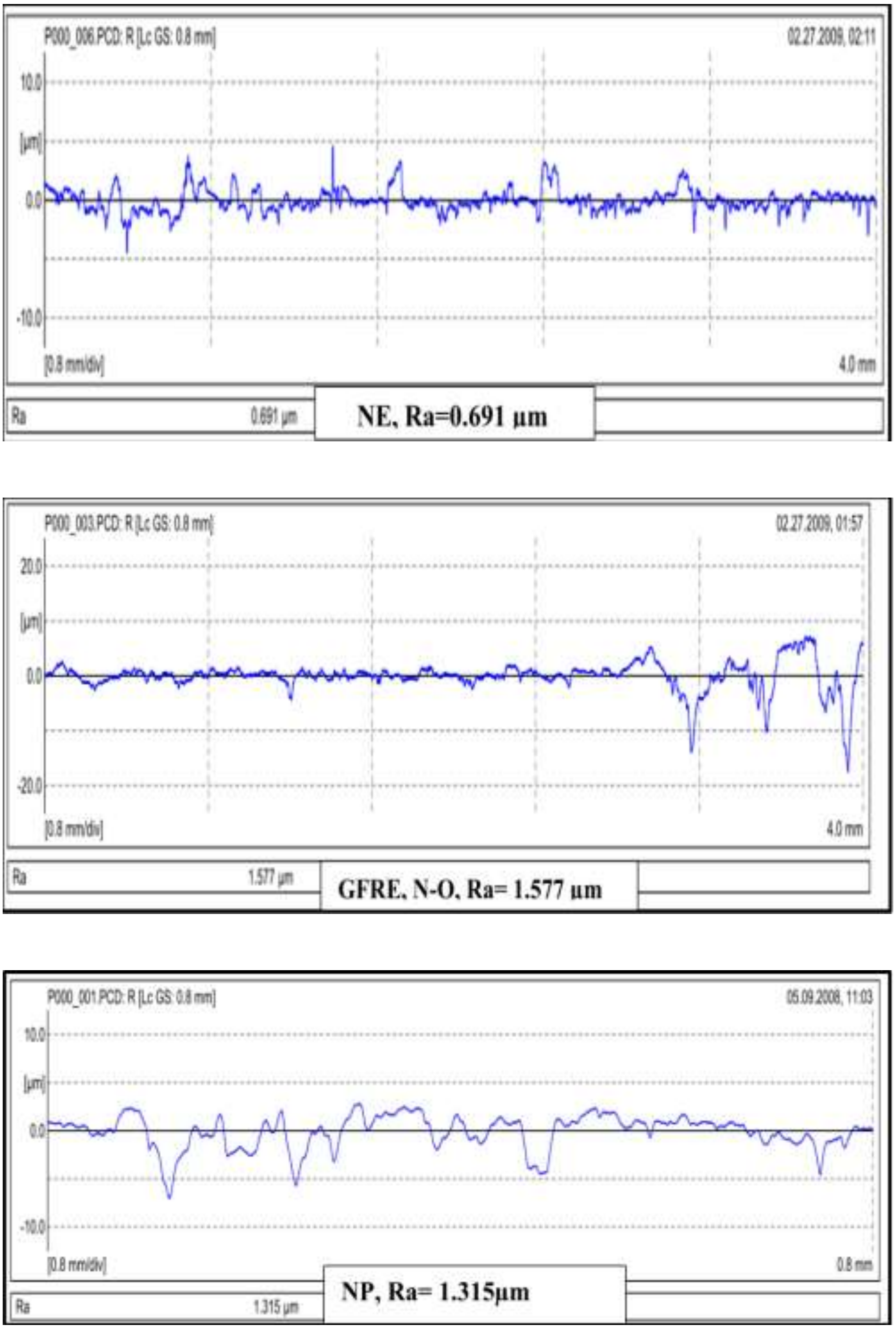
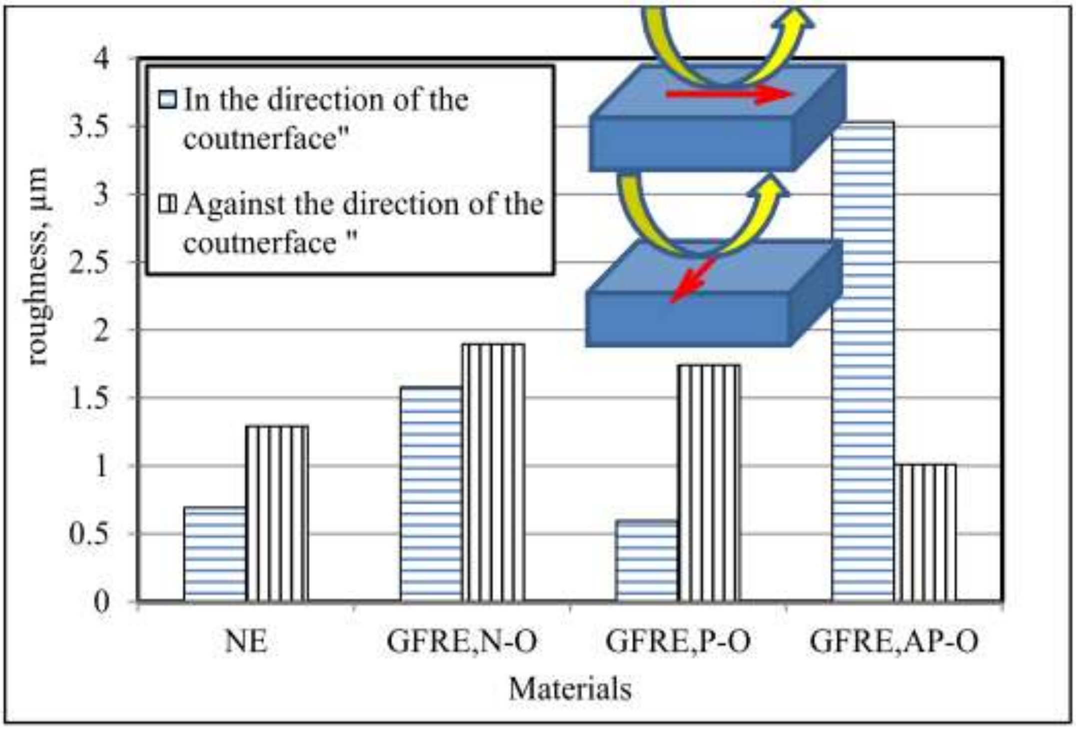
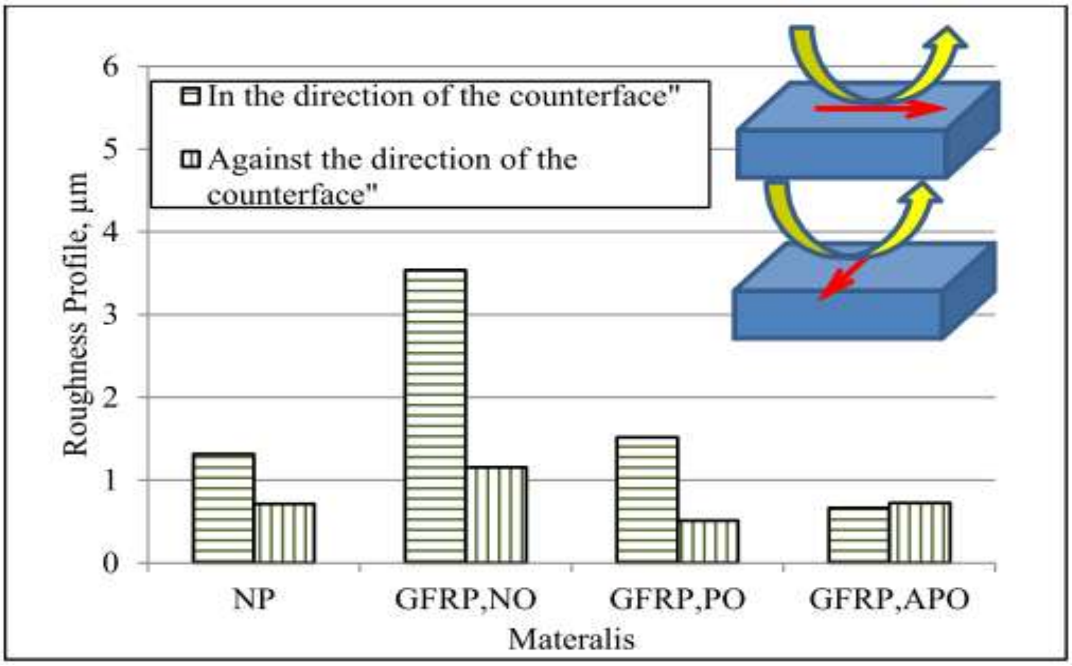


Fig. 4. 6 Samples of the roughness profile of the selected materials at different operating parameters

Fig 4.8 shows the effect of the sliding distance on the worn surface of the GFRE and GFRP composites. Concerning the composite, severe damage on the worn surface of the GFRE (N-O) is recorded. At the maximum value of the sliding distance the rubbing is partially different compared with lower distance. In order to reduce the friction coefficient, a set of fibre has been removed and peeled off from the rubbing area. At 2Km and 30 N, there is no indication of movement of fibres. Whereas, micro-cracks have risen on the surface, indicate the elevated wear performance of the composite at the rubbing region. As a result, it can be concluded that at ruthless conditions of higher load and/or sliding distance micro-cracks dominate on the wear resistance of GFRE in (N-O).



