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Keywords

skin tribology, synthetic skin, blisters, polyurethane, biotribology

Disciplines

Applied Mechanics | Other Mechanical Engineering | Tribology

Comments

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Investigation of the effect of the normal load on the incidence of friction blisters in a skin simulant model

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Abstract

A laminar skin simulant was constructed to study the incidence of friction blisters. The skin simulant consists of a thin polyurethane top layer and textured gum foam rubber bottom layer adhered to an acrylic backing plate to emulate the layered structure of the human skin. Friction blisters were produced on the skin simulant by using a dual axis tribometer. The effect of the applied normal load on the number of cycles required to produce a blister was investigated. The skin simulant was also analyzed as an adhesive bonded laminar composite to determine the relationship between the applied normal load and the number of cycles for blistering. The normal load and the number of cycles were found to be inversely related and vary by a power law function, as observed in previous work on human subjects in Naylor's pioneering study. The results obtained from the experimental data and the fracture mechanics modeling of the skin simulant indicate the potential of elastomeric skin simulant in providing useful insight into blister mechanics and other tribological properties of skin.

Keywords

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Introduction

Skin is the largest organ in the human body, and is the body's first line of defense against damage and infection. Friction blisters are one of the most common forms of damage that occur to human skin. Friction blisters usually cause mild discomfort but can be a major cause of concern when they lead to intense pain, cellulitis and sepsis. They can compromise performance in athletes and military personnel. In a study where soldiers participated in a 20 km road march, 69% were found to have blisters and 10% of them had severe enough blisters to require medical intervention [1] . Blisters are also one of the three most important types of injuries in marathon runners [2]. The first significant effort towards studying skin friction blistering began with Naylor's experiments to study the effect of skin friction on load carrying for Army operational

research. Naylor showed the existence of a parameter similar to coefficient of friction for the skin and that it depends on environmental conditions [3]. To better understand the mechanical properties of the skin, and analyze skin damage, like blisters, from a mechanical failure standpoint, it is important to have a basic idea about the structure of the skin.

Human skin is a complex system with two distinctive layers called the epidermis and the dermis, which are connected to the subcutaneous bone and muscle tissues through the hypodermis. The outermost layer, the epidermis, is in turn divided into five layers, outermost to innermost being the stratum corneum, the stratum lucidum, the stratum granulosum, the stratum spinosum and the stratum basale. The stratum basale is a layer of living cells, and it marks the transition from living cells in the dermis to dead cells in the epidermis. In his experiments on friction blistering, Naylor showed that when there is a sufficient friction force between the skin and the rubbing surface, blister formation occurs through an intra-epidermal split caused by prickle cell necrosis and filling of the split with blister fluid [4]. In his pioneering work with human subjects, Naylor also showed that there exists an inverse relationship between the number of rubs required to produce a blister and the frictional force. [4]. Two conditions were proposed to be critical for blister formation: 1) firm attachment of the lower epidermis to the adjacent tissue, and 2) sufficient thickness of the stratum corneum. This may be one of the reasons that the most common occurrences of friction blisters are on palms and soles of the feet [5]. Research done on extensibility of the skin has shown that when the skin extends, three factors act consecutively: 1) convolutions in the dermal collagen fibers straighten out, 2) the dermal collagen fibers get aligned parallel to each other in the direction of the load, and 3) as the load increases, the aligned fibers extend. This phenomenon is responsible for directional variations in extensibility of the

skin at various locations [6]. In this respect, skin behaves like a typical elastomer, and it suggests that elastomers can be used to model skin. So far, the study of friction blisters has been done primarily on human subjects. Friction blisters have also been successfully produced in animals to facilitate study on blisters without human subjects [7]. However, both of these methods are difficult due to current regulations on experiments with human and animal subjects, and because they also create huge variability in results due to variations in properties of the skin from subject to subject and from animals to humans. Recently, attempts have been made to characterize the blisters from an engineering standpoint by using a synthetic skin simulant platform, and blisters have been produced successfully under various conditions [8]. Using a synthetic simulant improved repeatability of the results and decreased variability across the sample.

