Influence of Dynamic Analysis by Infrared Thermography (IRT) and Non-Destructive Testing (NDT) on Alternative Predictive Diagnosis of Automotive Brake Rotors in Light Vehicles

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Latacunga

INFLUENCE OF DYNAMIC ANALYSIS BY INFRARED THERMOGRAPHY (IRT) AND NON-DESTRUCTIVE TESTING (NDT) ON ALTERNATIVE PREDICTIVE DIAGNOSIS OF AUTOMOTIVE BRAKE ROTORS IN LIGHT VEHICLES

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Abstract. This study presents an alternative to improve the conventional methods of diagnosis in the automotive brake rotors of light vehicles, through the application of non-destructive testing (NDT) such as infrared thermography (IRT) with a variation in the form of application of the Step Heating technique to dynamic heating, with the specifications of ISO 18434-1 and visible liquid penetrant testing (PT) according to ASTM E 165-02, for this it is necessary to chemically characterize the brake rotor material according to ASTM E1085-16 and the energy dispersive X-ray fluorescence spectrometry (EDXRF) technique, where an approximation of SAE 1215 steel is obtained. The influence of these methods in the alternative predictive diagnosis of brake rotors was evaluated, comparing them with the conventional methods of visual testing (VT) and thickness control. The alternative IRT method allows the analysis and sectorization of the defectologies located on the brake rotor, including the friction ring, cooling vanes and rotor hat, the defects found include crystallization, grooves, pitting, cracks, wear, and rust. To evaluate the reliability of the results, an analogy of the mentioned tests on the same defect is made, and it is concluded that the IRT method is the most effective, it has a superior inspection coverage of 8.33% compared to the VT method and 33.66% compared to the PT method, to clearly visualize the defects Fluke SmartView is used.

Introduction

Disc brake rotors are safety critical components, they allow controlling the vehicle in high-speed conditions. Cast iron is the most used material for their manufacture, the combination with alloying elements such as P, Mn, Cr, Mo, Cu, form a phase that improves their mechanical and thermal performance [1]. During their operation, brake rotors are exposed to high mechanical and thermal stresses, this causes various damages such as cracks, pitting, crystallization, oxides, wear, fatigue, roughness, and discontinuities [2-6]. In the automotive industry, detection of these defects is performed by conventional static non-destructive testing (NDT) such as visual testing (VT) and thickness measurement. However, these methods have limitations and do not provide a detailed evaluation of the quality of the brake rotor. Alternative NDT, such as dynamically applied infrared thermography (IRT) and liquid penetrant testing (PT) [7-9], are proposed for detailed evaluation. IRT is a widely used method in various industries for inspection and flaw detection applications [10]. The objective of this study is dynamic characterization to analyze the defectology in brake rotor using IRT. A comparative analysis of the results obtained with conventional and alternative methods is performed to evaluate their effectiveness in detecting defects in brake rotors. Dynamically applied IRT is proposed as a quality control method, which allows a quick inspection of the complete field and in real time, without contact and without the need to disassemble the disc brake rotor for a more accurate assessment of the integrity of these, this guarantees the safety of drivers and passengers on the roads [11-13].

Material Characterization

The material used in the disc brake rotors is determined, the chemical characterization is performed based on ASTM E1085 - 16 using the X-Ray Fluorescence (XRF) energy dispersive (ED) comparison method of materials [14], with the OLYMPUS DPO2000-C spectrometer, this at approximate temperature of 75.02 [°F], and with an energy of 40 [keV] the quantitative analysis reveals that the material is SAE 1215 steel, with a content of 98.66% Iron (Fe), elements such as Mn, S, Cr, Cu, P and Mo were found in small quantities, the manufacturing process is foundry.

Methods and Test

Defects in automotive brake rotors can be detected by conventional NDT, such as visual testing to assess the surface condition and thickness control to determine the level of wear, non-conventional testing methods can be applied such as infrared thermography, which is based on the detection and measurement of infrared radiation emitted by objects in the affected areas, and liquid penetrant to detect defects in the brake rotor surface. With the application of these tests, it is possible to identify defects in the functionality of disc brake rotors, as detailed in table 1.

