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THERMAL CHARACTERIZATION OF A GRAY CAST IRON VENTED BRAKE ROTOR DURING SEVERE-BRAKING USING INFRARED THERMOGRAPHY

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ABSTRACT

High resolution infrared thermography was used to analyze the thermal response of a vented brake disk (made of gray cast iron) during sudden braking. This research was conducted to test brake rotors made of a new gray iron alloy. Experience with current rotors has shown the formation of cracks due to thermal stresses developed during braking episodes. Such crack results in the shortening of the service life of the brake rotor but also and most importantly they may constitute a safety risk to the people using a vehicle with damaged brake rotors. Results from the thermal characterization reveal that our approach to minimize cracking during braking episodes is the correct one.

INTRODUCTION

A gray cast iron vented brake rotor is exposed to strong frictional stresses during severe braking episodes. Due to it, maximum temperatures near 700 °C can be attained during a sudden braking in a few seconds [1,2]. Complex temperature distributions developed under these conditions cause strong thermal stresses and phase transformations which produce damage in the rotor as cracking and thermal strains. From previous studies it is well known that vented and the optimal material design helps to reduce the thermal cracking damage. In this study the composition of the gray cast irons was specifically designed in order to test them mechanically and thermally. The dynamical interaction between the brake and pad was analyzed by using infrared thermography of high resolution. These studies validate our design of the materials through the determination of heat flows and temperature distributions in the track braking under severe conditions.
Brake systems in the automotive industry are one of the most important areas of concern for car manufacturers due to the safety issues inherent to them.

Brake systems are constituted by several mechanical components, among them a brake rotor which is attached to the tires and a caliper which holds the pads whose function is to apply pressure to the brake rotor to stop a moving vehicle. The pressure is applied through a hydraulic system controlled by a master cylinder, which in turn is operated from the drivers´ seat. These components are located in each of the wheels of a vehicle.

In terms of its operation, brake systems must extract all the kinetic energy of a vehicle in motion, to do so friction between the pad and the brake rotor is responsible for stopping or de-accelerating the vehicle.
The kinetic energy transferred from a moving vehicle to the brake rotor can be estimated by means of the following relationship (1):

$$E = \frac{K}{2} \cdot \gamma \cdot \frac{m(v_0 - v_f)^2}{2} \qquad (1)$$

Where K is the fraction of kinetic energy absorbed by the brake rotor (roughly 90 %), γ is the weight distribution coefficient per axis ($0<\gamma<1$), m is the mass of the vehicle (kg), v_0 and v_f are the initial velocity of the vehicle and that during braking respectively (m/s).
As mentioned, all the kinetic energy has to be transformed into heat; this heat is absorbed by the brake rotor since K ~ 0.9E (1), the rest of the heat is dissipated by conduction, convection and radiation:

$$Q = Q_{brake} + Q_{cond} + Q_{conv} + Q_{rad} \qquad (2a)$$

The term Q_{brake} in equation (2a) may in turn be associated to the thermophysical properties of the material used in the manufacturing of the brake rotor, thus it yields:

$$Q = c_p \cdot m \cdot \Delta T_{brake} + Q_{cond} + Q_{conv} + Q_{rad} \qquad (2b)$$

The latter can be schematically described by means of Figure 1.

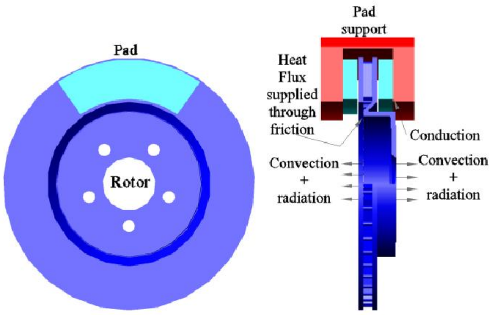

Figure 1 Rotor brake and pad assembly and the mechanisms involved in transforming the kinetic energy of the moving vehicle into heat.

In view of these facts, we have approached this problem as follows:

RATIONALE OF OUR WORK

Provided that the amount of kinetic energy transformed into heat renders the service life of brake rotors, two action courses can be taken in order to solve our problem:

- Change the design of the brake rotor (geometry)
- Modify the material used in manufacturing the rotors (Chemical composition change)

In a previous work [1], we have already shown that by doing small modifications to the chemical composition of the alloy used to manufacture the brake rotors, it is possible to enhance the mechanical properties of such components while keeping a good thermal response. Furthermore, we propose that by doing little changes in the chemical composition would result in better overall performance of the brake rotors which in turn will extend the service life of these components.
To prove the latter, we have conducted several tests on the rotors. The tests conducted include thermal measurements along with mechanical and non destructive inspection.

