Mechanism and Machine Theory 104 (2016) 81–99

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Determination of wear in internal combustion engine valves using the finite element method and experimental tests

Federico J. Cavalieri[a], Fernando Zenklusen[b], Alberto Cardona[a,*]

[a]Centro de Investigación de Métodos Computacionales (CIMEC), Universidad Nacional del Litoral-CONICET, Predio Conicet "Dr Alberto Cassano", Colectora Ruta 168 s/n, Paraje "El Pozo", 3000Santa Fe, Argentina
[b]Mahle Argentina S.A., Bv. Santa Fe 2350, S2300KUX Rafaela, Argentina

ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 17 May 2016
Accepted 23 May 2016
Available online 5 June 2016

Keywords:
Archard law
Contact mechanics
Mortar method
Wear testing machine

ABSTRACT

A methodology for the analysis of wear in internal combustion engine valves is proposed, which is the result of the combined use of numerical and experimental techniques. The numerical solutions are obtained using a specialized Finite Element Method, where a mortar contact algorithm is used to model a flexible–flexible contact along with an adhesive wear law. The experimental results are obtained in a wear testing rig specifically designed to evaluate wear parameters in valve operating conditions. A good agreement was found between the experimental worn profiles and the numerical computations of wear at the contact surfaces.

1. Introduction

Currently, the occurrence of wear in internal combustion engine valves represents a severe problem for valve designers and manufacturers. The primary cause of wear in this component occurs between the contact surfaces of the valve and the Valve Seat Insert (VSI) under unlubricated contact conditions [1]. The reduction in fuel consumption, decrease in levels of polluting gases and high contact pressures emerging from the combustion process are at the origin of this situation. A decrease in the fuels lubricity because of environmental regulations is observed in contact areas, which contributes to the wear process.

Lead was added to gasoline for several years to generate a more uniform combustion process, thus increasing the fuel efficiency and generating an increase in power and a decrease in fuel consumption. Furthermore, the lead deposits formed between the contact areas of the valve and the VSI lubricated and cleaned these surfaces which helped to reduce the wear between the parts [2,3]. However, current environmental laws impose severe restrictions on the emission of NO_x, and the use of lead in gasoline for cars and trucks engines has been eliminated since 1993. In the case of diesel engines, the continuous requirements given by the ASTM-D975 standard to obtain cleaner diesel fuels involve the removal of a large part of sulfur, which provides lubricity characteristics. This type of diesel fuel is known as Ultra-Low-Sulfur-Diesel (ULSF).

The European emission standards *EURO*, which define the acceptable limits for exhaust emissions, impose that emission levels have to be below 1.5 g/kWh of CO and 0.4 g/kWh of NO_x for diesel trucks and buses by 2014. These laws drive the re-design of several engine components, and the manufacturing process has become a demanding task. Thus, new technologies

* Corresponding author.
E-mail addresses: fcavalieri@santafe-conicet.gov.ar (F. J. Cavalieri), fernando.zenklusen@ar.mahle.com (F. Zenklusen), acardona@unl.edu.ar (A. Cardona).
URLs: http://www.cimec.org.ar (F. J. Cavalieri), http://www.ar.mahle.com (F. Zenklusen), http://www.cimec.org.ar (A. Cardona).

http://dx.doi.org/10.1016/j.mechmachtheory.2016.05.017

for internal combustion engine valves are oriented to designs that increase the life in terms of fatigue and wear by considering an increase in the combustion pressure to obtain a more efficient cycle, weight reduction, lower head thickness, hollow valves, hard alloys, accurate definition of the contact angles between the valve and the VSI and reduction in the roughness, among other factors.

One approach to study the wear process in valves is using dynamometer engine tests, where a complete internal combustion engine is incorporated into an instrumented test bench. This type of test is expensive, time consuming and does not help determinate the source of the wear. Additionally, it is difficult to isolate the physical parameters related with the loss of material by the wear process. The wear testing machines are specifically designed to evaluate the wear in valves, such as the machine presented by Chun et al. [4], which represents a tempting alternative. These machines simulate the contact conditions and the thermo-mechanical loads at which the internal combustion engine valves and the VSI are subjected. The tests require less time, allow a better characterization and analysis of the wear process and, are cheaper than those made in dynamometer engines. The experimental results obtained with these types of machines can be complemented by the use of numerical simulations to obtain the macroscopic wear coefficients. This information can then be used to optimize the existing designs or propose new ones in terms of wear, thus reducing the number of experimental tests.