Table 1: Non-destructive tests applied to the detection of disc brake rotor defects.

Non-destructive testing	Principle	Standards	Equipment and materials	Guidelines
Visual Testing VT	Surface observation of the object to evaluate discontinuities.	UNE - EN 13018 ASME Section V, subsection A, article 9	Human eyes	- Place the eyes within 600 [mm] of the surface to be tested, at an angle greater than 30°. - Minimum luminance of 1000 [lx].
Penetrant Testing PT	Apply penetrating liquid to the surface, which will reveal defects due to the phenomenon of capillarity.	ASTM E165 -02 ASTM E1417 ISO 3452 - 1 ASME BPVC.V	Penetrant Kit	- The surface should be between 40 and 125 [°F]. - Precleaning, drying and penetrant application - Penetrant Removal and Developer Application - Inspect with a minimum luminance of 1000 [lx].
Infrared thermography IRT	It maps surface temperatures as a function of the infrared radiation emitted by an object as heat flows through, to or from that object.	ISO 18434 - 1	FLUKE TiR32	-Comparative quantitative thermography (CQT). -IRT chambers calibrated according to established industry practice. -Natural, induced means for heating, also for target cooling, this at least 68 [°F] above or below the apparent temperature.

Visual Testing (VT)

The direct visual testing was performed according to the UNE - EN 13018 standard, examining defectologies on the brake rotor surface at 45° and at 250 [mm] between the human eye and the object to be tested. The test is applied in daylight with a luminance higher than 1000 lux, this according to ASME BPVC.V - Article 9. It is necessary to calculate the speed of light in the considered medium, in this case steel (v_{ph}) obtaining 119916983.2 [m/s], with a refractive index (n) of 2.5 subjected to a speed of light in vacuum (c) of 299792458 [m/s], according to Eq. 1 [15].

$$v_{ph} = \frac{c}{n} \tag{1}$$

Penetrant Testing (PT)

The evaluation is performed according to ASTM E 165-02, Type II, with visible liquid penetrant, method B - solvent removable. The surface temperature to be tested is 22.4 [°C]. As the brake rotor material is SAE 1215 steel and its process is foundry, the penetrant and developer application times to obtain adequate capillarity suggest 5 and 10 minutes respectively. For the removal of the penetrant liquid, the cleaner is applied with the wiping mopping technique. The test is performed in daylight with a luminance above 1000 lux. Figure 1a shows open discontinuities on the friction surface of the brake rotor and porosity on the outer edge of the friction ring, with zoom x15 identifying apparent tangential thermal cracking and porosities due to poor contact of the brake pad with the brake rotor surface are identified, figure 1b shows grooves and open discontinuities on the edges of the friction surface, zooming x11 visualizes discontinuities and reliefs on the outer edge of the brake rotor, also grooves are identified that are presented in the form of rings on the friction surface, figure 1c shows rust on the outer edge of the friction ring and discontinuities product of the machining of the brake rotor, these defects are clearly visualized by zooming in x9, the macro perspective shows rust on the rotor hat of the brake rotor.

(a) Zoom x15 (b) Zoom x11 (c) Zoom x9

Figure 1: a) Open tangential discontinuities and porosity, b) Grooves and open discontinuities, c) Rust and machining discontinuities.

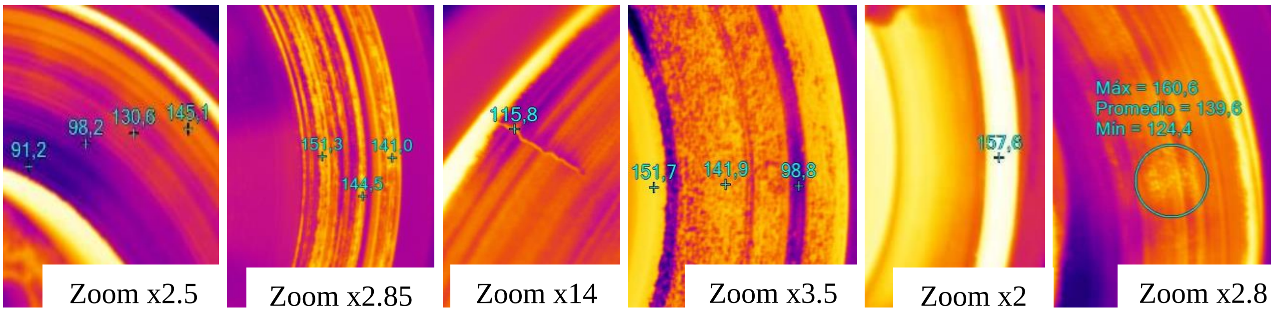
Infrared Thermography (IRT)

