

Preface

The motivation to write this monograph was to share engineering experiences related to thin film testing and vacuum systems. Testing of thin film lubricants applied to ball bearings that are used in rotating systems in high-voltage vacuum devices has received little attention in recent decades. This monograph has enabled us to share a unique combination of engineering experiences needed to solve practical problems related to testing of thin film systems. Design and mechanical testing involving vacuum chambers, pumps, plasmas, and the instrumentation needed to operate these has brought to light some less well known combinations of mechanics and physics needed to meet specific testing needs. Indeed, solutions to mechanical engineering problems require creative, cost effective, and innovative combinations of ideas and equipment to achieve sustainable and practical solutions. Necessity is the mother of invention, and this is certainly true when applied to mechanical testing in the context of manufacturing problems.

The impetus behind this monograph is that tribology testing in vacuum in the range of 10^{-5} to 10^{-8} Torr was required to meet a specific testing need. Thin solid film lubrication has been used extensively in rotating anode x-ray tube applications. A non-volatile, carbon-free lubrication, such as silver or nickel-copper-silver, is used to lubricate bearing parts during operation in high vacuum and in the presence of very high voltages, up to 140,000 V. Rotating element bearings that are used in x-ray tubes are a sealed lubrication system, that is, lubrication is added at bearing assembly and the system operates as a closed system for the remainder of its life. The goal to further understand solid lubrication films applied to ball bearings was a financial decision to reduce overall cost and extend bearing life. For example, improving film adhesion will help reduce infantile factory failures. Optimizing film thickness will extend ball-bearing life, and thereby extend the life of the x-ray tube for the customer. However, if the film is too thick it may flake off leading to catastrophic bearing failure. Choice of lubrication is key to prevent interaction with the fragile electronics inside the x-tube. For example, solid lubricants such as silver and gold are stable inside the x-ray tube environment and will not interact with electron beam components during operation. Improvements in film

adhesion, deposition techniques, and thickness control occurred in order of priority to add the most value to the customer in the shortest possible time.

The acquired knowledge shared throughout this monograph has been put into practice to correct engineering problems that reduce x-ray tube bearing life, and to deliver the highest value for the customer. The monograph organization has been dictated by necessity to improve ball-bearing system life. The steps to test thin films in rolling contact fatigue under vacuum conditions are outlined in the book. Procedures to prevent contamination and corrupt results are explained to help the reader understand the level of cleanliness required when testing hardware that will be used in a high-voltage and high-vacuum device. Our goal is to discuss and share with the reader issues and problems that may be encountered concerning bearing testing in high vacuum.

The book may be used by students and engineers for guidance to build, test, and commission any vacuum chamber application. Best practices that reduce risk of contamination as well as reduce operating costs are presented in Chap. 2. Diagnostic tools that can detect very slow leaks and that can be used to quantify chamber vacuum integrity are presented in this chapter as well. Within a manufacturing setting, one is often pressured to put a newly constructed vacuum system into use as soon as possible after it is built. However, without proper system commissioning and characterization, the data from the new machine may be corrupt from the very beginning. Time is wasted to either explain anomalies caused by the system or to reproduce all results due to suspect test chamber behavior.

This book is suited for all levels of expertise of scientists and engineers, as well as graduate students in the mechanical and electrical sciences. We start with a general discussion about chamber design, vacuum pumps, and vacuum diagnostic tools. While there are many vacuum-system design books available, in the literature; our goal is to help tailor the vacuum system for testing coatings in rolling contact fatigue (RCF) at high speed and vacuum conditions. We continue in Chaps. 3 and 4 with examples of RCF testing with emphasis on thin film silver lubrication applied to ball bearing steel and silicon-nitride rotating parts. A detailed discussion about the physical vapor deposition ion-plating method is presented in Chap. 6. The ion plating method is well suited for coating a large number of ball bearings at one time with minimal risk of contamination. We use SimulinkTM to model and control an ion plating process since it is readily available to both students and professionals alike.

A survey of the current literature reveals that there is little research concerning process aberration and RCF life. In this book, we use the rolling contact fatigue method to quantify the effects of process aberration on coating life. A discussion about dc-plasmas and their effects on coating performance is presented in Chap. 7. Plasmas are difficult to understand, and there are several text books available concerning the theory and application of plasmas for thin film deposition. We start with practical calculations, such as Debye length and mean-free-path, to help the reader to quantify the plasma related to their process. Our goal is for the reader to understand the plasma as a manufacturing tool using system level inputs such as process pressure and voltage.

In Chaps. 6, 8, and 9, we include a discussion about process control and disturbance rejection. Perhaps more important to a process engineer than a scientist or student, disturbance rejection enables consistent manufacturing coating quality and gives the manufacturing engineer a frame work from which to quantify the effects of process aberration. It is a given that disturbances and even process mistakes will occur in manufacturing coating processes. Choosing the optimal control scheme can help mitigate the effects of unpredictable disturbances on the coating process.

The reader of this book is encouraged to seek out and read further the references cited within the text. Throughout this book, it was our goal to bring together unique combinations of previous engineering work. Rolling contact fatigue testing in vacuum and at high speed is one such example. Upon reading this book, we hope that the reader will be inspired to bring together other such unique combinations of engineering work to help solve problems in engineering and manufacturing.

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