Tribology International 94 (2016) 591–605

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Effects of surface texturing on ring/liner friction under starved lubrication

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ARTICLE INFO

Article history:
Received 2 August 2015
Received in revised form
27 September 2015
Accepted 21 October 2015
Available online 31 October 2015

Keywords:
Surface texturing
Tribological behavior
Starved lubrication
Mixed lubrication

ABSTRACT

Well-designed surface texturing could reduce the ring/liner friction. However, so far most researchers have focused on the aspect of texturing under fully flooded lubrication. In this study, the performances of textures under starved lubrication are investigated. Specially for the textured ring/liner system, the flow conservation equations at the inlet region are built. In this way, the effect of the oil trapped in the texture features can be modeled clearly. The simulation results show that the textured liner can obtain a steady benefit on the tribological properties. However, the positive influence of the textured ring may remain unsteady under starved lubrication conditions.

1. Introduction

In the development of internal combustion engines, the reduction of frictional loss is regarded as an important issue to meet the requirements of high-efficiency and low-emissions. For internal combustion engines, the piston ring-pack is important as it contributes a large portion of the whole engine mechanical loss [1]. In industry, the texturing technique has been applied in the liners to reduce the friction between the piston rings and the cylinder liner. Surface texturing is an effective means to improve the tribological properties of sliding contact surfaces [2]. Both experimental and numerical studies have been conducted to study the effects of surface texturing on the friction, wear and load capacity.

Through the early studies, it is found that the microtextures can provide a hydrodynamic lift, when the sliding surfaces are under the hydrodynamic lubrication [3]. By a large amounts of experimental and theoretical works, it was confirmed that the reduction of friction can be achieved by means of surface texturing [4,5]. Afterwards, the lubrication of the ring/liner system with surface texturing becomes an important research topic because it is widely recognized that the microfeatures at the surface of ring or liner can provide the substantial influences on the friction, wear, oil consumption and power loss in an internal combustion engine. The applications of surface texturing in the piston ring/liner system are mainly divided into two categories: one is the surface texturing on the ring; another is the surface texturing on the liner. For the piston ring, Etsion and his co-workers have made some important observations for the textured ring [6–9]. In their works, it was found that there was an optimum aspect ratio to depend whether the textured surface reduced the friction or increased the load support maximally under many conditions. The partial texturing was also investigated in their works. They suggested that the partial texturing should be recommended for the flat piston rings. More recently, a one-dimensional model was employed by Tomanik and his co-worker to simulate the effects of surface texturing on the engine cylinder liner and piston rings [10,11]. In their studies, the mixed lubrication condition was considered, as well as two kinds of surface texturing (full texturing and partial texturing). Their predicted results also showed the partial surface texturing could obtain a benefit in the friction. Gadeschi and co-worker investigated the performance of the laser-textured piston ring by numerical simulation [12]. The parameters of surface texturing, such as the dimple depth, dimple density, and dimple distribution pattern, were optimized to minimize the friction coefficient for piston rings. The sensitivity of the optimal surface parameters to the ring curvature was discussed. Moreover, the texturing on the surface of cylinder liner is another research focus. Jocsak and co-worker analyzed the effects of the three-dimensional surface textures on the cylinder

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http://dx.doi.org/10.1016/j.triboint.2015.10.024
0301-679X/