NOMENCLATURE

E	[J]	*Kinetic energy transferred from a moving vehicle to the brake rotor*
K	[-]	*Fraction of kinetic energy absorbed by the brake rotor*
m	[kg]	*Mass of the vehicle, mass of the rotor*
v	[m/s]	*Velocity of the vehicle*
Q	[J]	*Heat*
C_P	[J/kgK)]	*Specific heat*
T	[°C]	*Temperature*
t	[s]	*Time*
R	[mm]	*Ratio of the real area and the apparent contact area*
A	[m^2]	*Area*
$\dot{E}$	[J/s]	*Energy storage (loss)*
Pa	[N/ m^2]	*Tensile strength*
HB	[-]	*Brinell Hardness number*
Special characters		
γ	[-]	weight distribution coefficient per axis
Subscript		
0		*Initial*
f		*Final*
brake		*Brake rotor disk*
cond		*Conduction*
conv		*Convection*
rad		*Radiation*
r		*Real*
a		*Apparent*
max		*Maximum*

EXPERIMENTAL

In order to verify the effect of the changes in chemical composition proposed, we conducted our research in several steps, namely:

- Alloy preparation
- Mechanical testing
- Non-destructive inspection
- Thermography

Alloy preparation:

The alloy was prepared by melting in an induction furnace with capacity of 40 kg, a mixture of carbon steel scrap and pig iron. Once melted, the alloy composition was fixed by adding different ferroalloys, inoculants and graphite. Carbon and sulphur contents in the alloy were analyzed by means of a LECO carbon analyzer. The remaining elements in the alloy were determined with an ICP apparatus.

Two alloys were prepared, one according to SAE J431/ASTM 159 standards, whereas the second alloy is the one we propose and it is out of specification. Chemical composition of both alloys is shown in Table 1.

Mechanical Testing

The tensile strength, the Brinell hardness number along with the metallographic features of both alloys were determined according to SAE J431/ASTM 159 standards. The values obtained for the tensile strength and the Brinell hardness number are shown in the results section. The metallographic features of the alloys are also shown in the next section.

Non-destructive inspection

Penetrating liquids inspection was conducted in rotor brakes made of the current alloy. This non-destructive evaluation was used to determine if any cracks or microcracks developed on the rotor surface after simulating a braking episode.

The penetrating liquids inspection revealed the amount, size and distribution of the different cracks developed on the test specimens

Thermography

The rotor brakes were assembled in a probe (dynamometer) in such a way that both the rotor and the pad were completely exposed to an infrared camera. The rotor was allowed to rotate up 2000 RPM and suddenly a braking episode was simulated. Snapshots of the heating of the rotor surface were taken continuously at intervals of 0.2 s. The digital pictures obtained from an infrared camera allowed us to analyze the surface temperature distribution on the rotor and to estimate the overall heat fluxes involved during braking.

RESULTS AND DISCUSSION

Results from mechanical properties of the alloys are shown in Table 1. The data reported in Table 1 for the current alloy are in compliance with SAE J431/ASTM 159 standards, whereas the data obtained for the proposed alloy are out of such standards, however, this alloy exhibits better mechanical properties than those by the alloy used for the manufacturing of brake rotors. This indicates that the alloy suggested in this research is able to withstand higher stresses.

Alloy	Brinell Hardness number (HB)	Tensile strength (MPa)
Current	200	240
Proposed	248	300

Table 1 Results from the mechanical evaluation of the alloys tested.

Furthermore, the metallographic examination of both alloys show better phase distribution in the case of the proposed alloy than the other one. The graphite flakes in the proposed alloy (Figure 2B), are randomly distributed throughout the alloy pearlitic matrix and they also show uniform size; whereas in case of the current alloy used (Figure 2A), it is evident an irregular shape and size of the graphite flakes, in addition to a less random accommodation of them.

Such metallographic features exhibited by the proposed alloy along with the mechanical properties evaluated on them allow us to assure a better performance of this alloy under stricter mechanical conditions, in other words, the microstructure of this new alloy ensures better mechanical properties thus an increased capacity to withstand higher stresses.