It has been proposed by Comaish et al. that epidermal fatigue due to shear stress from the frictional force on the surface of the skin could be the cause of friction blistering [9]. In the current study, the authors focus on improving the aforementioned synthetic skin stimulant platform to study the effect of normal load on blistering. A fatigue based fracture model is proposed that models the skin simulant as an adhesive bonded laminar system to provide some insight into blistering mechanics. Also discussed are some of the current methods for determining fatigue properties of laminar composites and their applicability to the skin simulant approach used in this work.

Materials and Methods

Skin Simulant Design and Preparation

The skin simulant used in this study consists of two layers with an acrylic backing plate. The top layer simulates the epidermis and the bottom layer simulates dermis, fat and muscle tissue beneath the epidermis. Each of them will henceforth be referred to as epidermal simulant layer (ESL) and dermal simulant layer (DSL) respectively. The acrylic backing plate adhered to the DSL has a two-fold use. It simulates bone beneath the tissues, and it acts as support for the tribological testing purposes. Previous friction blistering studies on the synthetic skin simulant platform showed that the simulant experienced significant substrate effects during testing due to thinness and compliance of layers, and that it is imperative to use a support beneath layers during tribological testing [8].

The simulant was designed to replicate the blister formation mechanism of human skin, more specifically blisters formed on the palms and soles. In light of this, the design takes into consideration the factors that were shown to play a role in the blister formation during experiments on human subjects. The first factor considered was the coefficient of friction (CoF) of human skin. A challenge in this field of research is the fact that the friction coefficient of skin varies widely based on a multitude of factors such as anatomical location and hydration state. Masen et al. reported a range of CoF values from approximately 0.2 to 1.3 of skin rubbing against a stainless steel counterface [10]. It has also been shown that elastomers, like polyurethane, exhibit friction values against steel that fall well within this range. Friedrich et al. reported on PUR composites with friction coefficients in dry sliding ranging from 0.2 to 0.52 [11]. The case for using PUR as a dermal simulant is further bolstered by the similarity with skin when rubbing against other materials, as well. For instance, PUR, when tested against wool exhibited similar coefficient of friction as the skin on the palms [12, 13], and Derler et al.

showed that PUR exhibited only slightly higher CoF than skin against a number of reference materials [12]. Therefore, due to its commercial availability in a liquid-castable form, its transparency when cured, and its frictional similarities to skin, a polyurethane RTV resin was used for the epidermal simulant layer. The ESL was made of a polyurethane (PUR) layer of thickness of 0.6 mm, approximating the thickness of the epidermis in human skin [14]. Sufficient thickness of stratum corneum is known to be an important factor to produce friction blisters [5]. The PUR film was casted from a two-part urethane RTV mold-making system (TAP Plastics, San Leandro, California, USA). Once cured, the ESL is transparent and has a resulting durometer of approximately 60 Shore-D (approximate equivalent elastic modulus of 7.0 MPa). The DSL consists of textured natural gum foam rubber with adhesive backing and has a thickness of 6.2 mm (McMaster-Carr, Elmhurst, Illinois, USA) and an approximate elastic modulus of 240 kPa. The textured surface of the DSL was selected to better mimic the ridged surface of the dermis than a smooth layer as was employed in a previous version of the skin simulant concept. The adhesive backing of the DSL was stuck to the acrylic backing plate. The ESL is cast to form a 70-mm diameter circular film on top of an 80-mm square DSL and was allowed to cure at room temperature for 24 hrs. The PUR film was cast without any mold release and when completely cured, attached itself firmly to the textured surface of the DSL. Figure 1 shows the skin simulant specimen with a completely cured ESL layer. Since no adhesive was used in bonding the ESL and the DSL, constant adhesive bond strength was maintained for all the specimens throughout the experiment.

