

High-Resolution CT Scan as Tool for Precise Quantification of Material Loss due to Localized Corrosion in Brake Calipers

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ABSTRACT

The evaluation of the extension and the magnitude of localized corrosion phenomena such as pitting and crevice corrosion occurring in brake calipers is usually performed by standard metallographic analysis. This approach can provide only bi-dimensional and qualitative information with a poor relevance both in terms of description of the failures and of prediction of corrosion trends. For this reason, in this work an experimental approach based on the high-resolution X-Ray Computed Tomography analysis (CT-Scan) is proposed, showing the potentiality of this non-destructive technique as a tridimensional probe for the precise quantification of material loss due to localized corrosion phenomena in braking calipers. Examples are reported both on laboratory specimens and on real calipers. Finally, the volumetric extension of material loss is correlated with corrosion rates calculated using voltammetry techniques thus providing a direct link between *ex situ* and *in situ* methods.

Key words: Localized Corrosion, Pitting, CT-Scan, Failure Analysis, Material Loss Rate, Voltammetry, Braking System

INTRODUCTION

Nowadays the disc brake system is the most widespread brake device in modern vehicles. As can be observed in **Figure 1**, it is schematically composed of three main interplaying entities: 1) the braking disc; 2) the caliper; and 3) a couple of braking pads. The caliper is the brake system core device: its main function is the transmission of an applied pressure from the brake pedal to the braking pads, typically by hydraulic actuation via braking fluid or, more recently, also by electro-mechanical

actuation.¹ This operation sets up the tribological interactions between the disc braking surfaces and the friction material of the braking pads, thus generating a braking torque on the disc which is in the end responsible for decreasing the speed of the vehicle or stopping its motion.^{1,2}

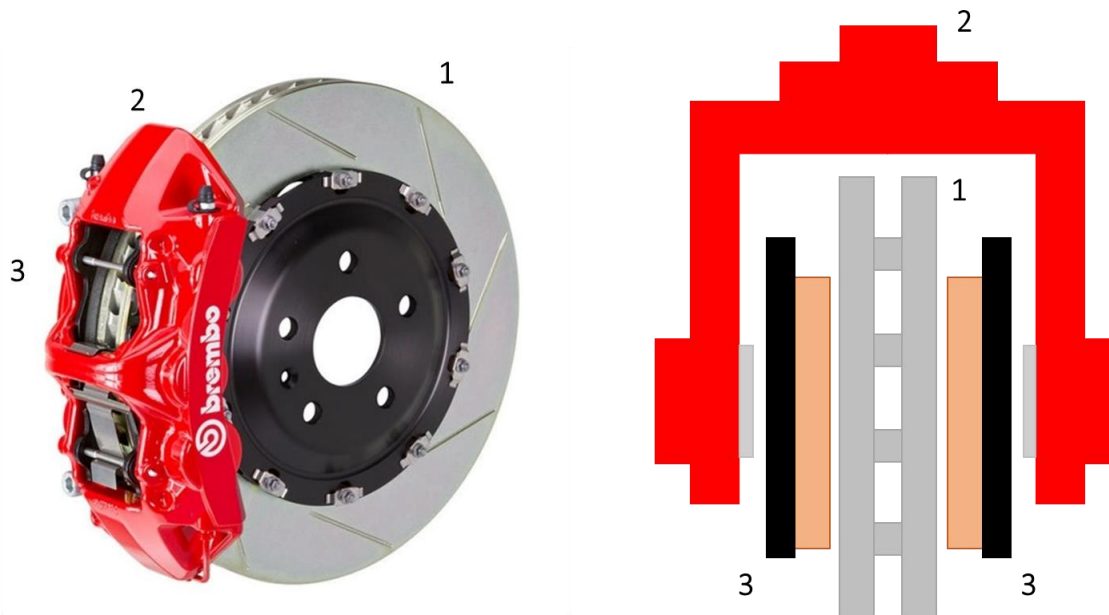


Figure 1: Schematic view of the disc-brake system (left side) together with section of interest (right side): 1 = Braking Disc, 2 = Caliper, 3 = Braking Pads.

