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Evolution of bi-Gaussian surface parameters and sealing performance for a gas face seal under a low-speed condition

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ABSTRACT

A spiral groove gas face seal, serving as a typical non-contacting seal, commonly encounters face contact during a low-speed condition such as the startup, shutdown, barring and warming-up operations. By using a discrete manner, the surface-topography evolution of the two mated sealing rings during a low-speed barring process is achieved, and is in a great agreement with the previous standard tests. The bi-Gaussian surface-topography evolution is found to well identify the end running-in, material adhesion and deep scratches. Furthermore, the surface-topography evolution exhibits a high correlation with the recorded seal-performance indexes including leakage rate, torque and acoustic emission signal, which is helpful in exploring the deterioration mechanism of sealing performance.

1. Introduction

A well-designed mechanical face seal has to strike a balance between the antagonistic demands on sealing and lubrication [1,2]. In contrast with a contacting face seal that commonly operates under the mixed lubrication, the gas face seal is a typical non-contacting face seal. During the normal opened operation, it owns a thin gas film to avert face contact, yielding the hydrodynamic lubrication. Even so, face contact does occur during the startup, shutdown, barring and warming-up operations, and is also a risk from disturbances during the opened operation. Face contact will damage the sealing pair, thus affecting the sealing performance and even leading to the sealing failure. Therefore, it is imperative to investigate the friction-wear mechanism and law of gas face seals.

Among the standard tribological tests, sliding wear is the most thoroughly studied wear mode with respect to a mechanical face seal. Accounting for the surface, serving as the fingerprint of a component [3–9], is closely related to lubrication, asperity contact, friction and wear, many researchers started their works with the surface topography. They attempted to link the surface topography to the lubrication, wear resistance, friction, transfer layer, etc. Based on the standard works, researchers [10–17] carried out the sealing rig tests where the amplitude parameters including the rms of surface height *Sq*, skewness *Ssk* and kurtosis *Sku*, as well as the spatial parameters including the autocorrelation function, correlation lengths and summit density were analyzed.

However, the above works were performed from a sing-stratum surface point of view. A bi-Gaussian stratified surface viewpoint [3–9,15,18,19] is more reasonable for a wear situation. The bi-Gaussian stratified idea arose from the plateau honing that is used to produce two-process surfaces such as the cylinder liner of an internal combustion engine [20–22]. Because of the similarity between the two-process manufacturing and the wear process, the bi-Gaussian stratified theory was then extended to the friction-wear field [4–9,15,18,19,23–26]. Thomas [27] regarded a worn surface as the original Gaussian surface superimposed with a truncating plane at a certain height, as shown in Fig. 1a. In fact, the truncating plane, generated by the wear, is not perfect smooth but follows a Gaussian distribution with a much smaller roughness scale comparing to the truncated Gaussian surface [23], as shown in Fig. 1b.

Williamson [28] found that for a Gaussian surface, if the probability coordinate of the material ratio curve (i.e., Abbott curve) is scaled to a Gaussian standard deviation coordinate, the resulting probability material ratio curve is a straight line. By this, the slope is *Sq*, and the intercept is the mean value. Therefore, the probability material ratio curve of a bi-Gaussian surface should exhibit two linear regions, as shown in Fig. 2. In previous works [20–22,24–26,29], the segmented linear regression, i.e., the segmented separation method, was used to characterize the probability material ratio curve of a bi-Gaussian surface in order to separate the upper and lower Gaussian components, thus obtaining the

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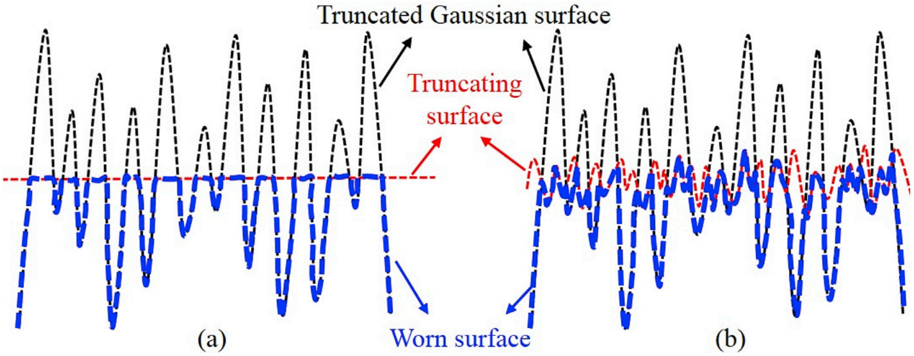

Fig. 1. Sketch of modeling a worn surface in 2D; (a) a Gaussian surface truncated by a smooth plane; (b) a Gaussian surface truncated by another Gaussian surface.

