Wear 268 (2010) 316–324

Contents lists available at ScienceDirect

Wear

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

Multi time scale simulations for wear prediction in micro-gears

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ARTICLE INFO

Article history:
Received 6 June 2008
Received in revised form 13 June 2009
Accepted 7 August 2009
Available online 15 August 2009

Keywords:
Wear simulation
Finite element method
Ceramics
Pin-on-disc
Twin-disc
Gears

ABSTRACT

Reliability of micro-gears is known to be adversely affected by wear. In this work we report a strategy to predict local wear with the aim of predicting their effective life span. For the prediction of local wear we start from the relevant model experiments, choice of a suitable wear model and identification of the wear coefficient from these experiments. This wear model is then implemented in an efficient finite element based scheme to predict local wear. Here we report the further development of this finite element based wear simulation tool, the Wear-Processor, to handle this multi time scale problem of gear tooth wear. It is needed to bridge the various time scales between the very fast pass of a contact over a surface point and the long-term wear simulation that is required for a prediction of the life span. Additionally it is necessary to account for any change in the slip rate due to wear. The results presented in this article show how fast the gear tooth geometry, the slip rates and the line of action deviate from their original values as a consequence of wear. We predict a maximum of 3 μm of wear on silicon nitride micro gear tooth flank with width of 200 μm just after 3500 contact cycles.

1. Introduction

Microsystems and micro-machines in particular are a rapidly emerging technology, finding a wide variety of applications. Tribology is expected to play a strong role in enabling microsystems technology because surface forces dominate body forces [1]. Wear being a surface phenomenon was identified as a critical factor for limiting their lifespan since Gabriel et al. [2] observed wear in a silicon surface micro-machined gear spun on its hub at high speed using an air jet. Williams [3] has shown that 1 min of life for a micro-machine represents a degree of wear and degradation equal to more than 10 years for a well designed watch bearing. Additionally, micro-machines like the ceramic micro planetary gear train shown in Fig. 1 have fabrication tolerances that cannot be as stringent as in the macro world and there is hardly any possibility for correction to the specified tolerances after fabrication. However, Hall et al. [4] have suggested based on their experimental study that by patterning the side walls of the mold, the side walls of LIGA[1] parts can be engineered thus giving control over friction, adhesion and wear in LIGA devices. For the particular case of the planetary gear train, the number of teeth in the gear train has to be adjusted to be an integer and so it has a non-ideal geometry to begin with, thus making it tribologically disadvantaged. Wear in engineering systems normally does not change the geometry in a way, that it has an effect on the kinematics of the system. Micro-machine designers have to take into account the fact that surfaces can wear considerably in relation to the dimension of the component and that the geometries change. Design for tribological performance should not always be based on the assumption that Hertzian loading conditions will be maintained, however in some cases assuming Hertzian loading may be a good approximation. New fabrication methods (see the volumes edited by Loehe and Hausselt [5]) for micro components have been developed by employing various wear resistant materials like ceramics. Such technologies have increased the choice of the available materials, thus giving larger room for micro-machine designers. However, the ability to predict wear and life-span is still essential for the development of reliable micro-machines.

Study of wear in micro-machines is often carried out using experimental techniques like pin-on-disc, twin-disc, scratch test, AFM etc. to characterize the tribological properties of various materials used for fabricating micro-machines. These experiments attempt to mimic the contact conditions of the micro-machine under study in terms of contact pressure, sliding velocity, etc. The specimens in the tribometer have the same microstructure as the micro-machine itself and the loading chosen in the experiments are such that they mimic the actual condition (chapter 21

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[1] LIGA is a process developed at Forschungszentrum Karlsruhe that enables mass production of polymer micro components and it stands for the German acronym for Lithography, Electroforming and Plastics Molding.

0043-1648/$ – see front matter
doi:10.1016/j.wear.2009.08.017

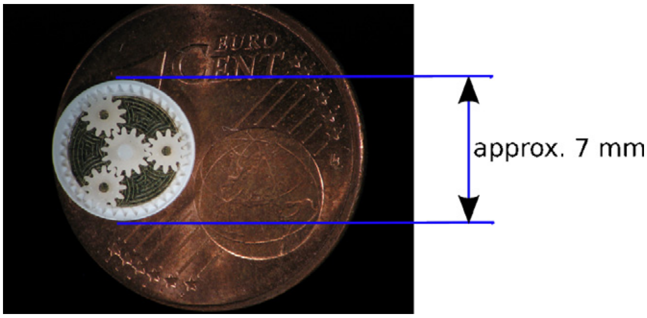

Fig. 1. Micro planetary gear train made from ceramics pictured here on a 1 euro cent coin. It was fabricated at the Karlsruhe Institute of Technology within the collaborative research centre, SFB 499.

of [5]). For example, twin-disc rolling/sliding tribometer tries to mimic the rolling/sliding contact experienced by the teeth of two mating gears. Hegadekatte et al. [6,7] proposed an approach that involves a computationally efficient incremental implementation of Archard's wear model [8] on the global scale for modeling sliding and rolling/sliding wear in such experiments. It was shown that this fast simplistic numerical tool can be used to identify the wear coefficient from pin-on-disc and twin-disc experimental data and also predict the wear depths within a limited range of parameter variation. It was also shown that the wear coefficient in the Archard's wear model identified on the global scale was also valid on the local scale. Tribometry allows for a qualitative study of the suitability of a particular material combination and therefore modeling of wear with data from such experiments is necessary in order to predict local wear in complex micro-machines with time dependent local pressure and slip. In this article we use the identified wear coefficient from model experiments to simulate local wear on a ceramic micro-gear tooth flank in a micro-planetary gear train shown in Fig. 1.