The theoretical study of the wear process is described by making assumptions to obtain the relationships between the environment conditions and the tribological behavior of the materials in contact. Throughout the years, several analytical equations have been proposed to solve this problem. For example, Meng and Ludema [5] identified more than 300 wear equations for different material pairs and operating conditions. However, few of them can be used in real world engineering applications. Currently, most of the models describing the wear phenomena are based on the studies of Holm and Archard [6,7]. In 1953, Archard proposed an equation derived from the early studies of Holm, which is known as the Holm–Archard wear law, or, as commonly cited in the literature, the “Archard wear law”. In this equation, the volume removed by the wear effects is inversely proportional to the softer material hardness and directly proportional to the following variables: (i) the normal load applied to the component; (ii) a dimensionless factor, usually known as the wear coefficient, which indicates the severity of the wear; and (iii) the relative sliding distance between the components.

The computational simulation of wear is an active research area, which is strongly focused on solving applications with general geometries in two-dimensional (2D) or three-dimensional (3D) configurations, where the analytical equations have important limitations. In the context of numerical methods, a few general applications of wear have been published using the Finite Element Method (FEM) [8,9,10,11,12,13,14,15,16] as well as the Boundary Element Method (BEM) [17,18,19,20]. In most of these studies, the formulations have been based on the Archard wear law, and the solutions were computed as the post-processing of a finite element code that solves the contact problem between the bodies, e.g., [21].

Several experimental studies on the wear in internal combustion engine valves can be found in the literature, e.g., [22,23,24,25]. Numerical studies on the wear in internal combustion engine valves using the finite element method are scarce; however, the studies conducted by Cavalieri and Cardona [26,27] addressed the problem in a rather tangential approach.

The experimental wear tests on dynamometer or on wear testing machines allow obtaining wear profiles and the maximum wear depth on the valve and Valve Seat Insert (VSI). However, with this technique, it is not possible to calculate the contact pressure developed during the test, which is mandatory to obtain wear coefficients. Other alternative to estimate wear coefficients is by using analytical equations. The main drawback is that this technique can be used only with very simple geometries. Furthermore, by the wear effects, the shape of the contact surfaces changes during the running and thus, the contact pressure also varies. The use of wear numerical simulation allows taking into account the change of the contact surface and the contact pressure. However, a wear coefficient is required in the formulation. In this study, a new methodology is proposed to study the wear in internal combustion engine valves using a finite element formulation combined with experiments on a test rig, which avoids the already mentioned inconveniences and simulates the working conditions in an internal combustion engine.

In Section 2, an introduction to the wear process in internal combustion engine valves is given. Section 3 describes the experiments performed on an ad-hoc valve testing machine to determine the type of wear and the values of the wear coefficients. A scanning electron microscopy and a dispersive X-ray spectroscopy were used to analyze the contact surfaces in the experiment and verify the adhesive wear mode. The numerical calculations of the wear are based on the Archard equation, which is briefly recalled in Section 4. The wear algorithm, which allows for a simultaneous coupled calculation of the displacements, contact pressures and wear fields [48], is described succinctly in Section 5. The numerical model is described in Section 6, and a comparison of the results from the experiments is presented. The wear coefficients values, which can be used for the design of the valve/seat insert pairs in similar operation conditions, are provided in this section. Lastly, the conclusions of the study are given in Section 7.

2. Wear process in internal combustion engine valves

The charge of fresh mixture and the discharge of combustion gases in the internal combustion engines are controlled by the intake and the exhaust valves, respectively. Fig. 1 illustrates a typical schematic drawing of a valve inside an internal combustion engine.

Valves are subjected to very demanding conditions: they have to support an aggressive atmosphere at extremely high temperatures (especially the exhaust valve) and time variable mechanical loads [28]. One important loading that a valve has to withstand is the impact of the VSI at the instant of closing, which generates time variable stresses at high frequencies. This event