a) GFRE



b) GFRP

Fig. 4. 7 Roughness value of the selected materials after test under 30 N applied load for 10 15km sliding distance

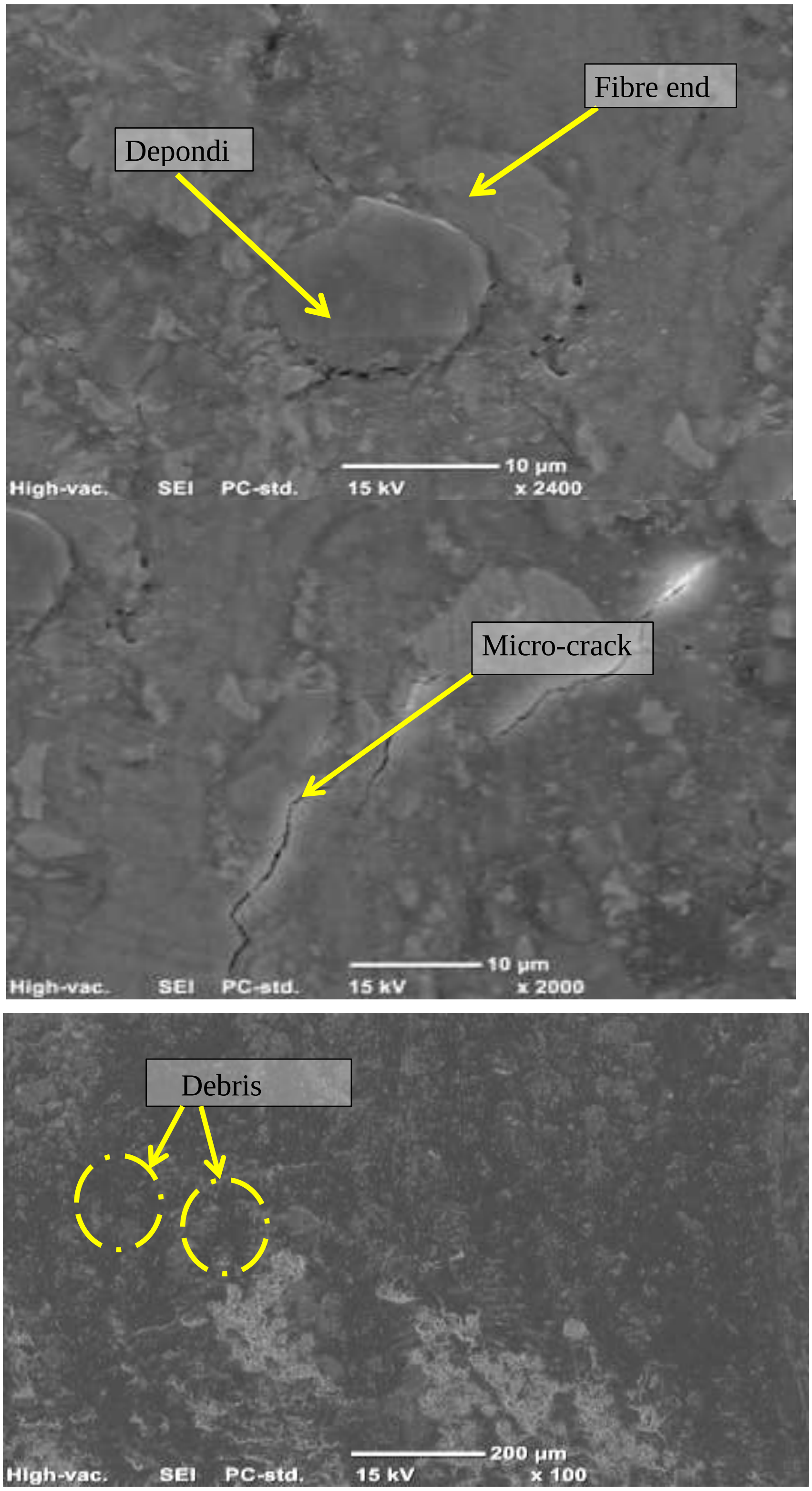


Fig. 4. 8 Micrographs of GFRE worn surface after the test under 30 N applied load in N-Orientation

Fig 4.9 represents that micrograph of GFRP worn surface after the test under 30 N applied load in AP-Orientation. The weakened interfacial adhesion in the fibre end is between the fibre and the resin zone. This concludes that (at sliding distance) the wear mechanism of GFRP in N-O is dominated which related with the same orientation and its wear mechanism.

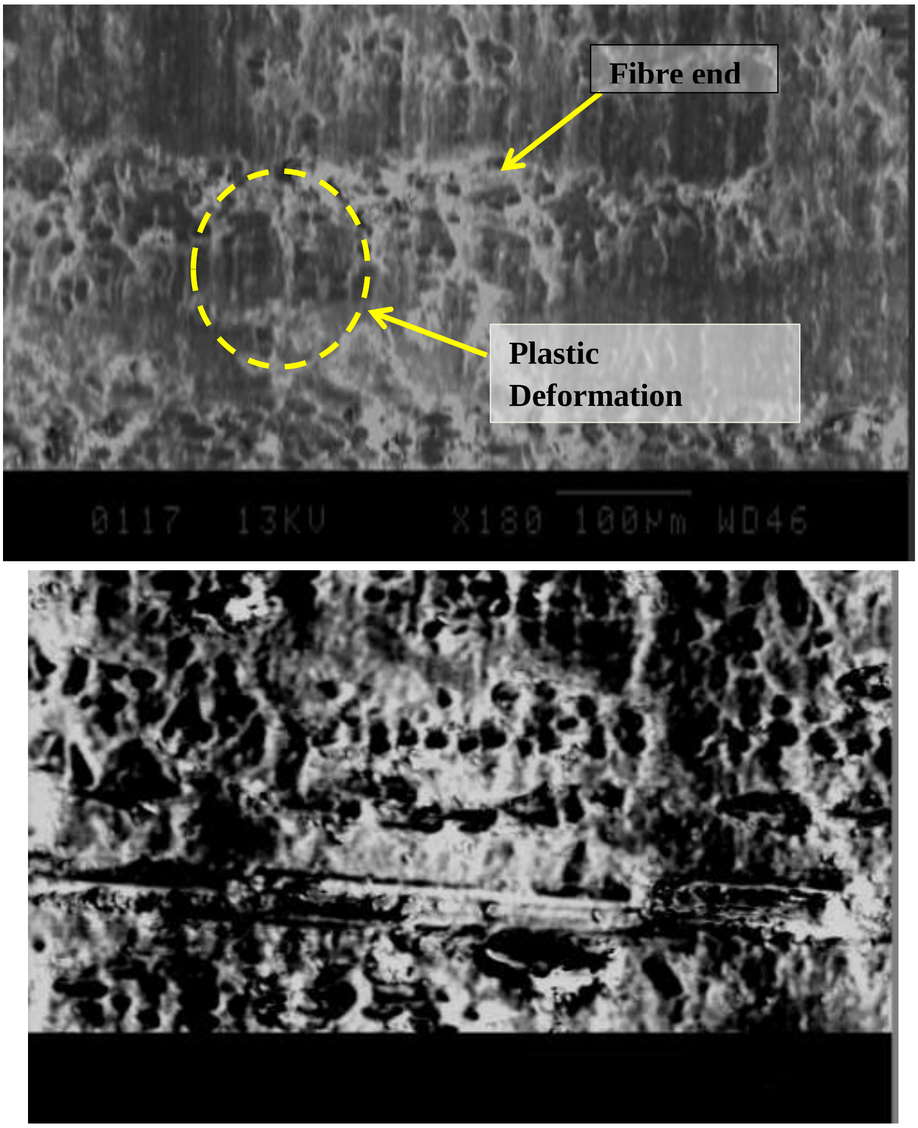


Fig. 4. 9 Micrographs of GFRP worn surface after the test under 30 N applied load in AP-Orientation

4.5. Discussions **and Comparison with Previous Published Works**

In this chapter, the experimental results on neat epoxy, glass fibre reinforced epoxy/polyester composite in three orientations as (N-O, P-O, and AP-O) are compared with some of the studies in terms of weight loss and frictional behaviour at various operating parameters. **Fig 4.10** presents several researches and studies that have determined the values of specific wear rate and frictional behaviour of several composites, and current outputs are painted of different colour. Shi et al., (2003) have investigated the highest value of specific wear rate of neat epoxy composite compared to the specific wear rate of this work (Shi et al., 2003). Furthermore, neat polyester has marked the lower friction coefficient and weight loss, specific wear rate and friction coefficient were measured about (0.03234), and (0.23) respectively, (El-Tayeb, 2008). Moreover, the present specific wear rate of glass fibre/epoxy shows the lowest value and the highest friction coefficient is recorded than the other one which was studied by Pihtili (2009)(Pihtili, 2009). The friction coefficient and wear rate of glass fibre/polyester composite are shown in figure below. The same friction coefficient is produced compared to the value was defined by Shalwan and Yousif (2012) (Yousif, 2012). However, glass fibre/polyester exhibits low specific wear rate (0.02).