Due to their role as central devices in a vehicle safety system, calipers have to be designed as solid and robust as possible in order to resist to high inertia and to endure long-lasting life cycles, as well as to transmit the applied pressure in the most reproducible, constant and precise manner. Their localization inside the car semi-axis or in the motorbike wheel corners leaves these devices greatly exposed to the environment, potentially making them experiencing a whole range of harsh conditions, such as all the possible adverse atmospherical events, the direct contact with de-icing agents and plenty of different electrochemically active contaminants from air and ground. In the case of the high-end automotive market, calipers are usually made of Al-Si alloys due to their superior mechanical properties with respect to other typically used materials with higher density.¹ In spite of these advantages, Al-Si alloys generally suffer from poor corrosion resistance. Due to the just cited wide variety of aggressive environments, Al-Si calipers are usually protected by anodization layer, as well as painting, in order to limit excessive corrosion phenomena which can eventually lead to a deterioration of their mechanical and functional properties.^{3,4} Finally, another level of complexity has to be ascribed to the fact that the calipers host the braking pads together with a number of secondary components such as springs and pins. This ensemble of different objects introduces inside the caliper a pool of different materials, such as steels and Cu-based alloys, which can eventually be in contact with the anodized Al-Si alloys, potentially leading to severe galvanic coupling effects.³

For all these reasons, a growing attention in the research on both topics of Al-Si calipers protection strategies and the preventive corrosion-proof design of the braking system is gaining momentum in recent years.³⁻⁶ Nevertheless, during their life-cycle, calipers still might be affected by localized corrosion phenomena.^{3,4} In particular, these events are more likely to occur with higher frequency and magnitude in internal sections where the draining of the liquid media can be more difficult, the protective layer can be applied with lower efficiency and anomalous galvanic couplings between parts may occur.^{3,4,6} Considering the current market trends, pushing toward lighter and smaller braking

systems able to resist wear and corrosion for the entire vehicle life cycle, it is of primary importance to develop reliable analytical methodologies for the correct evaluation of the interactions between corrosion phenomena and functional properties.^{4,6} For instance, the precise, quantitative and volumetric quantification of material loss due to localized corrosion represents an extremely precious information in order to understand and calculate corrosion rates in terms of material consumption under different conditions. Such information can be usefully used during both the failure analysis investigations as well as the project and design phase in order to properly size calipers and secondary components as a function of a suitable level of corrosion resistance or galvanic interaction. The evaluation of the extension and the magnitude of corrosion phenomena occurring in brake calipers is usually performed by standard metallographic analysis.⁴ In spite of being a valuable observational tool and a well-established visual inspection method, potentially exploitable with relatively low-cost instrumentation, this approach suffers from two main drawbacks: *i*) it is necessarily a destructive analysis, carried out after delicate handcraft sample preparation consisting in cutting, mounting, grinding and polishing of sample specimens; and *ii*) it provides only bidimensional and qualitative information with a poor relevance both in terms of description of the failures and of prediction of corrosion trends. In order to supply to these typical drawbacks, in this work a new experimental approach based on the high-resolution X-Ray Computed Tomography (CT Scan) analysis is proposed, showing the potentiality of this technique as a tridimensional probe for the precise quantification of material loss due to localized corrosion phenomena in braking calipers.

Since its first medical applications in the early 70's, X-Ray Computed Tomography has raised nowadays to the state of the art status of the Non Destructive Techniques (NDTs), due to the tremendous improvements reached both in terms of spatial resolution and acquisition times.⁷ It is based on the ability of X-Rays to pass through objects and, more in detail, on their proportional attenuation with respect to the different material densities encountered during their path toward the detection, *i.e.* inside the materials being penetrated. In contrast with all the other imaging techniques, such as optical or electron microscopy, it offers an *in situ* tridimensional insight into the investigated sample, potentially without any specimen preparation. Presently, sub-micron resolution can be easily achieved and typical analysis times are in the order of the minutes. Thus, CT scan can provide an unprecedented tool in order to observe directly inside an object, aiming to obtain precious information such as, but not limited to: *i*) the structural integrity of the sample, by the detection, localization and sizing of defects such as voids, inclusions or cracks; *ii*) the dimensions, the position and the connectivity of internal parts; *iii*) the evaluation and quantification of porous networks; and *iv*) the tri-dimensional distribution of fibers and their orientation tensors. Due to its virtually enormous versatility, Computed Tomography easily finds application in a wide range of research as well as industrial fields, ranging from health sciences to construction, automotive & aerospace industry, from more classical medical examinations and failure analysis, to the design and modeling of advanced materials and production processes.⁶⁻⁹ In this paper, CT analysis is presented as a quantitative tool for corrosion studies, which indeed represent historically a less explored field of application. With particular reference to the localized corrosion phenomena occurring at the braking system, it is first showed how to obtain quantitative information about the mass loss caused by localized corrosion in laboratory specimens. Then, the combination of CT-Scan analysis with more classical and well-established electrochemical probes is unveiled.