Blistering Device

A dual axis tribometer was used to produce the blisters. The tribometer had a motion-controlled platform on which the specimen was firmly placed and had fixed stations to which a wear head

was attached. The platform with the specimen reciprocated linearly under the stationary wear head. To enable blister formation without tearing the top layer on the thin-layered skin simulant, and to test the effect of the normal load over a wide range of loads, a low-weight station was specially constructed. This low-weight station used standard weights to apply normal load in the range of 3.11 to 5.56 N. Figure 2 shows the tribometer with the corresponding station used in the testing. The wear head used was an 18-8 stainless steel acorn nut (McMaster-Carr, “1/4 inch - 20” thread, 11.1-mm width, 11.9-mm height). The diameter of the probe head was approximately 11.5 millimeters. Assuming a spherical head, and with the observation that the depth of penetration of the head was significantly greater than the thickness of the ESL, the range of predicted maximum contact stresses was from 130 to 155 kPa, using a Hertzian elastic model.

Experimental method

The effect of the normal load on the number of cycles taken to form a blister was tested. Other parameters that were known to affect the blister formation on human skin like the coefficient of friction, adhesion between the layers, thickness of the layers and the shear speed [4, 5, 8] were kept constant. Both the surface of the simulant and the surface of the wear head were unlubricated and untreated in any way throughout the experiment to maintain a constant coefficient of friction. Additionally, the ambient temperature during the test was controlled and monitored to be in the range of $23 \pm 1^\circ\text{C}$. The length of travel of the wear head over the surface of the simulant was 60-mm per cycle. A constant crosshead speed of 20 mm/s was maintained throughout the experiment, with the exception of the very short decelerations and accelerations experienced at the ends of the reciprocated path when direction was changed. The numbers of cycles taken to produce a blister at a given normal load were measured. The experiment was started with no weights added to the station, with a corresponding normal load of 3.11 N. The

trials were repeated with incremental increases in normal load of 0.25 N with each step. The experiment was repeated until the upper limit on normal load was reached. The upper limit on the normal load was defined as the minimum load at which the outer layer of the simulant fails by tearing before any blister was formed. The blister formation was characterized by the appearance of an opaque oval with a distinctly raised surface along the length of the travel as shown in Figure 3. Due to the viscoelastic nature of the materials used, it is likely that some inelastic recovery occurred after a significant time post-test, thus blister height was not directly measured. The production of the blister was manually observed and the test was terminated for each sample once a clearly distinguishable blister was produced. The tribometer control software recorded the number of cycles at which the test was terminated. This yielded the number of cycles for blister formation in each trial. One simulant sample was used for a total of three test runs. Trial and error were employed with pilot samples to determine a minimum spacing of approximately 15 mm between affected areas. This spacing was sufficient to ensure that none of the individual tests were affected by previous tests using the same sample. One test run was conducted for each load setting, thus statistical variation in blistering behavior was not able to be determined in this study.

Mechanical modeling of the skin simulant: relation between the normal load and the number of cycles

Fundamentally, the synthetic skin simulant is an adhesive bonded laminar system. The PUR in the ESL acts as an adherand as well as the adhesive joining the ESL and the DSL layers. The most common modes of failure in adhesive bonded joints are: cohesive, adhesive and substrate failure, respectively [15]. Separation of layers at either the inter-laminar or intra-laminar level is

the result of such failures. For the current synthetic simulant, considering one of the layers acts as an adherand as well as the adhesive, it was hypothesized that a probable failure mode is adhesive failure (AF). In the AF mode, separation appears at the adhesive-adherand interface [16]. During the blistering experiments, the synthetic skin simulant was subjected to cyclic normal compressive and shear loads. One way to describe blister formation is as an adhesive delamination due to fatigue loading. In such a model, the blister appears due to crack propagation between the adhesive and one of the layers. Fabrication and material defects like cavities, inhomogeneities, improper curing, were shown to act as nucleation site for cracks in the polymer-based adhesive bonded laminar composite systems [17].

Fatigue failure in the adhesive bonded laminar interfaces is a complex phenomenon and there is no universally accepted criterion to explain it. However, assuming low numbers of fatigue cycles and a linearly elastic and isotropic system, linear elastic fracture mechanics (LEFM) techniques have been used in the past to evaluate the crack growth under fatigue loading and have made reasonable predictions for fatigue life [18]. The fatigue process is characterized by three stages: 1) crack initiation, 2) crack propagation, and 3) fast crack propagation [18]. A classic model by Paris suggested that the relationship between rate of crack growth and fracture toughness follows a power law [19]. With reasonable estimates of initial crack length and stress intensity factor, the model can describe stage II crack propagation with reasonable accuracy [20].