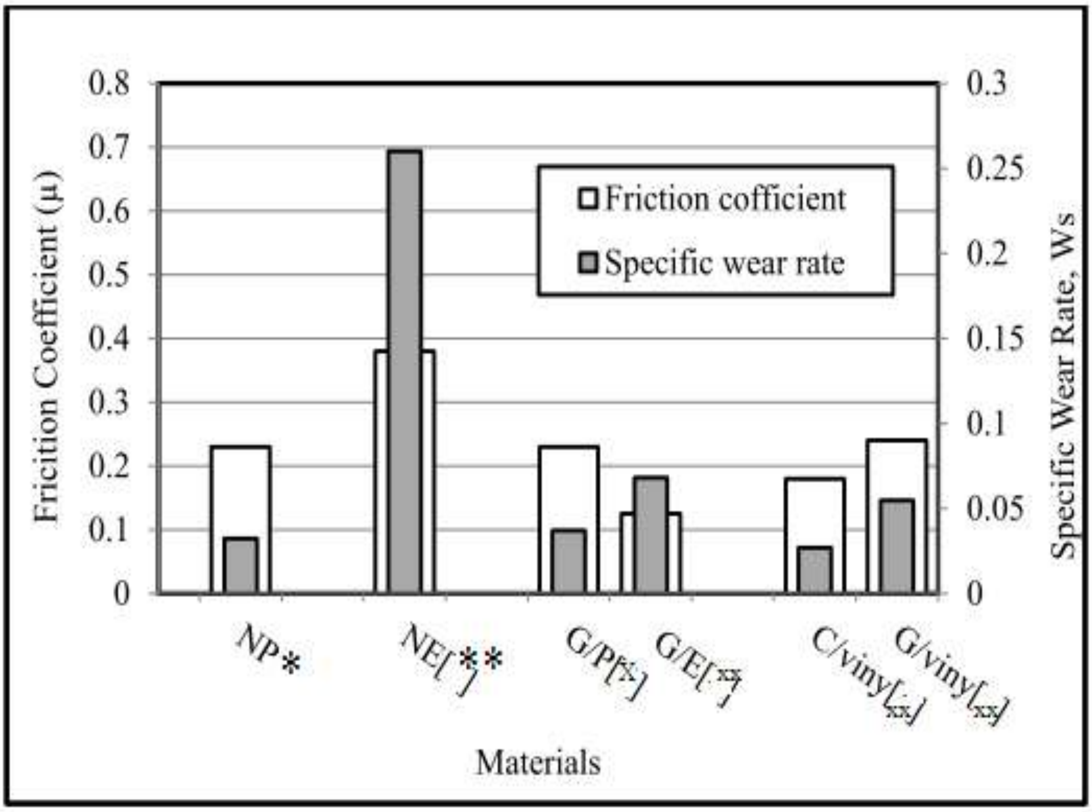


Fig. 4. 10 Specific wear rate and frictional behaviour of several composites,

(El-Tayeb et al., 2008),(Shi et al., 2003)**,(Pihtili, 2009)[x],(Suresha and Kumar, 2009)[xx]*

CHAPTER 5:

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

Few points are concluded as follows:

1. Presence of fibres and oriented have a significant influence on the wear and frictional behaviour of polymeric composites. In the case of glass fibre reinforced epoxy composite, the better wear and frictional behaviour were performed when the composite was tested in N-O.
2. The fibre orientations has highly influence and similar in controlling the friction and wear performance. However, the specific wear rate of the composite is consistently and essentially high in AP-O compared to N-O of the composites. Moreover, the sliding distance and applied load have a little influence on the tribological properties.
3. The detachment and breakage of fibres were the most effect on the wear mechanism. Meanwhile, micro-cracks at the end of the fibres is the declare wear technique in (N-O and P-O).
4. The worn surface of the composite showed different wear mechanisms. For the GFRP, plastic deformation was clear and softening process occurred during the sliding which deteriorates the composite surface. For the GFRE,

this less damage on the surface with the presence of the micro-cracks which indicate the high wear resistance in the interface.

5. even though, the increasing temperature and frictional force have a substantial and consequently effect on the tribological properties of both polymeric composite. However, the interface temperature has a pronounce influence on the frictional force on the material removal from the composite surface. Moreover, there are different appearances of wear mechanism depending on the temperature can be resulted by the heat generated by the frictional force.

5.2 RECOMMENDATION

It is suggested that more researches have to be done on other type of materials in order to evince and reach the existing work returns. While the tribology is the interaction between different responses to the polymers, metals are preferred due to their responses to the interaction. Additional discussion has to be the main consideration so as to reduce the friction force of the glass fibre based on epoxy and/or polyester composites. Therefore, the high friction coefficient of the glass fibre reinforced epoxy composite is minimized by using solid lubricants.

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APPENDIX A: PROJECT SPECIFICATION

ENG8002 Research Project

PROJECT SPECIFICATION

Project title: Adhesive Wear and Frictional Behaviour of Glass Fibre Reinforced Thermoset composites

Student: Gabrel Mehoub

Supervisor: Dr Belal F Yousif

Amis and Objectives:

1. To study the specific wear rate and friction behaviour of epoxy and polyester composite based on glass fibre.
2. To study the influence of fibre orientations on specific wear rate and friction coefficient.
3. To examine the worn surfaces of the composite after the test and categorize the wear mechanism.
4. To understand the influence of interface temperature on specific wear rate and friction behaviour
5. To investigate the influence of the rubbing process on the roughness profile of the composite.

Project Synopsis:

There are many troubles in the field of industries. It is known that the friction is the major pronounce resulting from the motion of contacted surface; therefore, high temperature and shear force are generated in the rubbing area. Friction and dry wear behaviour of glass fibre reinforced epoxy (GFRE) and glass fibre reinforced polyester (GFRP) composites will be studied in the current project. The adhesive wear experiments will be carried out using block-on-ring (BOR) configuration at room temperature, applied load of (30N), and sliding velocity of (2.8 m/s). Interface temperature and frictional force will be captured and recorded during the sliding. Worn surfaces will be examined by using (SEM) to classify the damage.

APPENDIX B: CONFERENCE PAPER

Adhesive Wear and Frictional Behaviour of Glass Fibre Reinforced Thermoset composites

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Abstract

Friction and dry wear behaviour of glass fibre reinforced epoxy (GFRE) and glass fibre reinforced polyester (GFRP) composites are studied in the current project. Three sliding orientations of fibre with respect to the sliding distance are considered in the investigation, i.e. parallel orientation (P-O), anti-parallel orientation (AP-O), and normal orientation (N-O). On the other hand, different sliding distances 0- 15 km are accounted. The adhesive wear experiments were carried out using block-on-ring (BOR) configuration at room temperature, applied load of 30N, and sliding velocity of 2.8 m/s. Interface temperature and frictional force were captured and recorded during the sliding. Worn surfaces were examined by using (SEM) to classify the damage. The results revealed that the highest wear rate is taken place in (AP-O) of GFRE. (P-O) is the highest wear rate of GFRP. On the other hand, the lowest wear rate is exhibited for (N-O) at longer sliding distance. The maximum friction coefficient is observed when sliding take place in N-O and P-O at higher speed level. Although, AP-O shows 0.25 which is the lowest friction coefficient value than other orientations. (P-O) orientation of GFRP gave higher wear rate at maximum speed test in comparing to normal orientation.