The inspection is performed according to ISO 18434-1 [16], the Step Heating technique is applied with a variation in the way of raising the temperature of the object to be tested, the proposed method suggests that the brake rotors do not they must be disassembled for evaluation and the test must be of dynamic application, in this context the brake rotor is heated by subjecting the vehicle to controlled braking processes at a speed not exceeding 60 [km/h] for 90 seconds until reaching an inspection temperature that allows visualizing the contrasts of the discontinuities in the object, the defects present on the surface of the brake rotor are visualized in the form of contrast changes. The IRT chamber is calibrated considering the ambient temperature in which the test is performed, this is

290.64 [°k] since it is suggested that the test is performed in the shade, this with a relative humidity of 93%, the emissivity (e) determined by means of a reference contact thermometer and the IRT camera is 0.86, with a surface temperature (T) of 355.37 [°k]. The infrared emission used with the equipment is about 8 [μm] wavelength obtained according to Wien's equation, by Stefan Boltzmann's constant law (B) with Eq. 2 [17], and some of the environmental factors, it is possible to calculate the radiation heat emitted by the disc brake rotor (W) obtained 652.5 $[W/m^2]$.

$$W = eBT^4 \tag{2}$$

With Fluke SmartView, the temperatures of the images captured with the IRT camera are verified in the most affected sectors of the brake disc. Figure 2a shows crystallization at a zoom x2.5 on the brake rotor surface, figure 2b with zoom x2.85 shows the presence of grooves resulting from abrasive wear due to total wear of the brake pad and the presence of particles between the pad and the friction ring, figure 2c shows a radial thermal crack detected with zoom x14 on the edge of the brake rotor disc, the thermal stress caused by the heating and cooling transients during service is responsible for the formation of these cracks, figure 2d presents a friction surface rust at a zoom x3.5, appears due to the inactivity of the vehicle for long periods, humid environment and insufficient pressure when applying the brakes, they can also appear in the rotor hat, clamping plane, edges of the brake rotor and cooling vanes, this because the brake pads contain materials that wear during the braking process and can generate dust and particles that are deposited on the brake rotor, figure 2e shows the wear on the friction surfaces with a zoom x2, when there is excessive wear the disc brake rotor tends to concentrate more heat, this is because the thickness is outside the safety limit and its capacity to absorb and dissipate heat is reduced, figure 2f shows pitting with a zoom x2.8, these appear due to embedded particles, wear, corrosion, overheating, they appear as irregular spots with a brighter contrast.



(a) Crystallization (b) Grooves (c) Crack (d) Rust e) Wear (f) Pitting

Figure 2: IRT applied on the friction surface of the brake rotor.

Results Analysis

Figure 3 resume the different defects located mainly on the friction ring, circumferential grooves and rotor hat of the brake rotor, classified by temperature range and considering the most common color shades according to this, the shape of the defect detected by infrared thermography is shown.

In the brake disc, the location of six types of defectologies is determined and the effectiveness of diagnostic methods for detecting them is compared. By applying IRT using the Step Heating technique, crystallization can be observed in the friction ring of the brake disc, this crystallization appears in the form of rings when the temperature oscillates between 95 [°F] and 160 [°F], showing shades of colors ranging from blue and violet tones through a red hue to incandescent yellows.