For simulating wear in micro-machines, the Archard's wear model is the most popular model as discussed by Williams [3], where it is used to predict wear in rotating pivots for moving micro mechanical assemblies. Zhao and Chang [9] have developed a micro-contact and wear model for predicting the material removal rate from silicon wafer surfaces during chemical–mechanical polishing, where the developed equation is a representation of the Archard's wear law. Sawyer [10] used a simulation scheme based on the Archard's wear model for the surface shape and contact pressure evolution during copper chemical–mechanical polishing. Wu and Cheng [11,12] proposed an analytical expression for partial elasto hydrodynamic lubricated contacts in spur gears and showed that the highest wear occurs at the beginning of engagement of the gears in the macro world. The micro planetary gear train shown in Fig. 1 is expected to run also without lubrication and therefore we concentrate on unlubricated contacts in the present work. Simulation of unlubricated wear employing Archard's wear model for spur gears [13], helical gears [14] and conical gears [15] have been proposed by Andersson and co-workers.

In this work we report a strategy to predict local wear with the aim of predicting their effective life span. For the prediction of local wear we start from the relevant model experiments, choice of a suitable wear model and identification of the wear coefficient from these experiments. This wear model is then implemented in an efficient finite element based scheme to predict local wear. Here we report the further development of this finite element based wear simulation tool, the Wear-Processor [16], to handle the complex geometry of mating gear tooth and the multi time scale problem of gear tooth flank wear. This is needed to bridge the time scales

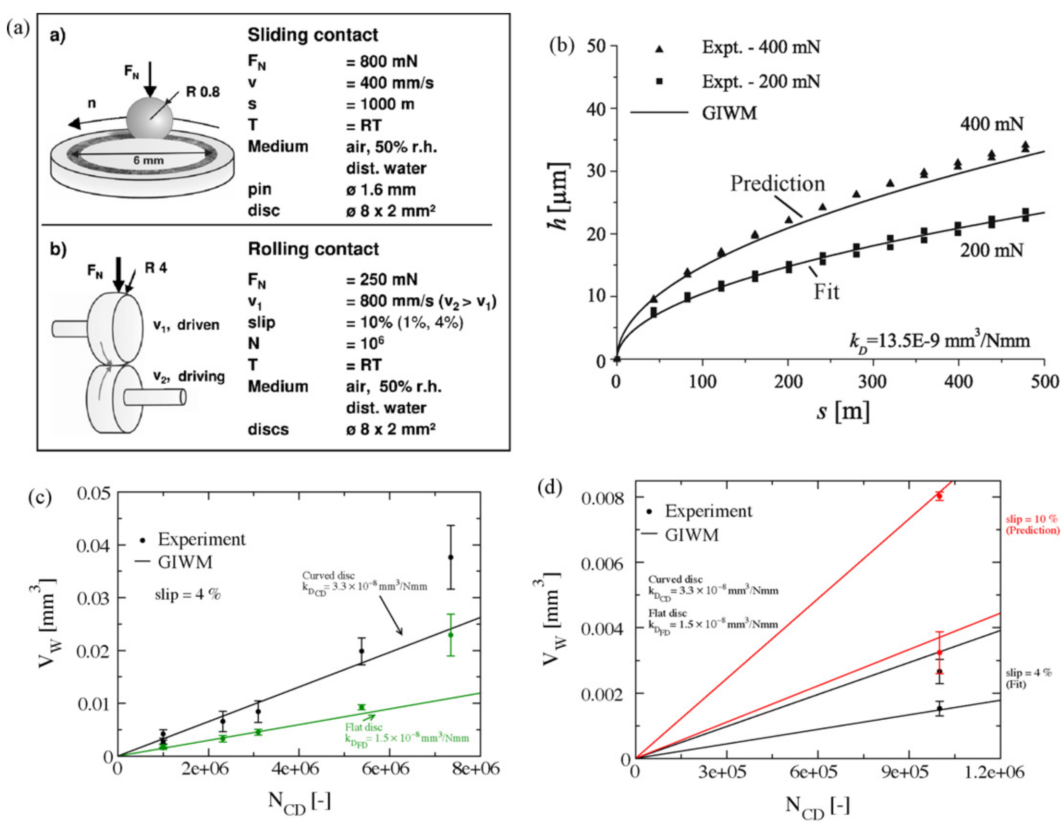

Fig. 2. (a) Tribometry experimental setup for pin-on-disc and twin-disc along with the various parameters. (b) Wear depth as a function of the sliding distance from pin-on-disc tribometer in comparison with results from GIWM. Volume of material removed from the GIWM in comparison with the experimental results from the twin-disc tribometer for the fit (c) at 4% slip and the prediction (d) for 10% slip.