Keywords: Adhesive wear, Thermoset, Fibre, orientation

1. Introduction

As a result of the rapid development that the world witnesses and the challenge in using metal materials in tribological industrial applications, the tribological behaviour of polymeric composites has recently experienced a create development, and attention by many researchers. Fibre reinforced polymeric composites have numerous advantages compared to the metal materials due to their competitive mechanical properties of high specific strength, low weight, low cost of raw materials, low processing cost…etc. Recently, composites materials are heavily used in many applications that have been determined for these materials. Furthermore, composites materials have been provided superlative solutions to produce structural materials of aerospace industries, (Pihtili, 2009). Tribological properties of such materials have been a core of interest for many scholars and researchers. The friction and wear performance are the significance characteristics that have taken place by several researches,(Yousif, 2013b, Bajpai et al., 2013) focusing on the composite application in brakes, clutches, bolts and nuts. On the other hand, Shalwan and Yousif (2013) have been expounded that friction is the value of energy which dissipated at the material contact surface. Wear, the resistance to remove of solid surface, has been defined in various aspects such as weight loss, wear resistance and specific wear rate, (Bajpai et al., 2013). Friction and wear are classified to become a main effect on the machinery in the field of industry as so to work efficiently. Such deficiencies are mainly related to lifetime of the machinery, (Holmberg et al., 2012). In other words, it is important to arouse many researches to study the tribological behaviour of polymeric composites. Nowadays, friction and wear are the most common problems that encountered in industrial engineering and machine parts which causes to the replacement of components and assemblies in engineering, (Unal et al., 2004). As a result, the uses of polymer materials have been increased by industrial countries. Therefore, the need to understand the tribological behaviour of polymer is clear of this fact of polymer science and engineering, (Brostow et al., 2010). There have been several types of productive friction and wear such as brakes, clutches, bolts and nuts. Also the unproductive friction and wear is equally considerable such as gas turbine, cams and bearings, and external combustion engines, (Bhushan et al., 1995). Nevertheless, the influences of deformation and adhesion of friction are addressed. Friction on surface energy is affected by different factors which are sliding velocity, applied load, and temperature, (Myshkin et al., 2005). In addition, the authors have reported that friction comprises of three elements namely, interfacial bonds, strength, and shearing and rupture of rubbing around the contact area of materials. It may also lead to damage materials' surface and then change the mechanical properties of the composite. Finally, the results from friction are temperature during converting mechanical energy to heat, this heat is produced by friction and deformation of materials leads to generate heat. On the other hand, few beneficial applications are provided by the friction such as tyres, and brakes friction. There are several studies have been done to inspect the tribological performance of polymeric composites based on synthetic fibres such as glass, (Pihtili, 2009). Carbone fibres were investigated by (Suresha and Kumar, 2009). From the literature, there is a lack of understanding on the tribological behaviour of thermoset composites based on synthetic fibres such as glass. In the recent work by Shalwan and Yousif (2013), it is highly recommended further studies on the thermoset composites to identify the wear and frictional characteristics of thermoset composites based on glass fibres. This motivates the current study. In the current report, the wear and frictional behaviour of two fibre thermoset composites are considered as epoxy and polyester. Three different orientations of fibre with respect to the sliding distance are accounted in the study and different sliding distance 0- 15 km. As a result of the rapid development that the world witnesses and the challenge in using metal materials in tribological industrial applications, the tribological behaviour of polymeric composites has recently experienced a create development, and attention by many researchers. Fibre reinforced polymeric composites have numerous advantages compared to the metal materials due to their competitive mechanical properties of high specific strength, low weight, low cost of raw materials, low processing cost etc. Recently, composites materials are heavily used in many applications that have been determined for these materials. Furthermore, composites materials have been provided superlative solutions to produce structural materials of aerospace industries, (Pihtili, 2009). Tribological properties of such materials have been a core of interest for many scholars and researchers. The friction and wear performance are the significance characteristics that have taken place by several researches,(Yousif, 2013b, Bajpai et al., 2013) focusing on the composite application in brakes, clutches, bolts and nuts. On the other hand, Shalwan and Yousif (2013) have been expounded that friction is the value of energy which dissipated at the material contact surface. 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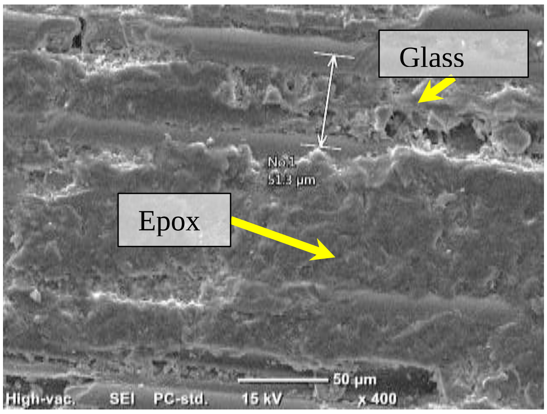
In the current article, the wear and frictional behaviour of two fibre thermoset composites are considered as epoxy and polyester. Three different orientations of fibre with respect to the sliding distance are accounted in the study and different sliding distance 0- 15 km.

2. Materials preparation and experimental procedure

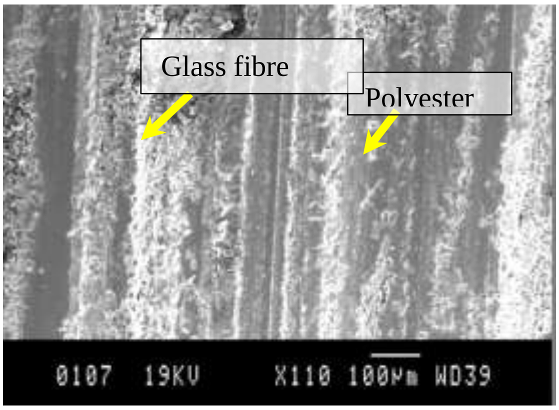
2.1. Materials preparation

This study proposed to use these materials in terms of their surface damage characteristics meanwhile they were experimented under diverse sliding conditions. Hence these materials have to be used in these experiments easier than other materials which may appear no surface damage. This project has used well known materials such as Neat Epoxy (NE), Glass Fibre Reinforced Epoxy (GFRE).

There are combinations of materials being used to meet technical procedures. Glass fibres based composites have been specified of a set of mechanical characteristic. In addition, this work has been used the liquid of epoxy resin (DER 331). It is occasionally used for several purposes such as automotive parts and casting. Epoxy resin supplies good resistance to adhesive and alkalis properties. The epoxy resin and hardener has been mixed with 2:1 of ratio. Also the mixture was systematically made, melted down in the mould and placed in the vacuum room (MCP 004PLC). In order to dispose of air bubbles between fibres in the mould at room temperature 24 hour. Glass fibre reinforced epoxy and glass fibre reinforced polyester were chosen as reinforcement materials. In order to provide prestigious properties for, this specimens were conducted with the specific volume of fibre is v_f =48%. Micrographs of the original composite surface for both materials selected are shown in **Fig.1**. Consequently, the orientations of fibre have been paid attention. GFRP were used as a reinforcement material that it provides a high chemical resistance and high resistance to environmental influences. Epoxy resins are preferred so as to commonly of available rates from high melting solids, and viscous liquids. They have numerous of mechanical properties, and chemical resistance. Furthermore, epoxy resin had approximately less than 2% of the shrinkage and high hardness. The provided composites were formed in size 30mm*20mm*20mm and different orientations of fibres were displayed in **Fig.2.**



a) GFRP



a) GFRE

Fig.1 Micrographs of the original composite surface for a) GFRP and b) GFRE

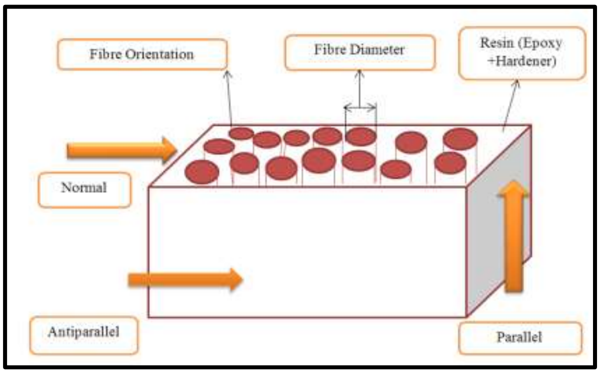


Fig. 2 Schematic drawing showing the orientation of the fibre with respect to the sliding direction

Similar techniques are conducted in fabricating the synthetic specimen, three orientations have been considered in the tests. Polyester is a thermosetting resin that has been used a. Glass fibre reinforced polyester has been produced under a different of lengths, widths, and weights. 20-30mm, 450g/m^2 are used as measurements of current specimen of fibre lengths and mass of fibre respectively. (Revesol P9509) is an unsaturated and addition of Methyl Ethyl Ketone Peroxide (MEKP) which can be used for ambient the surrounding temperature. Kong Tat Company of fiberglass engineering (Malaysia) has been provided both reinforcement and polyester materials.

2.2. Experimental set up and procedure

2.2.1 Experimental set ups

Block-On-Ring (BOR) is the main machine that it has been used to conduct the experiments. The specimens surface (10mm*10mm*20mm) was tested against a counterface made of stainless steel (AISI 304, hardness =1250HB, Ra=0.1µm). Before each test, (Sic G2000) was utilized to smooth the counterface and thereafter a piece of wet cloth with acetone was used to clean the counterface. **Fig. 3** shows the block on ring step up showing the load cell, samples, counterface and the sample holder. The load cell is connected to the computer to capture the frictional force during the experiments.

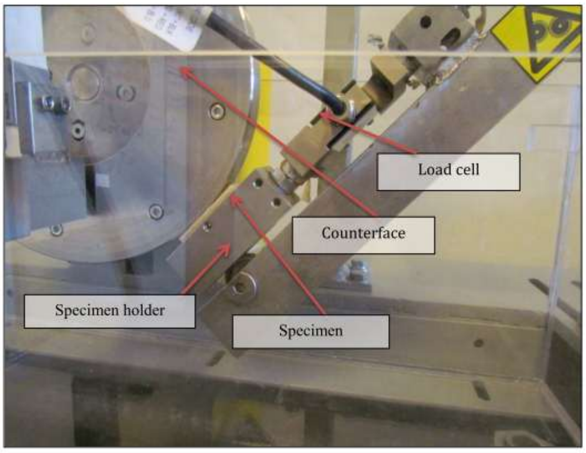


Fig. 3 Photo showing the Block-on-Ring configuration of multi-purpose machine, (Yousif, 2013a).

The roughness of the wear track was gauged before and after experiment by using Mahr Perthometer S2, As a result for higher close contact between the stainless steel and the specimen, abrasive paper (Sic G2000) and dry soft brush was used to polish and cleaned respectively the specimens contact surface. The composite surface varies in each orientation in terms of the roughness. For instance, in N-O, the composite roughness measures were in rate of the (0.70µm). While, in P-and AP-orientation were the average of (0.30µm).