The grooves appear in the friction ring, the defect extends in the form of bright rings over the entire surface, depending on the thickness and depth, they appear in a temperature range of 135 [°F] to 165 [°F] in shades of color from orange to bright yellow, this temperature range and color tones can also identify the wear defect, wear manifests itself on the cooling vanes located between the friction rings, this defect is identified by CQT , the brake rotors in the mentioned area are analyzed and the temperatures are compared. If there is a temperature differential greater than 16.57% between the brake rotors, there is wear.

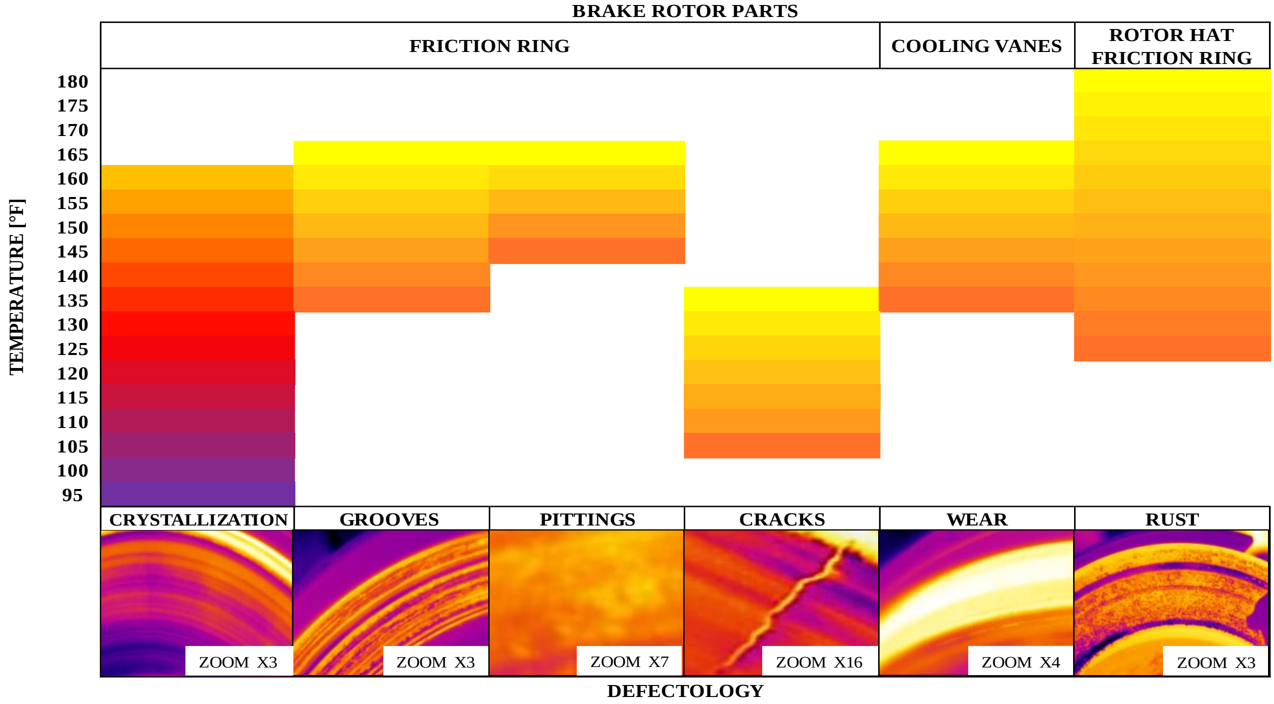
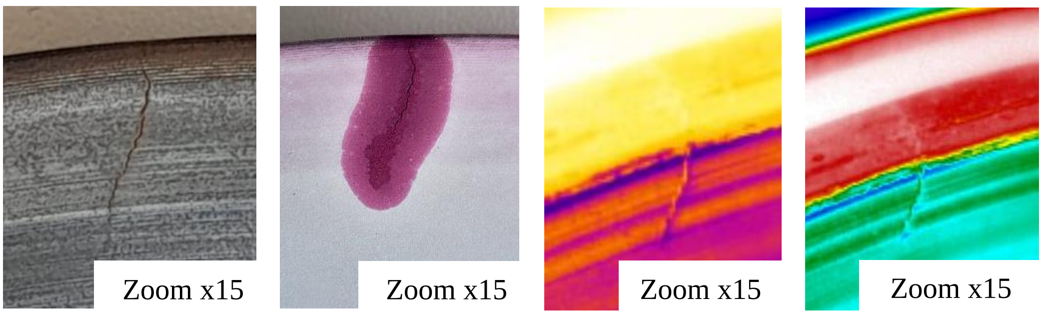


Figure 3: IRT applied to the characterization of defectologies in brake rotors.