The blisters formed on the synthetic skin simulant were oriented in the direction of motion of the wear head. Assuming a crack already exists due to fabrication defects or material inhomogeneities, the corresponding Paris model is

$$\frac{da}{dN} = C \cdot \Delta K_{II}^m \quad (1)$$

where da/dN is the rate of crack growth per loading cycle, C and m are empirical constants, and ΔK_{II} is the fluctuation in mode II (shear loading) stress intensity factor during the loading cycle. The top layer of the skin simulant was approximately 0.65 mm in thickness. Assuming a plane stress condition, the change in mode II stress intensity factor under a given fatigue loading is estimated by

$$\Delta K_{II} = 2\tau Y \sqrt{\pi a} \quad (2)$$

where Y is a dimensionless parameter whose value depends on the geometry of the specimen and the crack dimensions, and τ is the shear stress due to friction force. Y is assumed to be independent of crack length for short cracks. The stress intensity factor can be substituted in the power law equation and can be integrated to give number of cycles for failure thus yielding

$$N = \frac{2(a_f^{1-\frac{m}{2}} - a_i^{1-\frac{m}{2}})}{C(2-m)(2Y\sqrt{\pi})^m} \cdot \tau^{-m} \quad (3)$$

where a_f and a_i are the final and initial crack lengths respectively. This equation provides a means of predicting the number cycles required to produce a blister on the skin simulant based on applied normal load.

Results and Discussion:

Blisters were formed under the given test conditions in all the trials at all normal loads. For each trial, during initial cycles of wear, as the wear head started to move long the surface of the skin simulant, the skin simulant was compressed in front of the wear head and was stretched behind it giving rise to a wave like disturbance across the surface of the skin simulant. This disturbance

was similar to the “bow wave” observed by Kwiatkowska et al. during in-vivo testing on human skin rubbed against a reciprocating steel probe [21]. This was followed by the appearance of small opaque regions indicating localized debonding at the ESL-DSL interface. As the number of reciprocated cycles increased, the debonded regions extended along the length of the wear path, and coalesced to form a larger debonded region of the ESL. The debonded region of the ESL exhibited a wave like disturbance as the wear head reciprocated. This proceeded to form a blister with a distinctly raised opaque surface compared to the surrounding region of the ESL. However, not all of the debonded regions coalesced to form blisters, as can be seen in Figure 3. For all the trials, the blister formation occurred through this sequence of events as illustrated in Figure 4. For lower applied normal loads, all the above stages were clearly noticeable. These stages were similar to the blister formation stages of the Synthetic Skim Simulant Platform system by Guerra et al. [8]. As the applied normal load increased, the number of cycles required to form a blister drastically decreased.

At higher normal loads, blisters formed before each of these stages could be individually observed for any appreciable amount of time. All the blisters formed were oval in shape and the major axis of the blisters formed is oriented in the direction of motion of the wear head. The position of the blister along the length of the wear path varied. Blister area was observed by visual inspection. While no noticeable pattern was found between the applied normal load and the position or the area of the blisters, there appeared to be an inverse relationship between the normal load applied and the number of cycles required to produce a blister, as shown in Figure 5. This is in accordance with Naylor’s results from the blistering experiments on human skin [4]. There was a sudden drop in the number of cycles required to produce a blister, from the first trial

with normal loading of 3.11 N to the next load incremental trial with normal load of 3.35 N. For the subsequent trials, the number of cycles required for blister formation decreased with the increasing normal load increments at a much slower rate. This could be due to an existence of a threshold with respect to the normal load required to produce a blister at the given set of parameters for the skin simulant specimen (layer thickness, adhesion strength, cross-head speed and dermal stiffness).