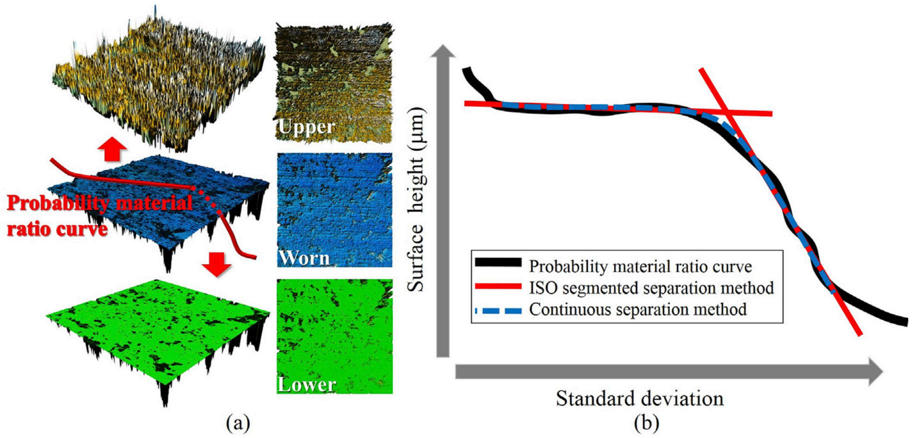

Fig. 2. Characterization of a worn surface by using the probability material ratio curve method; (a) method function [9]; (b) method type [8].

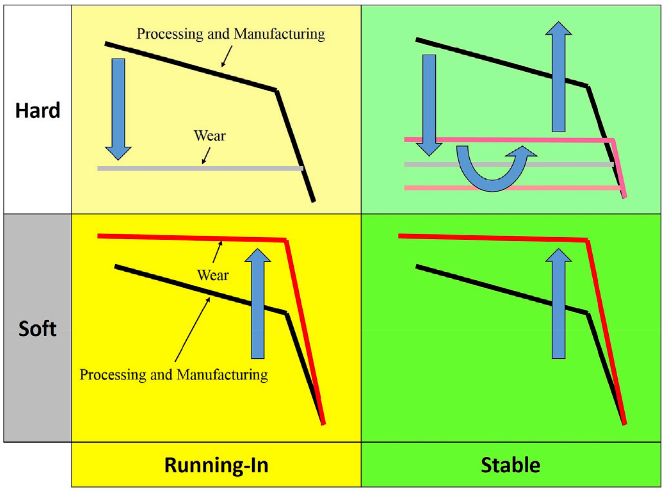

Fig. 3. Two bi-Gaussian surface-topography evolution modes obtained in the standard tests [9].

bi-Gaussian surface parameters including the rms of the upper component *Spq*, the rms of the lower component *Svq*, and the transition point *Smq*. A simple segmented separation method was firstly proposed [22], and was then normalized and optimized by ISO 13565-3 [29]. Recently, Hu et al. [4] proposed a continuous separation method to fit the probability material ratio curve unbrokenly. The continuous separation method was demonstrated to overcome the defect of the segmented separation method in the unit-area probability density function. Moreover, Hu et al. [5,18] also found that the continuous separation method exhibits high efficiency, perfect fluctuation resistance and roughness-scale independence. To date, Hu et al. has applied their continuous separation method to the issues about lubrication [18], asperity contact [18,19], tribological behaviors [8,9] and acoustic emission (AE) performance [30].

Similar to the previous standard works, the bi-Gaussian surface parameters have been connected to the wear resistance and friction. Pawlus's group [24–26] analyzed the local wear amount and friction under the dry friction and starved lubrication conditions by using 100Cr6 steel vs 42CrMo4 steel and grey cast iron vs chromium-coated steel C45. In the field of seals, Hu et al. did a pioneering attempt [8,9]. They selected silicon-carbide and carbon-graphite materials in their standard tests because the above pair is widely used in gas face seals. They mainly focused on the evolution of the bi-Gaussian surface parameters during a dry sliding process. They proposed the bi-Gaussian evolution modes (described in Section 2) to reveal the essence of the running-in and stable periods from the surface-topography viewpoint. In Ref. [9], the bi-Gaussian evolution modes well explain the question why the coefficient of friction remains unchanged during the stable period wherein the surface topography varies with time.

In the present study, the first aim is to apply the conclusions drawn from the standard tests [8,9] to the real gas-face-seal rig test. Herein, because the gas face seal is a non-contacting face seal, its end wear mainly caused by some low-speed conditions such as the startup, shutdown, barring and warming-up operations. Therefore, a low-speed condition is adopted in the present sealing rig test. Furthermore, the leakage rate, friction torque and AE signal are recorded. The second aim is to explore the correlation between the bi-Gaussian surface parameters and the sealing performance.