2.2.2 Experimental Procedure

The experiments were processed at appropriateness parameters which are constant applied load (30N), sliding velocity of 2.8 m/s, and sliding distance (0-15 km) at room temperature (28˚C). The used of a new specimen had to be done for each sliding distance. Before and after the test, the dry soft brush cleaned the prepared composite specimen continually. Serta weight balancer (±0.1mg) being used in this operation to determine and ensure the weights of the composite specimen before and after test and then weight loss was evaluated. In addition, thermo-imager camera was applied as so to determine the initial interface temperature. SEM (JEOL) was used to investigate the composite surface morphology. The composite specimen surface was coated before to use the SEM machine. Thus, each tribological test was repeatedly done several times and the average of the magnitudes was measured. The weights of the specimens before and after test using Sera balancer and then specific wear rate were determined for each test condition by using Eq1.

$$SWR = \frac{\frac{\Delta W}{\rho}}{L} \times D \quad (1)$$

In the light of this weight, during and after the experiment interface temperature was standardized. Using a thermo imager can be used while after the test, can also show the heat allocation during the materials sample. Moreover, the temperature was generated and the thermo imager camera has been used because of interface temperature was calibrated during periods of time. The specific wear performance is one of the expected results as so to explore the impact of the wear damage on the specimen surface. Therefore, theoretical rules were applied to measure the relationship between the sliding distance and the weight of the specimen before and after the test in order to investigate the specific wear rate. As a result the required friction force can be obtained by the tribology software which was connected with the Block-on-Ring machine. Hence, shear force readings were automatically registered according to the results data.

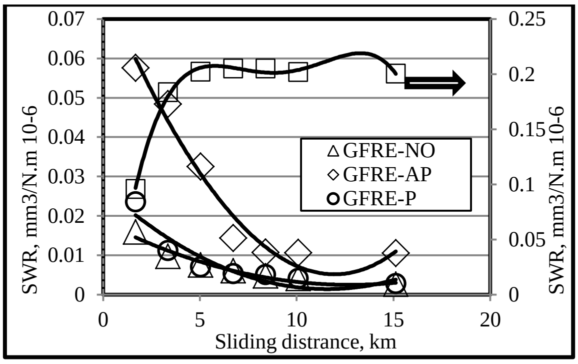
3. Results and Discussion

Tribological experimental results of glass fibre / epoxy and polyester are presented at various operating parameters. Frictional and wear behaviour of the composites and the thermoset are introduced in a form of friction coefficient, interface temperature, and specific wear rate. Surface morphology and roughness profile of the worn surfaces are given to assist in explaining the experimental wear and frictional results.

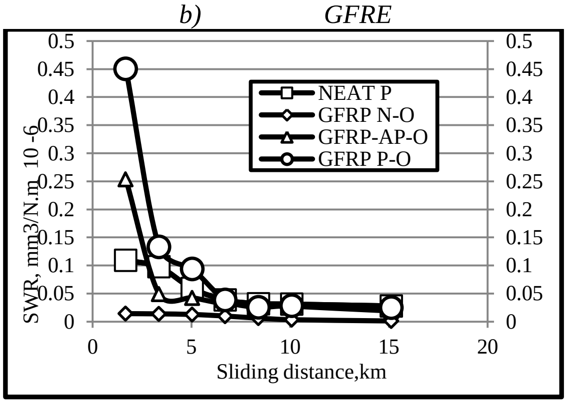
3.1.1. Wear Behaviour

In order to study the wear behaviour of neat epoxy, (NE), neat polyester (NP), glass fibre reinforced epoxy (GFRE) and glass fibre reinforced polyester (GFRP), a series of experiments have been conducted at different operating parameters and orientations. The orientations are (N-O, P-O, and AP-O)

The specific wear rate of the GFRE and NE against the sliding distance of different orientations is given in **Fig. 4.a**. Since the specific wear rate (SWR) value of all the selected materials is very small, the presented values are multiplied by 1000000, and i.e. the values should be multiplied by E-6. Moreover, the specific wear rate of the epoxy is relatively high compared to its composites that are why its values are on the right vertical axis with different scale. From this figure, one can see that the neat epoxy exhibits very high specific wear rate and reached the steady state after about 5 km. on the other hand, the epoxy composites show lower specific wear rate compared to the neat epoxy for all the fibre orientations. The steady state of the composites reached after about 10 km since the interaction between the asperities took longer time to adopt. Further explanation will be given with the assist of the roughness profile in the next section.



b) GFRE



c) GFRP

Fig. 4 Specific wear rate against sliding distance of neat polyester, neat epoxy, GFRP and GFRE composites

Regarding to the composite, (AP-O) orientation indicates poorly wear rate compared to (P-O) and (N-O) orientations, the composite in (P-O) and (N-O) directions exhibit lower wear rate after sliding distance of 5 km. moreover, in comparison with Neat epoxy and three orientations found that AP-orientation has approximately 30% less than Neat epoxy while P and N orientations gave about (20% less). The realization for this can be explained that the proportionally harder phase (CSM) is pulled out, broken, fractured of glass fibres and removed from CSM. It is generally accepted that the weight loss of the composite specimens have significantly increased with the effect of constant sliding velocity and sliding distance when applied load was about 30 N.

The results of specific wear rate of glass/polyester and neat polyester versus the sliding distance of different orientations is represented in **Fig 4.b**. It shows the specific wear rate of glass/polyester at various orientations with the neat polyester. Since the highest wear rate value is registered for the (P-O) at sliding distance of about 3 km since the interaction between the hardness some time to adopt, the right vertical axis is presented the values of specific wear rate. Because the specific wear rate (SWR) is very small, the obtained values are multiplied by 1000000. It is generally seen that the polyester composites show the highest specific wear rate for (AP-O and N-O) at approximately 3 km. Likewise, the composites reached the steady state after 6 km. Concerning to the composite, the wear rate has significantly decreased with increasing the sliding distance for the orientations, i.e. (AP-O and N-O) This lowering is pronounced after about 3 km. After about 6 km all the composites have reach the steady state. Meanwhile, for (N-O) gives less wear rate compared to the others for all levels of sliding distances are tested. Furthermore, there is no markedly difference in wear rate for all the composites when they reached the steady state. Differently, in comparison with (N-O) exhibits less wear rate at lower sliding direction and slightly decrease in wear rate at higher sliding distance. It is accepted that glass fibre gives superior wear performance and through the sliding of the (N-O) orientation. (Ws) Values of the composites are obviously decreased as a result the better wear behaviour of the composite is achieved for (N-O). Therefore, it can be due to the reinforcement of the adhesion properties between the glass fibre and the polyester resin. From the mechanical point of view, the interface adhesion is enhanced the mechanical characteristics of the composite. Thus, the material's strengthens is another reason, which can cause to lower weight removal. However, Summary of the specific wear rate of the selected materials after reaching the steady state at 10 km is shown in **Fig.5.** It seems that there is universal value of specific wear rate of GFRE and GFRP in which the best wear performance can be achieved, i.e. (N-O) for both fibre composites exhibited an optimum value. On the other hand, neat epoxy and neat polyester are reached the highest value for both composite. GFRP is shown the higher value compared to GFRE in the case of (AP-O). Moreover, there is markedly difference value between the composites in (P-O). However, the optimum wear value is produced in the (N-O) for both materials. Due to the lowering in the hardness of the film in the composite surface this can be related to the mechanical properties in term of interfacial adhesion and strength.

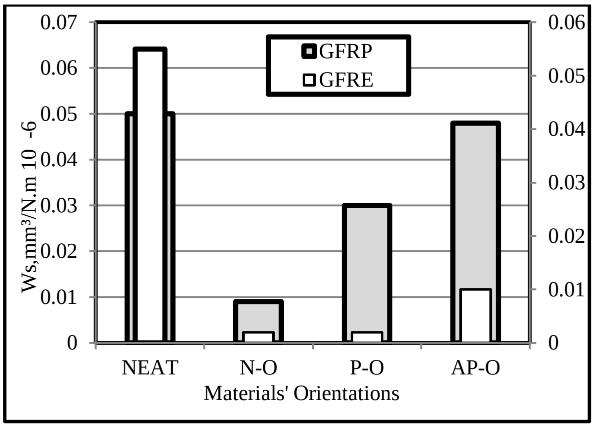


Fig. 5 Summary of the specific wear rate of the selected materials after reaching the steady state.

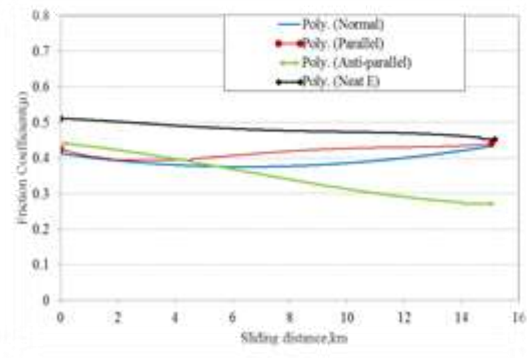
3.1.2. Friction Coefficient

Fig 6.a shows the distinction of friction coefficient values for all materials with sliding distance for three orientations and applied load 30N, and sliding velocity 2.8m/s. It can be indicated that the trend of the friction coefficient is slightly decreased with increasing the sliding distance for the neat epoxy. Moreover, friction coefficient of the normal and parallel orientations is partially increased at about 6 km and starts to reach a steady state. Differently, anti-parallel orientation provides the lowest value of friction coefficient comparing to neat epoxy (about 29% lass). As a result, the values of friction coefficient have evidently increased for the most orientations. The glass fibre epoxy composite confirms that similar behaviour to three orientations. However, the friction coefficient of the composite with fibres is higher than the glass fibre where glass fibre demonstrates about the range of 0.29 to 0.45 while the neat epoxy gives above 0.49 of friction coefficient.