Using the Paris model, debonding between the ESL and the DSL was analyzed as mode II delamination failure due to the interfacial shear stresses resulting from the tangential frictional force between the ESL and the wear head. In this approach, a constant coefficient of friction was assumed throughout the test as the surface texture and materials were held constant among all samples during the testing. Thus, as the normal load increased the frictional force increased accordingly as well as the shear stress experienced at the ESL-DSL interface. Hence, with increasing shear stress the number of cycles for failure decreased. **Figure 5** shows the experimental data. As shown, a Paris type power-law model was fit to the data to relate applied normal load to number of cycles required to produce a blister, yielding a least-squares fit of the form

$$N = 88300F^{-6.25} \quad (4)$$

The R-square value for the fit is 0.77 indicating the data are reasonably described by the crack propagation model (3). The degree of this correlation suggests that the mechanical aspects of friction blistering may indeed be tied to a fatigue mechanism in the ESL-DSL interface, analogous to the stratum basale.

The crack propagation model in this form did not take into consideration the effect of other important factors including shear speed, which undoubtedly affects viscoelastic systems such as skin. Also the assumptions of linearity and elasticity may not hold true through the entire process of crack propagation under cyclic loading. These issues can potentially be addressed by using the strain energy release rate parameter instead of a stress intensity factor, K . Modified crack growth models which use strain energy release rate have been used successfully to predict fatigue life of adhesive bonded systems such as the simulant used here [18]. Such models are generally of the form:

$$\frac{da}{dN} = C_i \cdot \Delta G^n \quad (5)$$

where ΔG is the change in strain energy release rate [17], while C_i and n are empirical constants. However, the value of n is smaller than that of m . The strain energy release rate parameter, G , takes into consideration mean stress along with change in stress state, as mean stress is known to influence crack growth. G and K are related by:

$$\Delta G = \frac{K_{\max}^2 - K_{\min}^2}{E} \quad (6)$$

where E is the elastic or flexural modulus of the adhesive [22]. Standard test configurations like the End Notched Flexure (ENF), the End Loaded Split (ELS) and the Four-Point End Notched Flexure (4ENF) have been used for studying the fracture in pure mode II and determining the strain energy release rate parameter, G . Finite element analysis has also been proposed to find the value of the parameter using methods like the virtual crack closure technique [23]. Such modeling of the skin simulant, as well as actual skin, may give an estimate of the sensitivity of the debond growth rate with respect to applied normal load [17]. Using the strain energy release rate approach might also provide better insight into the reasons why only certain debonded

regions became blisters in this investigation, thus giving further insight into blister mechanics. The ability to model this system from a fracture mechanics perspective may also increase the general applicability of the skin simulant to study other means of mechanical skin damage.

Future investigation employing this skin simulant approach is required in order to address limitations of the current study. Though it was beyond the scope of this study, failure mode analysis may be conducted in future work to better understand the debonding mechanism observed here. The simulant approach used here assumes that the coefficient of friction is constant throughout the wear cycle and as cycles are accumulated. Because of sweat, inflammation and temperature rise, it is known that the friction coefficient may change drastically before blister onset. Better characterization of the existence of a normal load threshold needs to be investigated by studying its dependence on other parameters such as layer thickness and inter-layer adhesion strength. Dermal ridges are known to affect the mechanical properties of the skin; however, the effect of dermal ridges on blistering is not known at this point. Also, the effect of other parameters like dermal stiffness and sliding speed needs to be further investigated over a wider range of normal loads. While the existing experimental approach shows merit, addressing these additional issues may aid in making the synthetic skin simulant more robust in representing human skin for friction blistering research.

Conclusions:

A two-layer elastomeric skin simulant was constructed to study the relationship between applied normal load and number of cycles required to produce blistering, analogous to Naylor's

pioneering work with human subjects. The results were analyzed to determine if they behaved in a manner consistent with a fatigue-based crack-growth failure process. The following conclusions can be made from the results:

1. The normal load and the number of cycles for blister formation are inversely related. This is in accordance with the behavior of human skin during blister formation as previously reported by Naylor.
2. There appeared to be a threshold value of interfacial shear stress that was required to produce friction blisters in the simulant. This agrees with empirical observations in human subjects.
3. The ex vivo elastomeric simulant approach was shown to be a promising tool for investigating dermal injury phenomena, thus helping to avoid the challenges encountered in frictional injury studies with human subjects.
4. A fracture mechanics based crack growth model showed some agreement with the friction-induced blistering of this multi-layer elastomeric system. This suggests that further investigation may be in order to determine if dermal blistering can be described as a crack-growth process.