Nomenclature

a_0	correlation parameter for calculating the viscosity
A	correlation parameter in the Greenwood and Tripp model
b	ring face width
C_f	boundary friction coefficient
E_1	elastic modulus of the slider
E_2	elastic modulus of the plane
E'	composite elastic modulus of the contact surface material
$F_{frc,asp}$	the asperity contact friction force
$F_{frc,oil}$	the hydrodynamic friction force
$F_{frc,total}$	the total friction force
h	mean film thickness
h_0	minimum oil film thickness
h_p	depth of dimple
H_σ	ratio of the mean film thickness h to the composite roughnessσ
K'	correlation parameter in the Greenwood and Tripp model
p_{cav}	cavitation pressure
q_{supply}	oil supply flow rate at the inlet
r_p	radius of dimple
S	distance between the two measured points
T	the period of the engine cycle
T_1,T_2	correlation parameters for calculating the viscosity
T_{BDC}	liner temperature at the position of the oil ring at the bottom dead center
T_{liner}	the temperature distribution along the liner
T_m	lubricant temperature
T_{TDC}	liner temperature at the position of the top compression ring at the top dead center
U	velocity of the piston ring
V_s	displaced volume of the cylinder
x	direction along the ring face width in global coordinate system
x'	direction along the ring face-width in the local coordinate axis which is in the center of texturing features
x_{in}	inlet boundary position
x_{input}	the location of the attaching point
y	liner location relative to the position of the top compression ring at the top dead center
Z	correlation parameter in the Greenwood and Tripp model
β	asperity radius of curvature
δ	ring crown height
η	number of asperities per unit contact area
μ	viscosity of the lubricant
υ_1	Poisson's ratio of the ring
υ_2	Poisson's ratio of the liner
σ	composite roughness of the piston ring and cylinder liner
ϕ_c	contact factor
ϕ_f,ϕ_{fs},ϕ_{fp}	friction-induced flow factors
ϕ_x	pressure flow factor
ϕ_s	shear flow factor
Ω	area occupied by a dimple

liner [13]. Their modeling results suggested that the reduction of the ring-pack friction was possible if the cross hatch angle of liner honing was decreased. Takata and co-workers studied the effects of surface texturing in large bore engines [14]. They thought the lubricant viscosity should also be optimized as well as the texture features. Ergen and co-workers focused on the oil consumption behavior of laser textured cylinder bores [15]. The effects of different laser surface texture patterns on the oil consumption were investigated and compared with the conventional plateau honing. Urabe and co-workers also studied the surface texturing on the liner [16]. The shape of the dimples was optimized in their study, as well as the treatment area for the cylinder. The improvements in fuel consumption ranging from 0.7% to 3.2% were obtained, allowing for differences between engine types. Yin and co-workers adopted the mixed lubrication model to consider the coupling effects between the surface roughness of non-texturing regions and microfeatures and the synergistic effects of multi-micro-features [17]. The parameters of microfeatures were optimized to obtain a better lubrication effect. Moving texturing for the textured liner was first proposed by the research group of Checo [18,19]. In their simulations, the texture features on the liner can move through the computational domain.

Most the above researches have been focusing on the well-lubricated ring-liner conjunction. However, in industry, the starved lubrication is a common phenomenon [20]. The performance of surface texturing under starved lubrication is worthy of special attention. Using μPIV (microparticle image velocimetry), Wang and co-workers carried out the experimental research of the fluid flow out of a microcavity [21]. The trapped oil in the textured features may provide an additional oil supply for the lubrication of the ring-liner, when the texture features are on the liner. Therefore, this poses a challenge in modeling the effect of the trapped oil in the texture features.

For this purpose, the piston ring/liner problem with textures on the ring and liner will be addressed, taking into account the oil supply. The flow conservation equations at the inlet region are developed to determine the change of the attaching point position in the inlet of clearance. By analyzing the trends relating the ring/liner friction, a general evaluation of the potential of the surface texturing to reduce the ring/liner loss is made.

2. Mathematical model

2.1. Governing equations

As the ring diameter is greater than the axial width for the piston ring in current paper, the ring/liner tribological conjunction can be viewed as an infinitely long sliding bearing [22,23]. Meanwhile, based on the assumption that the ring is perfectly conforming in the circumferential direction, the lubrication of the ring/liner system can be treated as a one-dimensional problem. In the simulation, the one-dimensional Reynolds equation is chosen to calculate the hydrodynamic pressure due to the suitable computing time and the acceptable calculation precision. In order to consider the influence of surface irregularities on the lubricant flow under the mixed lubrication conditions, the one-dimensional average Reynolds equation with a corrective flow is used [10,11,24]:

$$\frac{\partial}{\partial x}\left(\phi_x \frac{h^3}{\mu}\frac{\partial p}{\partial x}\right) = 6U\phi_c\frac{\partial h}{\partial x} + 6U\sigma\frac{\partial \phi_s}{\partial x} + 12\phi_c\frac{\partial h}{\partial t} \tag{1}$$

where ϕ_x is the pressure flow factor, h is the mean film thickness, μ is the viscosity of lubricant, p is the hydrodynamic pressure, U is the velocity of the piston ring, σ is the composite roughness of the piston ring and the cylinder liner, ϕ_s is shear flow