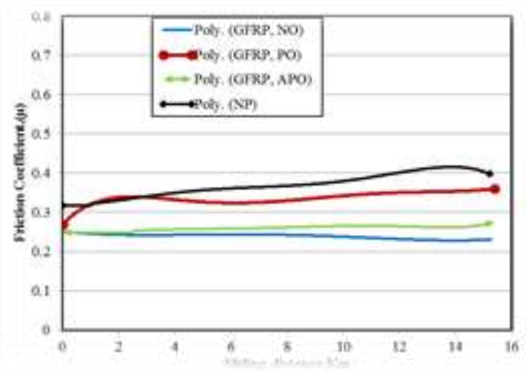
In the light of this, there is difference between the three orientations of the composite in terms of friction coefficient. It can be seen that there are close values for the friction coefficient between normal and parallel, however, the trend of the anti-parallel orientation exhibits the lowest value of (0.25-0.3) than the others.

The effect of sliding distance and applied load on friction coefficient of GFRP is presented in **Fig 6.b**. In addition to that, the influence of glass fibres on the tribological behaviour of the neat polyester and the composite are clarified.

Regarding to the composite, the findings of friction coefficient are provided as a function of sliding distance at 30N applied load. Generally, it can be seen that the friction coefficient increases at the beginning and starts to reduce at approximately (5 km) sliding distance. However, it appears that normal and anti-parallel (N-O and AP-O) orientations have achieved the lowest friction coefficient at the applied load of 30N which are about 0.23 and 0.28 respectively. Consequently, the higher value of friction coefficient is evident for the neat polyester, which is about 0.42 while the glass fibre composite at different orientations exhibit 0.2 to 0.3 of friction coefficient. There is no significant effect on the friction coefficient at different sliding distance. It can be seen that friction coefficient does not reach steady state at all sliding distance. Nevertheless, the friction coefficient is minimized whilst the sliding distance increasing.



a) *GFRE*



b) *GFRP*

Fig. 6 Friction coefficient against sliding distance of neat polyester, neat epoxy, GFRP and GFRE composites

This cause can be due to the strongly transfer film on the counterface and the existence of the fibres and polyester. During longer sliding may lead to impairs the adhesion between the two sliding surfaces and then associated interaction takes place between them. The influence of the friction coefficient and wear performance will be illustrated by the help of the micrographs of the composite's worn surface. With regards to the glass fibre polymer composite, the friction coefficient of both GFRP and GFRE are summarised in **Fig 7**. The highest friction coefficient during tribological conditions at 10 km is represented for neat composite. However, the friction coefficient is high for other direction of the composite. This can be noted that the deponding of fibre and the strong of interfacial adhesion are avoided breakage and bending. As a result, (AP-O) show the lowest friction value for both materials. Whereas, (N-O) in GFRE has a higher value than (N-O) in GFRP. However, (AP-O) in GFRP is achieved the lowest value compared with all the orientations for both composite.

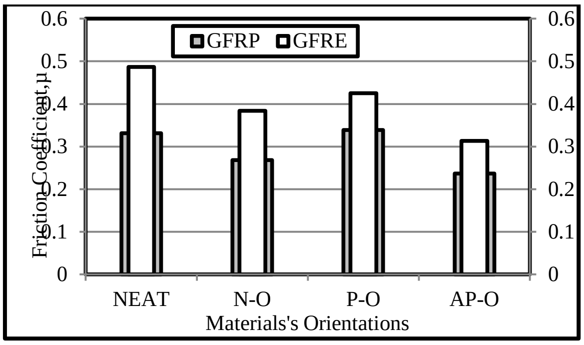
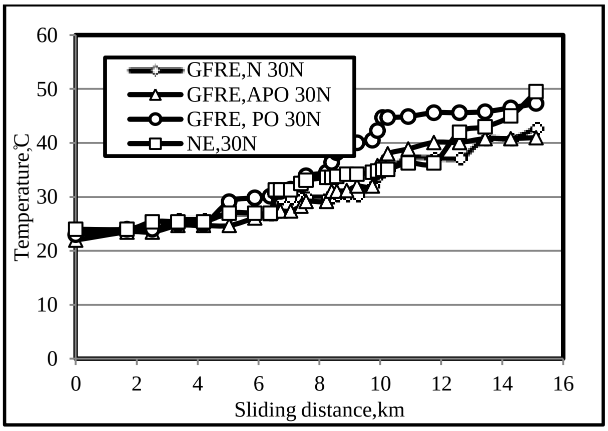


Fig. 7 Summary of the friction coefficient of the selected materials after reaching the steady state after 10 km sliding distance

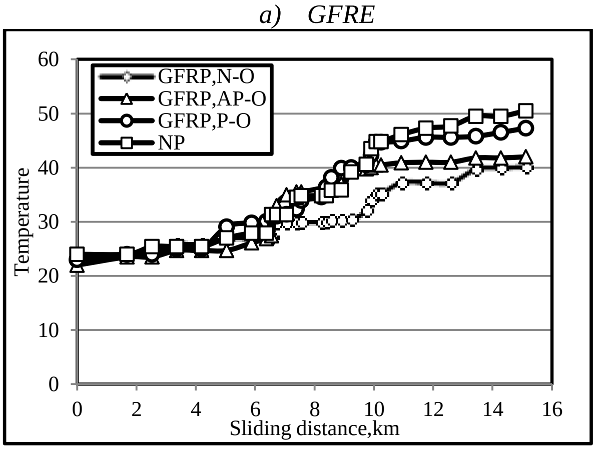
3.1.3. Interface Temperature

Fig 8.a shows the influence of the applied load and different sliding distance on the interface temperature of GFRE composite in different orientations (N-O, P-O, and AP-O) and the comparison with the neat epoxy composite. The friction coefficient, applied load and sliding distance are maximised. As a result, interface temperature is expected that it is likely to increase. There is intimate relation between the interface temperatures and sliding distance, at applied load of 30N interface temperature reaches gradually the high temperature when the sliding distance increases. it can be noted that there is linear trend of temperature at the beginning of the sliding distance until approximately 5Km, the highest degree is about 50ºC, after 14 Km for (NE). Meanwhile, in the case of (AP-O) and (N-O), there is no severe effect on the temperature degrees compared with (P-O) which reached 47ºC after 12km. Several experiments have indicated that temperature trend is elevated gradually when the sliding distance has long term effect on the composite. However, these outcomes have been gained with the assist of thermo-imager camera which has been used for every separate experiment at 30 N applied load, 2.8 m/s sliding velocity. Meanwhile, the GFRE (N-orientation) is examined at 2.8 m/s, increasing in the sliding distance does not observe any change in the temperature from 10 km until 14km.

Fig 8.b shows the maximum interface temperature that is evaluated during the rubbing, i.e. at sliding distance 15km at 30N. The highest interface temperature is measured due to the high friction coefficient of NP and GFRP (in P-O); higher interface temperature is gauged in NP compared to NE composite. Since AP-O has the lower temperature value than GFRE (in AP-O). Generally, the sliding distance has close relation with the interface temperature, and friction coefficient of the entire composite are increased. Therefore, we can record that the temperature starts in increase after 10 km. Finally, thermo-image camera has been applied for every test and provided more results.



a) GFRE



b) GFRP

Fig. 8 Interface temperature vs. sliding distance the selected materials under 30 N applied load

3.1.4. Composite surface observation

Further explanation will be exhibited with the assist of the roughness profile in the next dictation. The results from the test are recorded in the direction of the counterface and against the direction of the counterface. **Fig.9** shows some samples of the roughness profile of the selected materials GFRE/GFRP at different operating parameters. On the other hand, **Fig.10** summarises the roughness values of the selected materials after test under 30 N applied load for 15 km sliding distance.**Fig.10.a** presence the roughness value of GFRE. It seems that the highest value is recorded in the case of (AP-O) in the direction of the counterface while the lowest value is provided in (P-O). Compared to the GFRE, **Fig.10.b** shows significantly reduce the roughness value of the GFRP in (AP-O) for both directions; moreover, one can notice that (P-O) shows less effect value on the counterface in the direction of the counterface.