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Figures

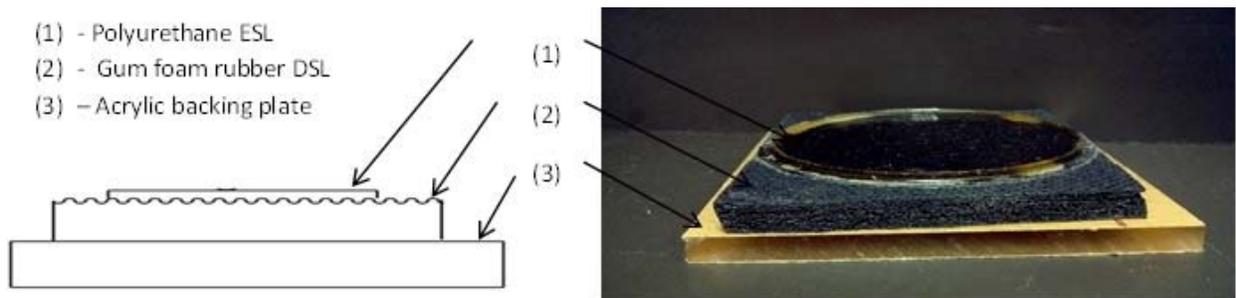


Figure 1: Synthetic skin simulant with different layers. The textured surface of the dermal simulant layer to emulate dermal ridges can be seen.

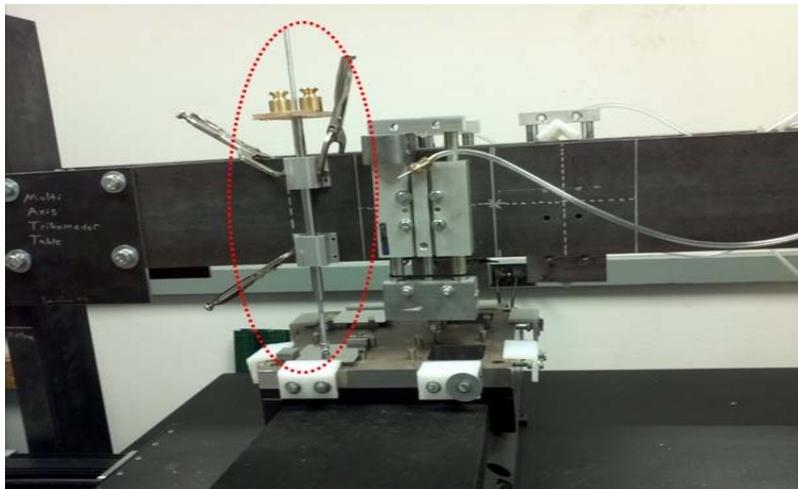


Figure 2: The dual axis tribometer with motion controlled platform and fixed stations. The low-weight station with standard weights used to apply normal load (dotted circle, left)

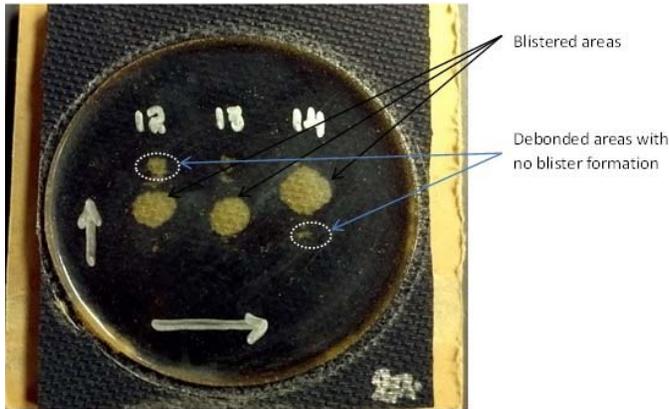


Figure 3 : The skin simulant with blisters (larger opaque areas), from left to right formed at normal loads 3.85N, 4.09N, and 4.35N respectively. Also shown are the smaller debonded areas with no blistering (dotted circles).