The pitting appears on the friction ring of the brake disc in irregular shapes, exhibiting temperatures from 145 [°F] to 165 [°F] in shades of color ranging from orange to bright yellow.

Cracks appear on the friction ring in a linear, irregular, and tangential manner to the brake disc, with shades ranging from orange to bright yellow over a temperature range of 105 [°F] to 135 [°F].

Rust can appear on the entire surface of the brake disc regardless of whether or not this area is in contact with the brake pads, however, in this study two preferred areas are identified which are the friction ring and the rotor hat, the defect spreads across these areas in irregular agglomerated shapes, it appears in contrasts ranging from orange to bright yellow in a temperature range from 125 [°F] to 180 [°F]. The friction ring surface of the brake disc shows bluish and purplish hues indicating the areas of contact with the brake pad. If these shades are not evenly distributed on the friction ring surface, it may be a sign that the brake disc has uneven wear, also known as brake disc runout [18].



(a) VT (b) PT (c) IRT (d) IRT High Contrast

Figure 4: Analogy of non-destructive testing (NDT) applied to a crack in a brake disc.

To validate the conclusions by performing the analogy of the different nondestructive tests applied to the brake disc in the same defect by means of a zoom x15, figure 4a shows the visual testing, an apparent crack is visualized, figure 4b shows the penetrant testing, a red mark is visualized due to the capillarity of the penetrant in the developer, indicates a crack, figure 4c shows the infrared thermography, identifies a crack, the defect is shown in different contrast, figure 4d shows the infrared thermography set in high contrast, allows confirming the presence of crack, this because a discontinuity appears shown by the change of contrast.

Conclusions

By infrared thermography, crystallization can be observed on the friction ring of the brake disc, it appears in the form of rings at temperatures between 95 [°F] and 160 [°F], it shows up in shades of blue, violet, and red to incandescent yellow.

The striations extend in the form of shiny rings all over the friction surface of the brake disc, depending on the thickness and depth, they appear at temperatures from 135 [°F] to 165 [°F], in shades of orange to bright yellow, in this range of temperature and color shades the wear defect can also be identified, but this is manifested on the vanes located between the friction rings, it is identified by the CQT technique with a temperature differential of 16.57%.

The pits appear on the friction ring of the brake disc in irregular shapes, they present temperatures from 145 [°F] to 165 [°F] in shades of color from orange to bright yellow, in these same shades, but at temperatures from 105 [°F] to 135 [°F] the cracks appear in linear, irregular, and tangential shape to the brake disc.

Rust spreads across the friction ring and brake disc bell in irregular agglomerated shapes, in contrasting orange to bright yellow at temperatures from 125 [°F] to 180 [°F]. The surface of the friction ring shows bluish and purplish shades indicating the areas of contact with the brake pad; if these shades are not evenly distributed in this region, the brake disc shows friction.

Making an analogy between the different non-destructive testing techniques it has been determined that the IRT test is the most effective, it has a superior inspection coverage of 8.33% compared to the VT method and 33.66% in relation to the PT method, it is able to detect six types of defectology found in the brake disc, such as crystallization, striations, pitting, cracks, wear and rust. It is important to mention that this technique presents a limitation in the detection of open discontinuities when performing a general thermography of the brake disc, it requires an approach and defect analysis using Fluke SmartView software. In detecting open discontinuities, it has been determined that the most effective technique is liquid penetrant testing.

The study will be complemented by the application of non-destructive testing such as ultrasonic testing (UT) and Eddy current testing (ECT) to detect variations in brake disc material density and composition, which may indicate possible defects in the manufacturing process, such as molding failures, machining errors or casting problems.

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