New Ultrasonic Sensor for a Simultaneous Mechanical and Electrical Characterization for the Contact Quality of a Mechanically Loaded Interface

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***Abstract*— This ultrasonic sensor made of a copper delay line operates in dry coupling configuration to detect modifications of the contact quality between two materials under compressive stress by measuring the acoustic energy reflected on the air volumes trapped at the interface. Frequency domain analysis of the first delay line round trip echo is useful to operate with harmonics for different selectivities to the interface properties but, pressed on a unpolished copper plate, the sensitivity of acoustic reflection to contact quality vanishes for high roughness level. To overpass this limitation, measurement with the sixth delay line echo has been successfully performed to investigate the stress dependence of the contact quality between a copper plane surface and rugged industrial materials such as amorphous carbon and carbon-carbon composite. This acoustic method, associated with an electric contact resistance measure, has given a direct insight of the deformability of the interface depending on the roughness and the mechanical properties of the two materials involved in the connection. Plasticity, anelasticty effects are observed. Acoustic waves and electromagnetic ones are also not perturbed in the same way by the gas interface modification versus mechanical loading.**

Keywords - Dry coupling; contact area; contact resistance; carbon composite; acoustic reflection coefficient.

I. INTRODUCTION

The interface between two mechanically tied materials in service is generally difficult to access in a non destructive way. Yet, evaluation of the contact area can be a reliable parameter to detect the wear level of the connection and to predict its tribological behavior. For instance, in some industrial applications, electric contacts are obtained by maintaining a given mechanical load on the two materials in contact. At this interface, the electric contact resistance is controlled by current constriction effect and by the insulating properties of pollution layer. From a mechanical point of view, contact surface roughness and material elasticity are predominant factors. Echography measurement performed in dry coupling configuration may give access to these parameters [1][2]. For all these reasons, we developed a specific ultrasonic sensor to detect in a non destructive way the variations of the contact quality from the reflection fraction of ultrasounds on the gas volumes trapped within two contact surfaces as function of the applied mechanical load [3]. When the two sides of the contact are conductive ones, the electric contact resistance can be also simultaneously measured [4].

II. SENSOR PRINCIPLE AND EXPERIMENTAL CONFIGURATION

By definition, a contact is the association of two materials. The concept of our device is to use, as our sensor delay line, one of these two materials and to press it against the second one lately called "the sample". In our demonstrator, a piezoelectric cell is placed in a cavity within a metallic rod mounted on a load cell. This piezo-ceramic emits the acoustic pulse and detects the reflection at the end of the rod acting as a delay line. For simultaneous electric contact resistance measurement, a source meter is used in a 4 wires configuration: current injection and voltage measurement are done with screwed contacts on the metallic rod and clamped ones for the sample (cf. Fig 1).

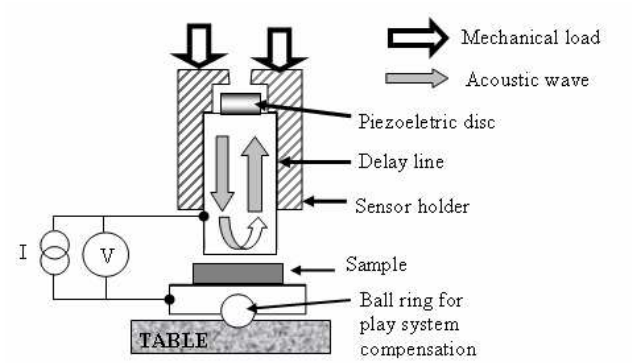

Figure 1. Sensor and experimental setup descriptions

To measure the acoustic reflection at the interface, we calculate the ratio of the reflected pulse energy to its value when the sensor is in air, since reflection coefficient between solid and gas is almost unity. This measurement is done from the first round trip echo digitized with a scope. This signal is recorded simultaneously with the corresponding value of the applied load reached during the mechanical test. To investigate the behavior of the contact interface versus mechanical stress, we chose to perform three successive loading and unloading cycles up to a compression strength of

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4500 N. The cross-head displacement speed is maintained down to a sufficiently low level in order to deal with the time response of our different equipments. Fast Fourier Transform analysis is used to get the reflection coefficient for various frequencies using the harmonic modes of the piezoelectric cell. For our demonstrator, we used a PIC155 type piezoceramic disc with a diameter of 16 mm and a thickness of 2 mm. The outer diameter of the sensor is 30 mm defining the geometrical size of its contact area. This last dimension gives only the apparent size of the sensor contact area. Nevertheless, the real contact area may be far smaller and not accurately known especially at the interface with rough surfaces. For this reason, we chose to present on figures the applied load and not the supposed stress values.