Several manuscripts can be found in the recent literature concerning the applicability of electrochemical techniques to the braking system. These regards, for example, *i*) the investigation of the corrodibility of friction materials;¹⁰⁻¹¹ *ii*) corrosion resistance of cast iron used for the production of brake discs;¹² *iii*) corrosion oriented design of brake calipers;^{3,5,6} and *iv*) anodization process refinement for treatment of AlSi_x based calipers.⁵ In all cases linear sweep voltammetry-based methods are used to obtain a prompt *ex situ* investigation of the corrodibility of several materials. In addition, Zero Resistance Ammetry (ZRA) measurements are typically used in those cases in which the evaluation of galvanic couplings among different materials is required.^{5,6} With particular reference to ZRA measurements, these allow to investigate the galvanic current flow between two coupled materials (*e.g.* Anodized Al-Si alloy and stainless steel).¹³ By the application of Faraday's law, it is possible to theoretically calculate the moles of oxidized/reduced species in the coupled condition. In this regard, in the following paper the quantitative volumetric mass loss provided as direct information by the tomographic analysis and

results of material loss from Zero Resistance Ammetry (ZRA) performed in controlled corrosion tests in laboratory are compared and discussed. The final aim is to provide a direct link between *in situ* and *ex situ* methods and to cross validate both analytical approaches. Finally, an example of the potential of the CT analysis as a fully quantitative probe for the failure analysis of real samples is also provided, taking as reference the case of a prototypal caliper that developed severe corrosion pittings during Neutral Salt Spray (NSS) test.

Notably, this combined multi-techniques experimental approach can be easily applied to an extremely wide range of different mechanical parts and materials undergoing corrosion studies.

EXPERIMENTAL PROCEDURE

The investigated samples are both obtained from Brembo S.p.A.⁽¹⁾ production lines. They are respectively two laboratory test specimens and one sector from a prototypal caliper under validation process, both made by a prototypal anodized Al-Si alloy, containing silicon in a concentration of 7 % in weight.

2.1. Zero Resistance Amperometry

The galvanic current (GC) flow between the couple composed by anodized Aluminum vs. reference stainless steel (UNS S30100 / AISI 301 / X10CrNi18-8, used in brake components production) is evaluated using a VMP-300 potentiostat/galvanostat used as a Zero Resistance Ammeter (ZRA). The GC is converted in moles of corroded Aluminum by application of Faraday's Law (**Eq. 1**) for the Aluminum oxidation:

$$n = Q / ZF \quad (\text{Eq. 1})$$

with n = number of moles of oxidized material, $Q = I(t)\Delta t$ = total amount of exchanged charge, Z = number of electrons involved in the oxidation ($= 3$ for Aluminum) and F = Faraday's constant = 96485 C/mol.

Results of material loss are then compared with the same results obtained from CT analysis by simple conversion of volume to mass. In order to perform the corrosion test, a three-electrodes experimental setup is used with: *i*) the anodized Aluminum as working electrode (WE); *ii*) the stainless steel as counter electrode (CE); and *iii*) a standard calomel electrode (SCE) as reference electrode (RE). The experiments are performed in a 5%_{wt} NaCl_(aq) solution at $30 \pm 0.5^\circ\text{C}$. In agreement with the literature,⁶ measurements are carried out in stirred electrolyte, using an area ratio between WE and CE equal to 1 : 20 and for at least 40h of measurement. This is made in order to enhance the galvanic corrosion phenomena and to obtain pronounced localized corrosion with the aim to reproduce pitting behavior similar to the one observed in the caliper after NSS test.

2.1. Corrosion Neutral Salt Spray Test (NSS)

Corrosion test of the caliper is performed in a controlled environment chamber, following the NSS test procedure from ISO⁽²⁾ 9227:2017 standard.¹⁴

2.3. Computed Tomography Analysis

Computed Tomography measurements (CT-Scans) are performed with a V|tome|x m CT instrument equipped with two different X-Ray tubes, operating respectively at maximum voltages of 180 and 300 kV, and a Dynamic 41|100 X-Ray detector panel with 410 x 410 mm of active area (16 MPixels) and pixel dimensions of 100 μm .

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