In terms of the non-destructive testing, it was only performed in an actual damaged brake rotor. Figure 3, shows a picture of the inspection once the penetrating liquids were revealed. It can be seen in the right side image in Figure 3 the development of several microcracks along the surface of the brake rotor.

On the other hand, Figure 4 shows how a crack penetrates into the brake rotor, it was determined that cracks develop inwards the component up to 2.5 cm in deep. Such crack size is detrimental to the integrity of this type of critical components, more so, such defects may induce catastrophic failure at any given time.

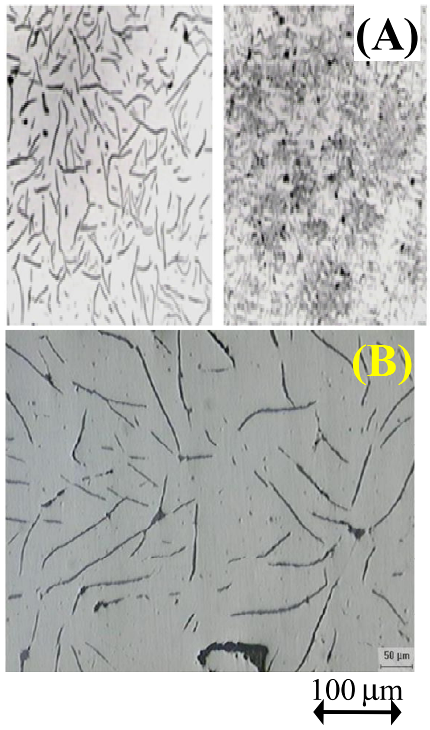

Figure 2 (A) Micrograph of the alloy currently used in the manufacture of brake rotors, (B) Micrograph of the proposed alloy

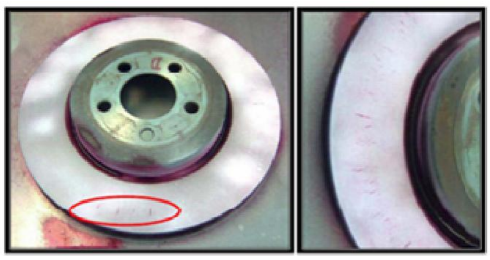

Figure 3 Results from the non-destructive testing on a brake rotor removed from service

These cracks are the result of the thermo-mechanical interaction between the rotor and the pad. Since the pad is normally made of an abrasive material, it is expected that due the friction between these components some localized stresses develop along the contact surface. In addition to the mechanical interaction, the friction among the pad and the rotor also generates heat so the rotor heats as the braking system operates. The heating of the rotor is more evident in the case of emergency braking.

The rotor brakes were assembled in a probe bank (dynamometer) in such a way that both the rotor and the pad were completely exposed to the sensing of a high resolution infrared camera. The rotor was allowed to spin up 2000 RPM and suddenly braking episodes were imposed. Figure 5 shows the plot of the average surface temperature as a function of time for a succession of breaking episodes.

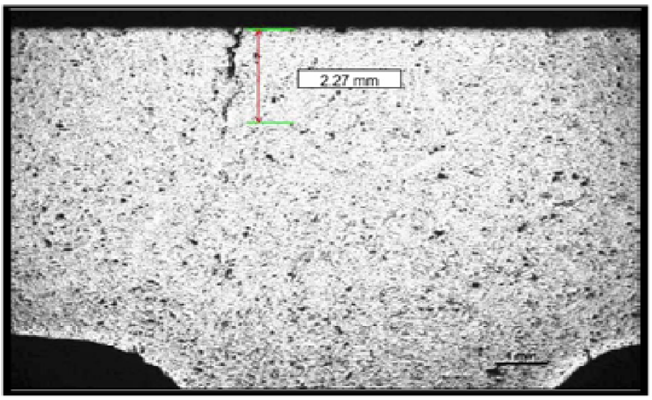

Figure 4 Transversal cut of a rotor brake showing the penetration of a crack developed onto the rotor´s surface

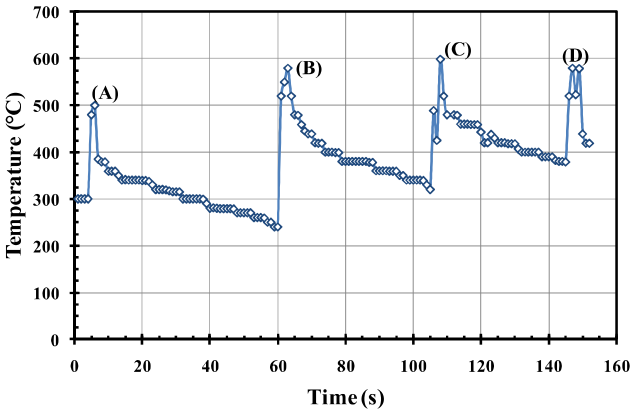

Figure 5 Evolution of average temperatures for a series of breaking episodes (peaks). Temperature values were obtained from the infrared images