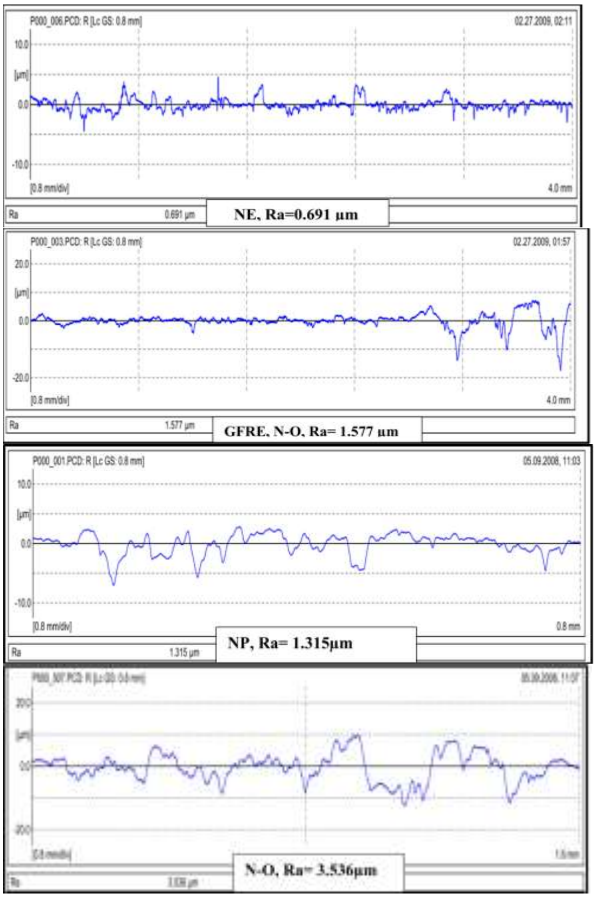
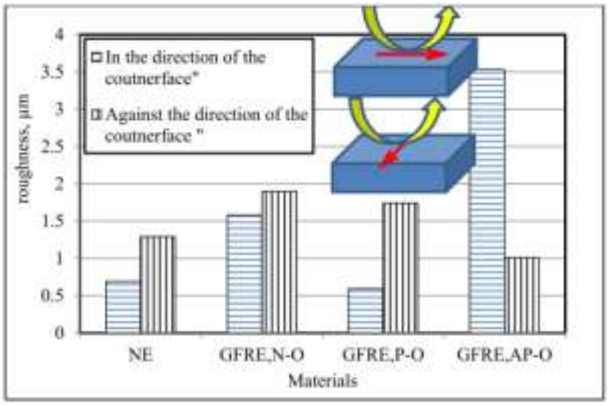


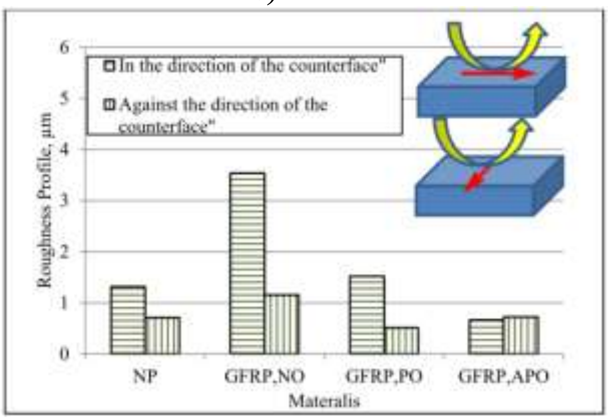
Fig. 9 Samples of the roughness profile of the selected materials at different operating parameters

Regarding to the surface roughness profile of the neat polyester and GFRP in three orientations, it seems that the roughness profile of the (N-O) orientation has reached the highest value of roughness profile of 3.536m. However, the roughness profile of the AP-O is the lower value. **Fig.10.b** shows the relation between the roughness values of the GFRP after test under 30N applied load for 15 sliding distance. In addition to that, the roughness profile of the neat polyester is slightly decrease compared to the surface roughness profile of the neat epoxy in the previous section.

Fig.11 shows the effect of the sliding distance on the worn surface of the GFRE and GFRP composites. Concerning the composite, severe damage on the worn surface of the GFRE (N-O) is recorded. At the maximum value of the sliding distance the rubbing is partially different compared with lower distance. In order to reduce the friction coefficient, a set of fibre has been removed and peeled off from the rubbing area. At 2Km and 30 N, there is no indication of movement of fibres. Whereas, micro-cracks have risen on the surface, indicate the elevated wear performance of the composite at the rubbing region. As a result, it can be concluded that at ruthless conditions of higher load and/or sliding distance micro-cracks dominate on the wear resistance of GFRE in (N-O).



a) GFRE



b) GFRP

Fig. 10 Roughness value of the selected materials after test under 30 N applied load for 10 15km sliding distance

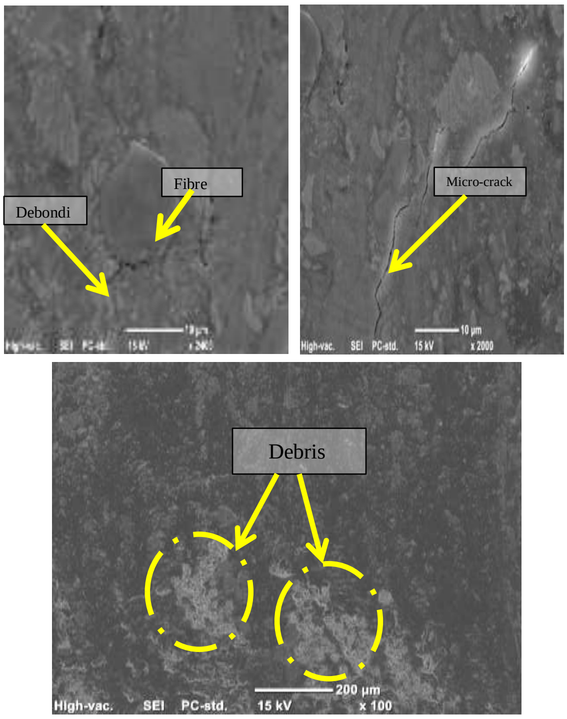


Fig. 11 Micrographs of GFRE worn surface after the test under 30 N applied load in N-Orientation

Fig.12 represented that micrograph of GFRP worn surface after the test under 30 N applied load in AP-Orientation..

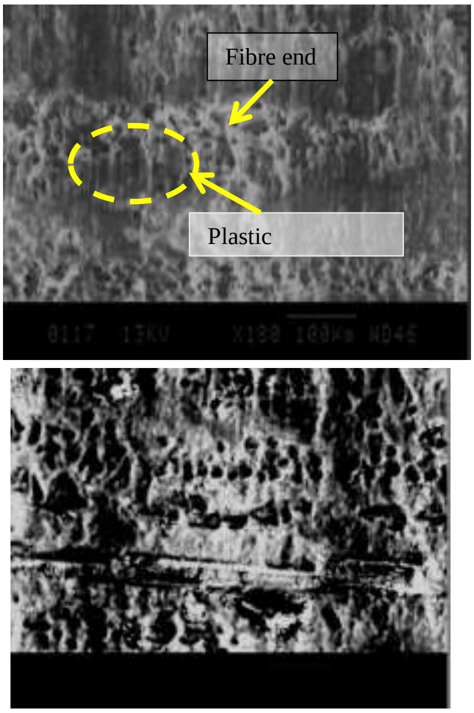


Fig. 12 Micrographs of GFRP worn surface after the test under 30 N applied load in AP-Orientation

The weakened interfacial adhesion in the fibre end is between the fibre and the resin zone. This concludes that (at sliding distance) the wear mechanism of GFRP in N-O is dominated which related with the same orientation and its wear mechanism

4. Discussion And Comparison With Previous Published Works

In this chapter, the experimental results on neat epoxy, glass fibre reinforced epoxy/polyester composite in three orientations as (N-O, P-O, and AP-O) are compared with some of the studies in terms of weight loss and frictional behaviour at various operating parameters. **Fig 13** presents several researches and studies that have determined the values of specific wear rate and frictional behaviour of several composites, and current outputs are painted of different colour. Shi et al., (2003) have investigated the highest value of specific wear rate of neat epoxy composite compared to the specific wear rate of this work (Shi et al., 2003). Furthermore, neat polyester has marked the lower friction coefficient and weight loss, specific wear rate and friction coefficient were measured about (0.03234), and (0.23) respectively, (El-Tayeb, 2008). Moreover, the present specific wear rate of glass fibre/epoxy shows the lowest value and the highest friction coefficient is recorded than the other one which was studied by Pihtili (2009)(Pihtili, 2009). The friction coefficient and wear rate of glass fibre/polyester composite are shown in figure below. The same friction coefficient is produced compared to the value was defined by Shalwan and Yousif (2012) (Yousif, 2012). However, glass fibre/polyester exhibits low specific wear rate (0.02).