III. APPLICATION TO CONTACT EVALUATION FOR COPPER/COPPER INTERFACE

Copper is a material commonly used for electric connections and, for some applications, this is achieved by mechanically loading or tightening two plane surfaces. To investigate this kind of connection, our sensor has been made of a copper rod pressed against a thick copper plate in order to prevent time superposition of the successive round trip echoes in this plate with the multiple delay line echoes.

In Figure 2, we present the variation of the reflection coefficient at the interface with a mirror polished sample.

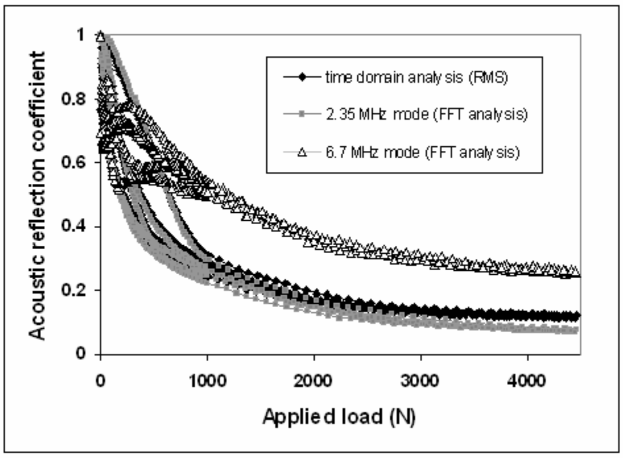


Figure 2. Evolution versus applied load of the acoustic reflection amplitude measured from time or frequency analysis for a copper mirror polished samle

For this test, the energy of the first delay line echo is measured versus applied strength. Two calculation methods are presented: the peak to peak amplitude or equivalently the RMS value of the acoustic echo and a second approach using the amplitudes of the modes (fundamental and harmonics) obtained from FFT analysis. This figure shows that the contact quality increases rapidly for mechanical load smaller than 1000 N and then reaches slowly an optimum value around 4000 N. Indeed, as strength increases, the air volumes trapped within the vicinity of the two surfaces decrease due to the compressive strain of the surface asperities and this decreases the reflection of the incident acoustic pulse. Compared to time domain analysis (RMS), information contained by FFT for the fundamental mode (2.35 MHz) is slightly more sensitive to the acoustic reflection evolution. For a given load, the acoustic reflection value measured using the first harmonic mode (6.7 MHz) is systematically higher compared to fundamental mode analysis. This is explained by wavelength consideration : the smaller the wavelength is compared to the interface defects, the worst wave propagation through the interface is.

Next, we compare the interface behavior between the previous mirror polished copper sample and the same material unpolished with a 120 grade sandpaper (cf. Figure 3). It can be noticed on the curve for the mirror polished surface that the reflection coefficient evolution is different for the first compression loading compared to the rest of the mechanical test due to surface plasticity.

For the unpolished surface, ultrasounds remain almost completely reflected because the interface is too much filled with air even for a 4500 N mechanical load.

This test demonstrates the sensitivity of this method to measure the mechanical contact quality and the roughness level detectable range.

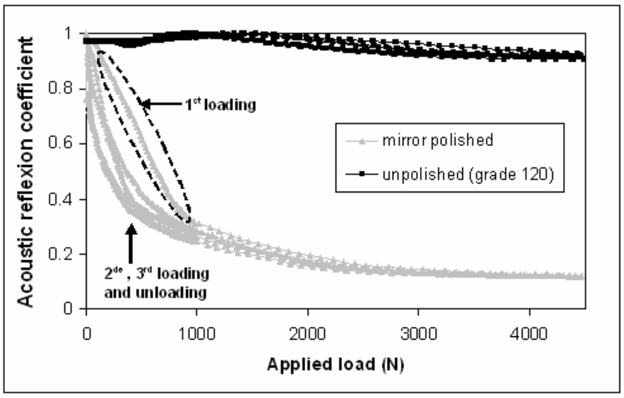


Figure 3. Effect of roughness on the evolution of the interfacial acoustic reflection for a plane copper to copper contact

With our experimental set-up, the electric contact resistance is measured simultaneously with acoustic reflection in order to give a further insight of the quality contact between the two copper surfaces. Electric contact resistance is known to depend on an electric field constriction effect due to the contact area delimited by the air volume trapped in the residual roughness. Surface pollution can also create an insulating layer strained by the mechanical load. Copper oxide has generally to be taken into account but we assumed that, using later samples with rough surfaces, their asperities should be large enough to sufficiently indent this insulating layer limiting its effect on electric measure. Despite the surface roughness created with the 120 grade sandpaper, the Figure 4 shows a fast decrease of the contact resistance down to only few fractions of milli-ohms as expected for a copper made contact. Secondly, its value is already smaller than few milli-ohms for a mechanical load of only few Newtons.

