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Improvements in the measurement of metallic adhesion dynamics

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ABSTRACT

Adhesive interactions between surfaces have many engineering implications, since they may be exploited to promote joining between bodies but may also jeopardize the functionality of mechanical systems, when they affects surfaces subjected to relative motion. In some applications the interest arises to develop a model which makes it possible to predict the force required to separate two adhered bodies, given the properties of the materials and of the surfaces. Recent advances in the experimental study of metallic adhesion between engineering metallic surfaces lead to a more detailed investigation, where two main improvements are sought. First, the behaviour of the adhesive bonds is studied in dynamic conditions, i.e. when the separation between the adhered surfaces cannot be considered quasi-static. Second, not only the pull-off force but the complete behaviour of the adhesive bonds as a function of the separation between the surfaces is studied. Both aspects are involved in a dedicated experiment, in which adhesion force rules the transfer of momentum between two bodies if one of them is actuated to perform a dynamic separation. The test facility has been recently developed in order to provide a more representative experiment of the case of study, and a more complex measurement system is available to describe the dynamics of the adhesive bonds. The drawback of the evolution of the experiment is the presence of larger systematic effects and a more difficult estimation of adhesion from the experimental data. Therefore, in order to study and separate the behaviour of adhesion from disturbance effects, a specific grey-box estimation procedure has been set up. Thanks to the improved measurement system, the result of this method is the adhesion force as a function of elongation of the bonds, estimated with a better accuracy than that achieved before. The mathematical model, the regression procedure and the results are here presented and discussed.

1. Introduction

Adhesion between surfaces is a subject extensively dealt with in the literature [1,2], finding an increasing interest as it affects several engineering applications. Metallic surfaces produced by machining processes may develop adhesive bonds, especially when subjected to particular environmental conditions like vacuum, fretting, absence of surface oxides and/or

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lubrication. Space mechanisms yield an example of practical applications where the presence of these bonds may hinder the system functionality. These are subjected to strong inertial loads during the spacecraft launch phase, and the mating surfaces at the joints and at the constraining devices undergo strong impacts and fretting phenomena. Surface lubricants and oxide layers, which reduce adhesion between metallic surfaces, are then removed and due to the absence of atmosphere, oxides re-formation is inhibited [3]. This means that pairs of mating metallic surfaces may operate in conditions in which adhesive interactions oppose themselves to their separation, and this constitutes a risk of mechanism failure.

Some meaningful case studies of general tribology challenges in space mechanisms are collected in [4], whereas in [5] the issue of constraining and then injecting a reference body into a geodesic trajectory against adhesion phenomena is dealt with. Among them the LISA-Pathfinder mission [6] case is particularly critical. In such a mission a 2 kg gold-coated Au/Pt alloy cubic test mass must be caged inside the spacecraft during the launch phase and then released to free-fall to track a nearly perfect geodesic trajectory. The gold-coated contacting surfaces on the test mass and the release-dedicated tip of the caging mechanism are expected to develop adhesive bonds [7,8], which are broken by means of a quick retraction of the latter. However, during the retraction adhesion force exerts a pull on the test mass, which converts into residual momentum of the cubic mass after the release. A mission criticality is related to the release phase, if the test mass residual momentum exceeds the limit of 10^{-5} kg m/s, i.e. if adhesion develops a net impulse larger than such a threshold during its dynamic failure. In such a case, the capacitive control system has not enough force authority to stop and centre the 2 kg mass after release.

The Transferred Momentum Measurement Facility (TMMF) is designed and developed at the University of Trento (Italy) in order to characterize the impulse developed by adhesion between metallic surfaces upon dynamic failure [9], and an optimal filtering technique is adopted to extract from the measured signals accurate measurements of such impulses [10,11]. The results show that in the range of accelerations on the order of mm/s^2 the impulse is a decreasing function of the acceleration of the separation, while it is an increasing function of the maximum contact load experienced by the contacting surfaces [12–14]. In the development of the TMMF, particular attention is paid to the reduction of any environmental and experiment-related effect that could reduce the measured strength of adhesion. Among these, shear stress on the adhesion patch may constitute a spurious effect if the separation is realized along a direction which is not perpendicular to the mating surfaces, therefore the tests are repeated by exploring different directions of separation [15].

Key factor in the extrapolation of the experimental results to the real case of study [16,17] is the availability of a mathematical model of the adhesion force as a function of the elongation of the bonds. It is demonstrated [9] that the transfer of momentum is ruled by the work of adhesion, i.e. the integral of the adhesion force profile as a function of elongation. To this purpose, the analysis of the measured signals is focused on the estimation of the applied force(s) time history rather than the overall momentum transfer.

The method of indirect measurement of the adhesion force as a function of elongation is described in [18,19]. Recently, some changes have been made to the experimental facility and to the method of data analysis in order to increase the experiment representativeness and the accuracy of the measurement of the adhesion force profile. In the present paper an improved method of analysis is described, showing the performance of the testing system in the estimation of adhesion force under conditions of dynamic failure.

2. Experimental apparatus and procedure

The Transferred Momentum Measurement Facility (TMMF) is developed to study the adhesion phenomenon between metallic surfaces under dynamic separation. The concept of the experiment is to suspend an object (called test mass, TM) inside a vacuum chamber and measure its motion while adhesion exerts a pull. In the vacuum chamber, a tip moved by a linear actuator engages the suspended TM, produces a contact patch under a defined load, unloads the contact and then is quickly retracted to pull the TM with the adhesive bond. The measurement of the momentum transferred to the TM by this retraction is provided by measuring the TM law of motion.

In order to measure forces on the order of mN applied for a timeframe of a ms and minimize spurious effects that could affect adhesion strength, the TMMF has to fulfil several requirements. It has to provide a weak constraint to the suspended mass (at least in a plane), adequate vibration isolation and the capability to accommodate slow ground tilting. The surface contamination is limited by means of a vacuum environment and a plasma-based cleaning system. The experiment must be performed under a controlled contact force, therefore a blocking system is required to hold the TM in a stable way during the application of the load. Finally, the measurement of the TM position and attitude and of the tip retraction are needed. Details of the TMMF are described in Ref. [20]. We give here a schematic description of its main subsystems (Fig. 1):

- The TM is a 0.844 kg Ti cube (36 mm edge) suspended by a 1.1 m-long tungsten wire, hosting a cylindrical insert at the centre of one of the faces. The bulk material of this insert is Au–Pt; its outstanding face is micro-milled and then gold coated. The rear side of the insert is mirror finished to reflect the incoming laser beams of the optical readout system.
- The tip (Fig. 2) is a 2 mm disk lens-shaped with a 10 mm radius of curvature. It is actuated by an ultrasonic linear piezo positioner through a set of calibrated blade-springs, in order to control the normal force applied to the contact patch.
- A turbo molecular pump is used to evacuate the chamber to the pressure of 10^{-7} mbar, while an ion pump is used to maintain such a vacuum level avoiding the vibrations produced by the turbo pump during the measurement phase.