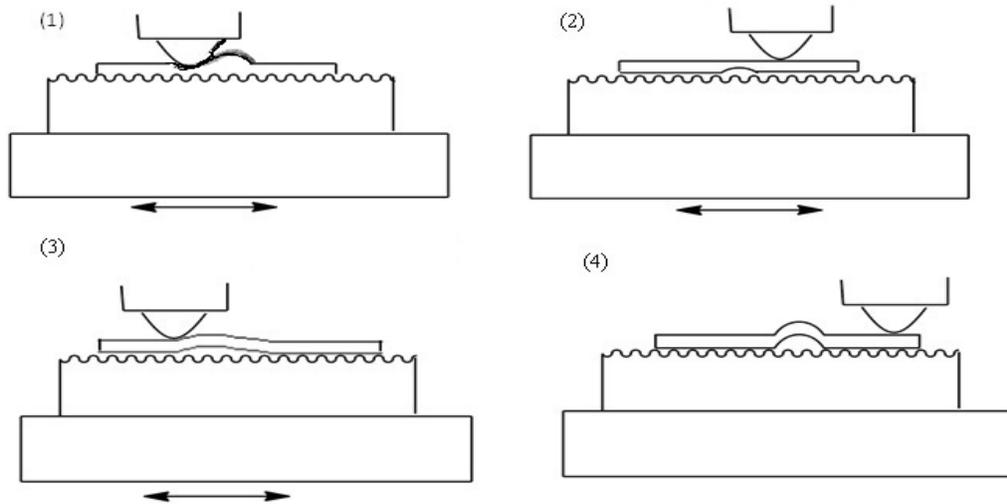


Figure 4: Illustration of the sequence of events leading to blister formation in the layered skin simulant. (1)As the wear head moves it compresses the surface of the skin simulant in front of it and stretches the skin simulant behind it forming a wave (2) Debonded regions appear at the

ESL- DSL interface (3) Debonded regions grow and coalesce to form a large debonded zone along the length of the wear path. Debonded zone of the ESL exhibits a wave like disturbance (4) Formation of distinctly raised surface blister at which point experiment is terminated.

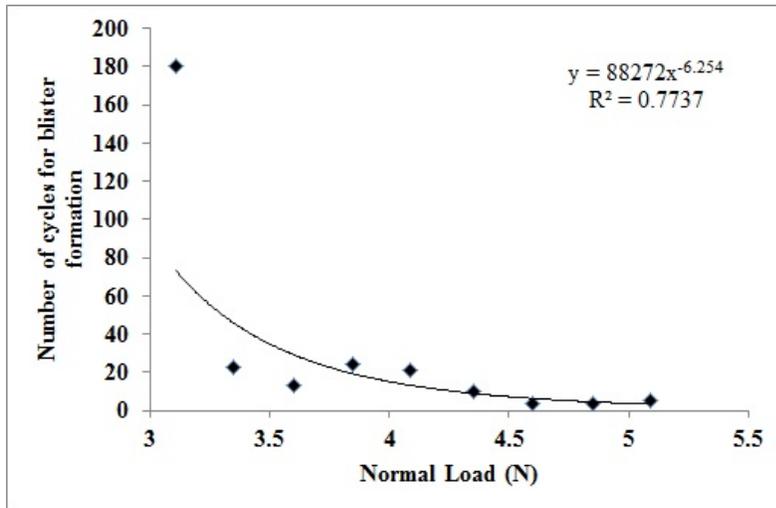


Figure 5: Curve showing the number of cycles required for blister formation as a power law function of the applied normal load, as fitted from the experimental data. Corresponding power law equation and the statistical parameter R^2 representing goodness of fit are also shown.