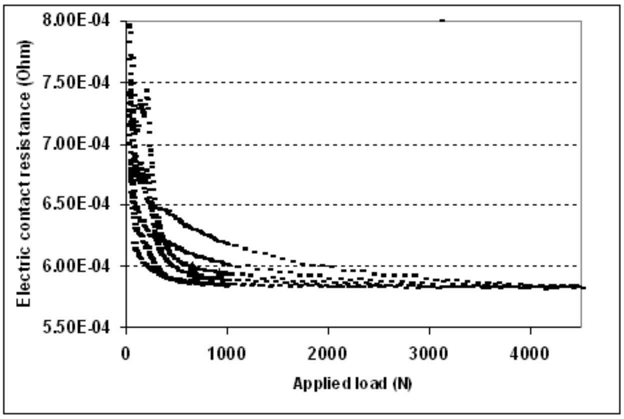


Figure 4. Evolution of the electric contact resistance versus applied load for the unpolished copper sample

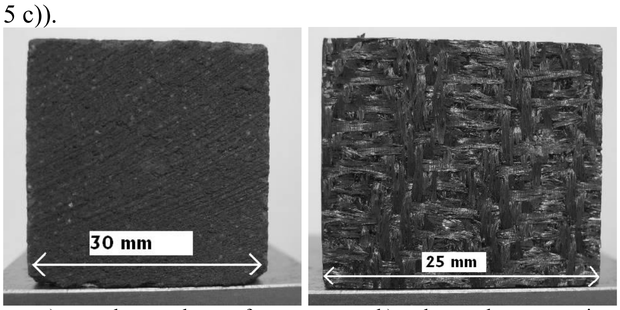
For the unpolished sample, comparison of Figures 3 and 4 shows that the correct contact resistance level is achieved at very low mechanical load whereas the mechanical contact area detected by Acoustics is very poor due to the large amount of air trapped at the interface. Indeed, for electric fields, few contact spots are enough to enable a good current flow. At the opposite, ultrasonic waves can not travel through air filled surfaces and are totally reflected. So, to extend the application range of our sensor to rougher surfaces such most of industrial materials have, we have increased its sensitivity using higher order reflection coefficient measurement.

IV. ACOUSITC REFLECTION METHOD DEDICATED TO ROUGH INTERFACE CONTATC QUALITY EVALUATION

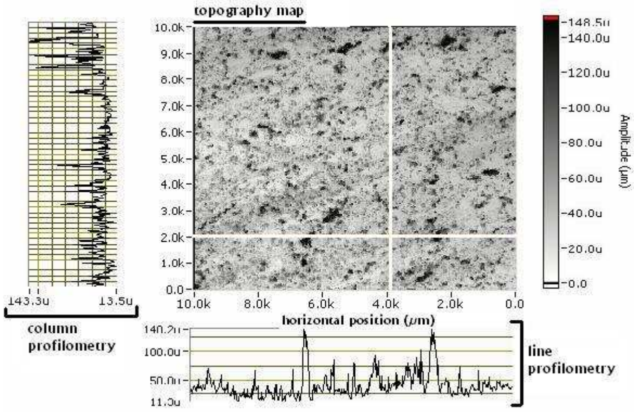
The aim of the following tests is to succeed in detecting the evolution of the contact between a plane copper surface and materials with a large roughness.

A. Samples description

For these tests, we used 30 mm wide cubes of amorphous carbon materials and plates of woven carbon-carbon composites (25 mm x 25 mm x 10 mm). These two carbon made materials have different surface states due to their fabrication process (cf. Fig. 5 a) and b)). Both materials have a large roughness with faults as deep as 200µm from topography maps obtained with a Scanning Acoustic Microscope using a 100 MHz acoustic focused lens (cf. Fig. 5 c)).



a) amorphous carbon surface b) carbon-carbon composite



c) topography map of the amorphous carbon surface (100 MHz SAM)

Figure 5. Caracterisation and comparison of the samples topography

B. Optimisation of the sensivity to the contact quality

Thanks to material elasticity or deformability, roughness tends to decrease under compressive stress but this effect will be quite small for our carbon samples due to the large size of their faults. So, to amplify the variation of acoustic reflectance at the copper/carbon interface, we used the sixth delay line round trip echo. Its energy is measured and normalised with sensor in air configuration but this "acoustic reflected energy" is not the interface reflection coefficient.

With this method, variation of contact quality has been successfully detected for amorphous carbon and carbon-carbon composite (cf. Fig. 6), showing a better deformability of this second material. On these curves, hysteresis loops are visible. For each material, the upper parts correspond to mechanical loadings and the lower ones to unloadings. This effect is associated to anelasticity.

