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Friction induced damage: preliminary numerical analysis of stresses within painted automotive plastics induced by large curvature counterfaces

D.J. Mihora [a,1], A.C. Ramamurthy [b,2]

[a] FM Analysts Incorporated, Santa Barbara, CA 93111, USA

[b] Ford Motor Company, ACD/Coatings, Dearborn, MI 48121, USA

Abstract

Surface damage to modern plastic automotive fasciae (bumpers) arises as a result of numerous physical 'sliding' contact scenarios. The most common tribological events include fascia contact with fixed obstacles, and fascia to fascia (vehicle to vehicle) sliding contact. The tribologically induced stresses may introduce abrasion, shear, tensile, and delamination failure in the paint and the plastic substrate layers.

Subsurface stresses imparted by a large curvature counterface and a thin plastic substrate on a hard foundation are compared using both classic analytical methods and finite element analysis. This is the first quantitative study of its kind for aiding in the development of a friction induced damage (FID) testing device. Phenomenological insights into FID are presented. Relevant analysis methods for FID are also reviewed. Both methods investigate a cylindrical counterface and a painted plastic substrate on a stiff foundation. A thin polymer coating on the counterface imparts a sliding frictional coefficient, $\mu \sim 1.0$. Results of three-dimensional numerical analysis are presented for the transverse contact stresses between counterfaces of different curvature, friction coefficient, and normal force. The subsurface maximum stresses move toward the counterface as the curvature is reduced, and the numerical calculations for TPO-on-foam substrates indicate the likelihood that shear initiates the failure in the subsurface. Classic Hertzian calculations are inadequate particularly, when material yielding and shear failure are present. © 1997 Elsevier Science S.A. All rights reserved.

Keywords: Implicit finite element; Polymer friction; Automotive fascia; Thermoplastic olefin, TPO

1. Introduction

Exterior painted plastics have become the norm for fascia in the automotive industry, for numerous laudable reasons. This paper addresses several of the most common automotive tribological occurrences where friction induced damage (FID) exists. Ramamurthy et al. [1] describe the numerous practical FID scenarios important to the quality and robustness of exterior fascia with newer automotive painted plastics using thermoplastic olefin, or TPO. Lightweight and pliant, TPO fascia materials of thickness generally less than 3 mm in the presence of high frictional forces can experience FID. Ramamurthy et al. [1] describe a new laboratory test machine, STATRAM II, which was developed with the guidance and insights of the two-dimensional computations described herein. The three-dimensional computations are also being used in the development of more general purpose test equipment.

In a parking situation, low-speed, vehicle-to-vehicle and vehicle-to-post contacts test the strength of painted plastics. It is the low-speed contact with objects of large curvature that is the subject of this study. The scale of the problem can be characterized by the curvature of the counterface ρ to the thickness t of the paint, or the substrate, that is damaged. The scale, $\rho/t > 50$ mm/0.125 mm = 400 is large; finite element analyses and laboratory tests with STATRAM II emphasize these large ρ/t scales.

Variables such as mechanical properties, adhesion layers, large plastic strains, and layer to layer defects, dominate FID. Generally, the scale effects of a large curvature counterface on a multilayer substrate dictate a contact analysis where 'discretization' is achieved through the two to five different material layers directly under a sliding counterface. The FID dry sliding contact is approached as classical Amontons' friction, but with several difficult non-linear complications. This problem includes plastic flow in the multilayers and the low density foam substrate which introduces a non-linear foundation stiffness. There are large deformations of the TPO and

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[1] e-mail: dmihora@asme.org.

[2] e-mail: ram320@aol.com.

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foam. There is a large non-linearity in the material response from yielding, plastic flow, and viscoelastic hardening. Even though the sliding is at low speed, rate-dependent mechanical properties come into play particularly when the stick–slip phenomenon develops. There is frictional rate dependence when polymers slide at these low speeds. The adhesion, or delamination of paint layers and/or the TPO boundary layer to the bulk TPO, is a variable in the presence of large shear and tensile stresses. Finally, for automotive fascia, the three-dimensional stiffness distribution has a large influence on the surface stress and FID.