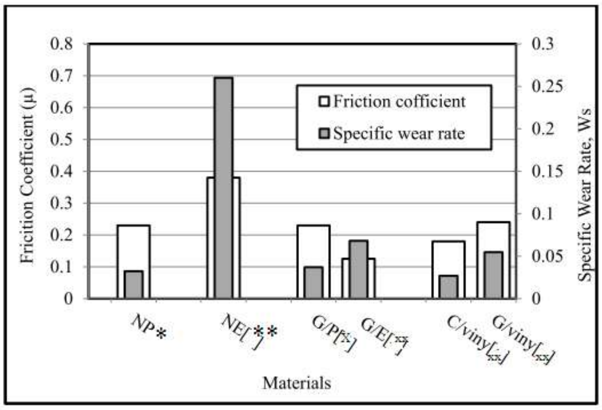


Fig. 13 Specific wear rate and frictional behaviour of several composites, (El-Tayeb et al., 2008)*,(Shi et al., 2003)**,(Pihtili, 2009)[x],(Suresha and Kumar, 2009)[xx]

5. Conclusions

Few points are concluded as follows:

1. Presence of fibres and oriented have a significant influence on the wear and frictional behaviour of polymeric composites. In the case of glass fibre reinforced epoxy composite, the better wear and frictional behaviour were performed when the composite was tested in N-O.
2. The fibre orientations has highly influence and similar in controlling the friction and wear performance. However, the specific wear rate of the composite is consistently and essentially high in AP-O compared to N-O of the composites. Moreover, the sliding distance and applied load have a little influence on the tribological properties.
3. The detachment and breakage of fibres were the most effect on the wear mechanism. Meanwhile, micro-cracks at the end of the fibres is the declare wear technique in (N-O).
4. The worn surface of the composite showed different wear mechanisms. For the GFRP, plastic deformation was clear and softening process occurred during the sliding which deteriorates the composite surface. For the GFRE, this less damage on the surface with the presence of the micro-cracks which indicate the high wear resistance in the interface.
5. Even though, the increasing temperature and frictional force have a substantial and consequently effect on the tribological properties of both polymeric composite. However, the interface temperature has a pronounce influence on the frictional force on the material removal from the composite surface. Moreover, there are different appearances of wear mechanism depending on the temperature can be resulted by the heat generated by the frictional force.

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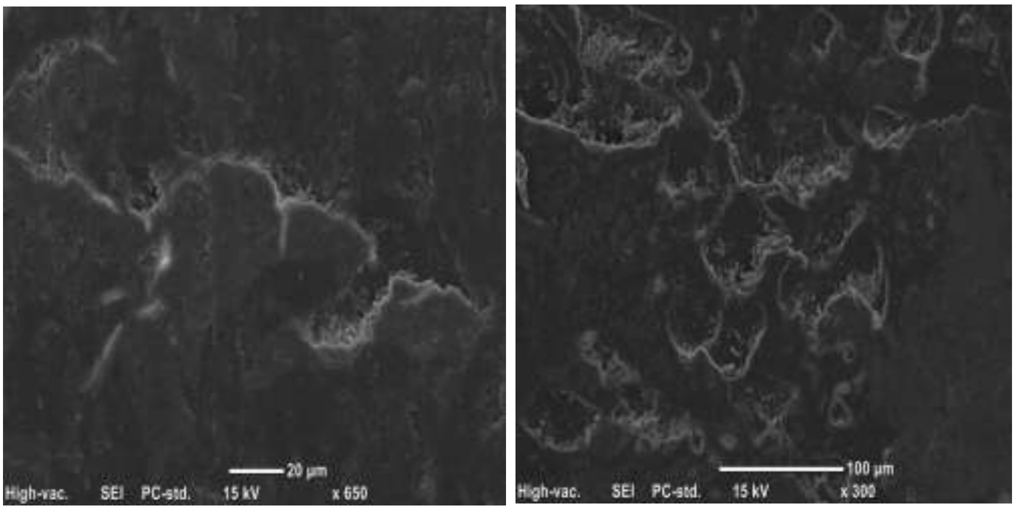
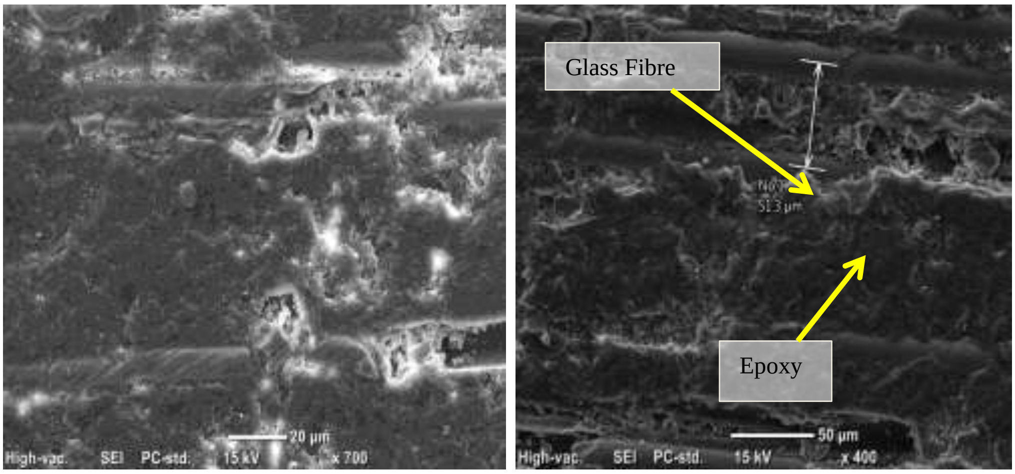
APPENDIX C: FURTHER RESULTS

1) Scanning electron microscopy observation

For GFRE

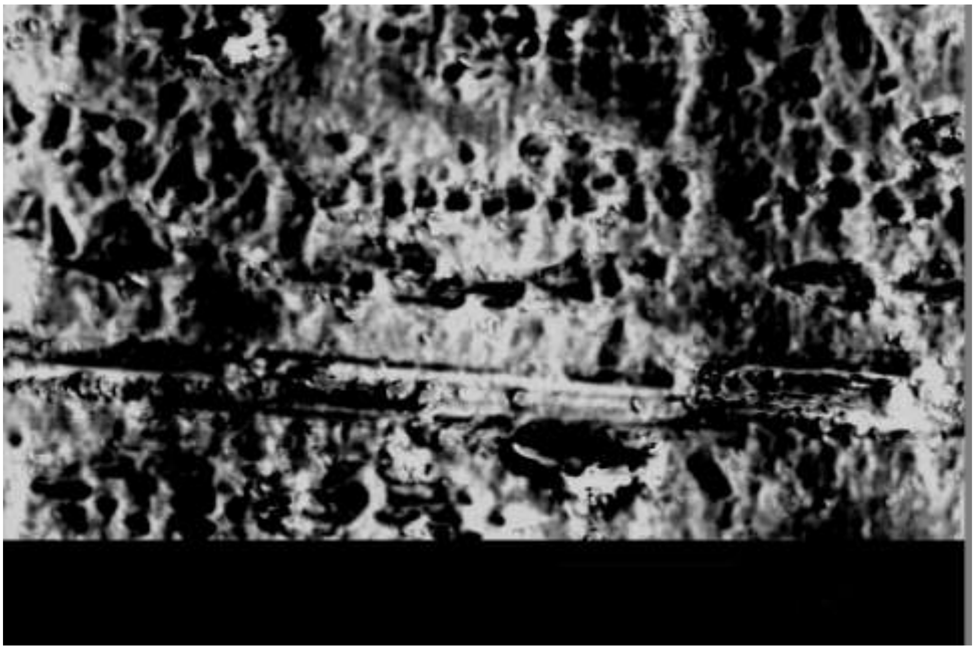


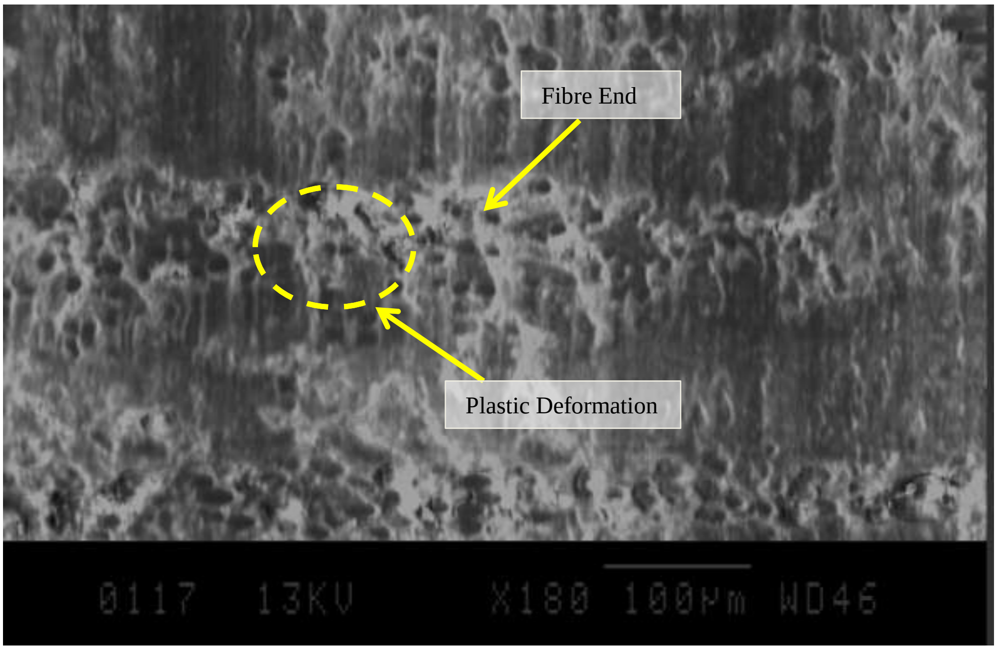
a) Micrographs of GFRE worn surface at normal orientation for 10 min



b) GFRE vergine surface

For GFRP





Micrographs of GFRP worn surface at 2.8 m/s