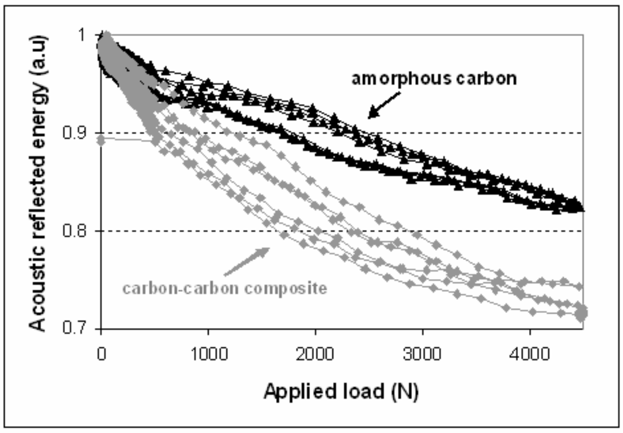


Figure 6. Detection of quality contact evolution for industrial carbon samples pressed against a mirror polished copper surface using the sixth round trip delay line echo

On these materials, contact resistance measurement reveals that the carbon-carbon composite provides the best electric contact (cf. Fig. 7). Compared to amorphous carbon, its contact resistance is smaller and is also decreasing faster.

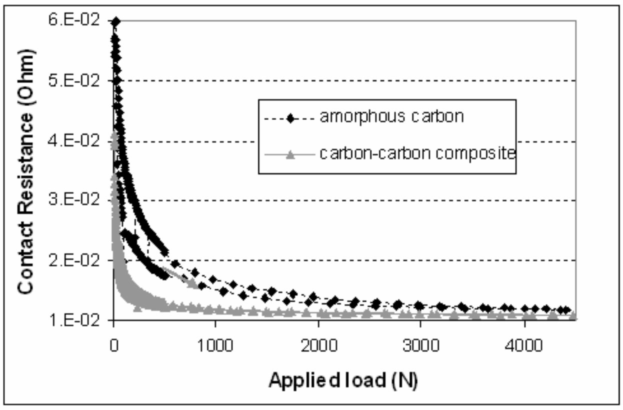


Figure 7. Electric caracterisation of the contact quality at the interface between carbon materials and a polished copper plane surface

This information could be helpful to determine for example the optimum torque to use in order to avoid cracks generation due to over loading when screw-binding is used.

C. *Surface rougnhess otpimisation for amorphous carbon material*

In an attempt to find the best contact conditions, we modified the roughness of the sensor by gradually unpolishing its copper surface. The figure 8 shows that unpolishing decreases the contact quality. The use of grade 800 sandpaper seems to increase the anelastic behaviour of this interface with a larger hysteresis loops. Large plasticity occurs for the first loading cycle when the copper surface is unpolished with grade 120 sandpaper. Indeed, sandpaper unpolishing creates sharp asperities where the mechanical load exceeds locally the material yield stress limit.

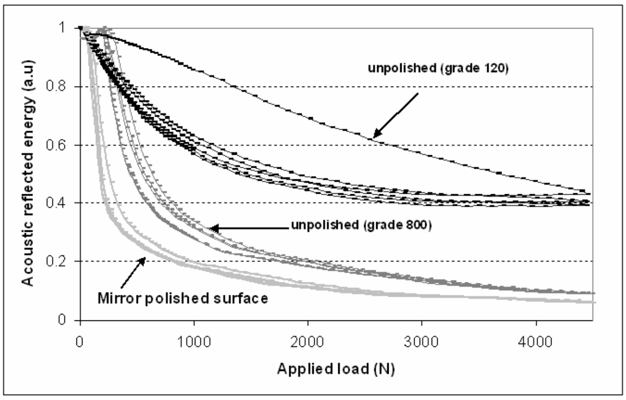


Figure 8. Effect of the copper surface roughness for the the contact quality with the amorphous carbon sample

V. CONCLUSION

This ultrasonic sensor is a new approach to characterize simultaneously the mechanical and electrical quality of the contact made by a compressive stress between two plane conductive materials. As demonstrated in this work, this technique is a non destructive means to optimize the materials roughness, the tightening torque and potentially surface treatments. This measurement could be performed for various temperatures too. Moreover, the contact quality sensitivity of this ultrasonic sensor can be improved to deal with high roughness level by using high order delay line round trip echo. As function of the materials properties and contact size, ultrasounds frequency could be further adapted to any given interface: small frequency yielding to large diameter sensors but larger wavelength giving easier propagation conditions through rough interface.

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