The goal of this paper is to identify the more significant physical parameters used in the development of the STATRAM II and secondly, the cause of FID with automotive fascia. The first-order predictions of failure conditions and the identification of methods that could produce fascia testing standards are important goals in the automotive industry. The fascia responses in two and three dimensions are known to be very different. Insights are sought on how the two-dimensional (2D) test and analysis results should be applied to three-dimensional (3D) configurations.

This is the first study of its type where analysis is used to develop an understanding of FID for decorated automotive fascia. Although there are analytic solutions for the frictional contact of similar quadratic counterface surfaces, Engels' [2] recommendations on the use of a numerical finite element solution for this class of problem will be followed. Mechanics insights acquired from these analyses are used to define the requirements for laboratory testing equipment. Preliminary STATRAM II laboratory tests are also used to provide friction coefficients and mechanical properties for the analysis. This is also the first quantitative study of its kind for directing the development of an FID testing device for automotive fascia. These laboratory tests are eventually to be used for a material system ranking and for implementing testing protocol for product quality assurance.

2. Specific finite element approach

The present friction contact problem is a subclass of the more general two-body, contact–impact problem. These problems are inherently non-linear when the dimension of the footprint between the two contacting bodies is a variable while friction is present. The recourse to computational solutions over analytic solutions has evolved because these FID problems are difficult to solve in closed form. However, it is valuable to make comparisons with analytic solutions if for no other reason than the understanding of closed-form limitations.

Relevant analytic contact solutions are found in Kalker [3] and Johnson [4]. Additionally, the updated analytic solutions of contact reviewed by Williams [5] utilize a family of pressure distributions to calculate contact stresses. In these cases, the indenter is assumed rigid compared with the substrate. The stresses from friction are obtained using a linear superposition of a 'Hertzian' stress field with a traction stress field. An estimate is made of the plastic region in the substrate under the rigid indenter, but little is known about the stresses within the plastic flow region.

There is no known literature on finite element methods most appropriate to FID tribology problems. A partial insight into the methods can be obtained from a review of the more general two-body contact problems. A formal development of the contact equations and a lengthy reference survey by Zhong and Mackerle [6] show that frictional problems are a small, but significant, subset of the work in present day two-body impact codes. Most of the numerical contact solutions tackle the friction problem by incremental updates in time or loading. A plethora of numerical analysis methods have become a standard tool because the sequential computational updates are what the large and fast computers are very capable of handling. Advances in computational techniques have significantly aided the study of FID.

In these FID problems, the disadvantage of numerical solutions relates to convergence and resolution, particularly in the highly localized region of contact. Discretization generally requires a much higher zoning fidelity in this region of interest. Even with supercomputers, a uniformly fine zoning of the bodies can exceed storage capability. Computational times also are an issue with uniformly zoned bodies. The quality of the zoning, the matrix bandwidth, and the numerical accuracy (word size) become an issue. A most effective variable zoning by geometric 'projection' methods developed by Rainsberger [7] has been adapted in these efforts. The numerical solutions to be presented are converged but retain a prescribed tolerance. The closed-form solutions are abetted since the exact solutions provide the baseline reference cases even though they are rather simplified contact problems.

The tribology problems discussed herein use the finite element codes NIKE2D and NIKE3D. These codes utilize generalized and very robust 'slide surface' algorithms. These two codes use slide surfaces to transfer nodal information between adjacent nodes on separate bodies. Slide surfaces have zero thickness and are located at the same geometric location of the exposed nodes. A 'slave surface' is attached to one solid and a 'master surface' is attached to the other solid body. Hallquist et al. [8] promoted this approach while introducing very efficient numerical search techniques for locating the contact points of nodes on opposing bodies. Different numerical algorithms are utilized for controlling the precise position of contacting nodes on opposing slide surfaces. Laursen and Simo [9] provide a wealth of references that advocate the well known 'penalty method'. In the penalty method, each slave node is checked for penetration through the opposing master slide segment. If the two surfaces cross, an interface force is applied to both the slave and master node to reposition these surfaces into intimate contact. Normal pressure at the contact face is the primary dependent variable that is influenced by the algorithm.

Lagrangian treatment of the frictional contact problem is used in the NIKE codes. The Lagrangian approach eloquently