Figure 6 shows four snapshots of the maxima temperatures indicated in plot of Figure 5. Notice that in the episode (D) their thermography shows a very uniform heating. Infrered thermographies were obtained with a digital infrared camera model FLIR-T710 that detects temperature differences as small as 0.08 °C.

By the way, representative infrared pictures of the heating of the rotor during breaking, are shown in Figure 7. Such pictures correspond to the episode (A). In this case, the thermal pictures were taken each 1/15 s. In the snapshots of Figure 7 three important temperature stages of breaking are given: (a) before, (b) during and (c) after the sudden breaking. The pictures also have a spatial high resolution that yields values each 1 mm along any direction. This detail degree allowed us to obtain accurate spatial temperature distributions on the rotor surface and to estimate, by employing analysis of digital images, important phenomena occurring during braking: for instance, in Figure 7(b) it can be noted that during braking, in the instant of maximum temperature, there are three hot rings that indicate a non uniform frictional contact and consequently a diminution of the effective contact area of the pad with the rotor.

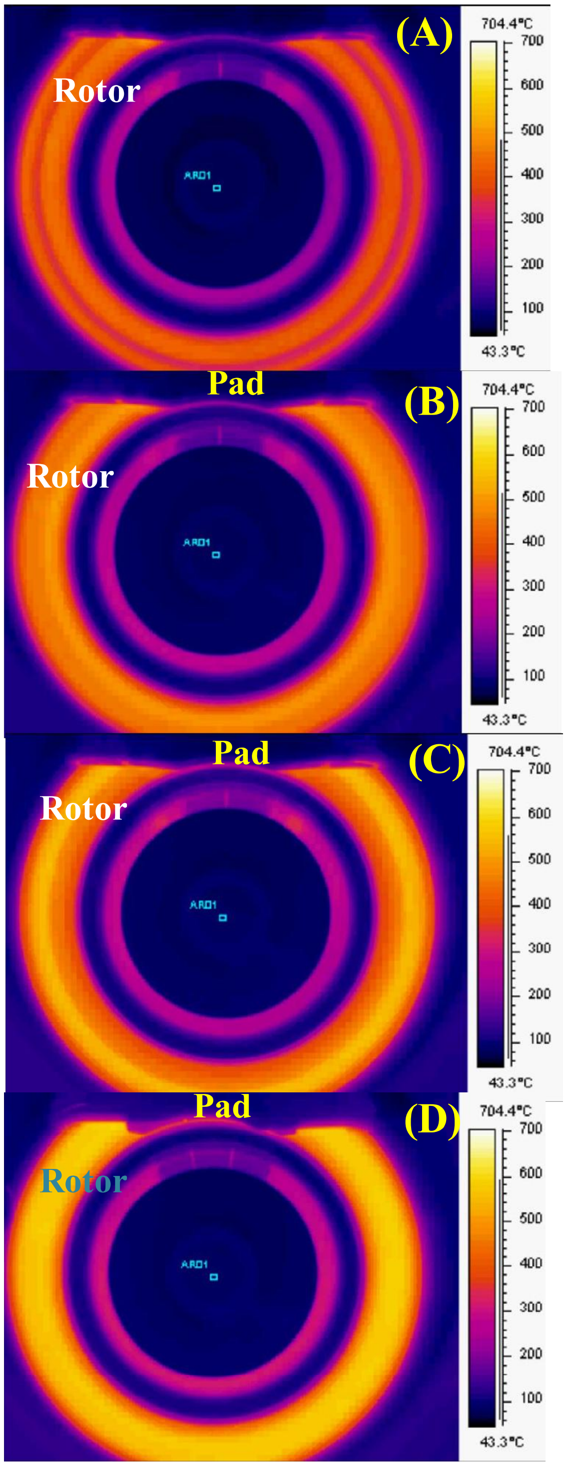

Figure 6 Infrared thermographies of the maxima temperature distributions during breaking, corresponding to points (A)-(D) of the plot in Figure 5. Notice that the most uniform temperature is attained in the last breaking episode (D)

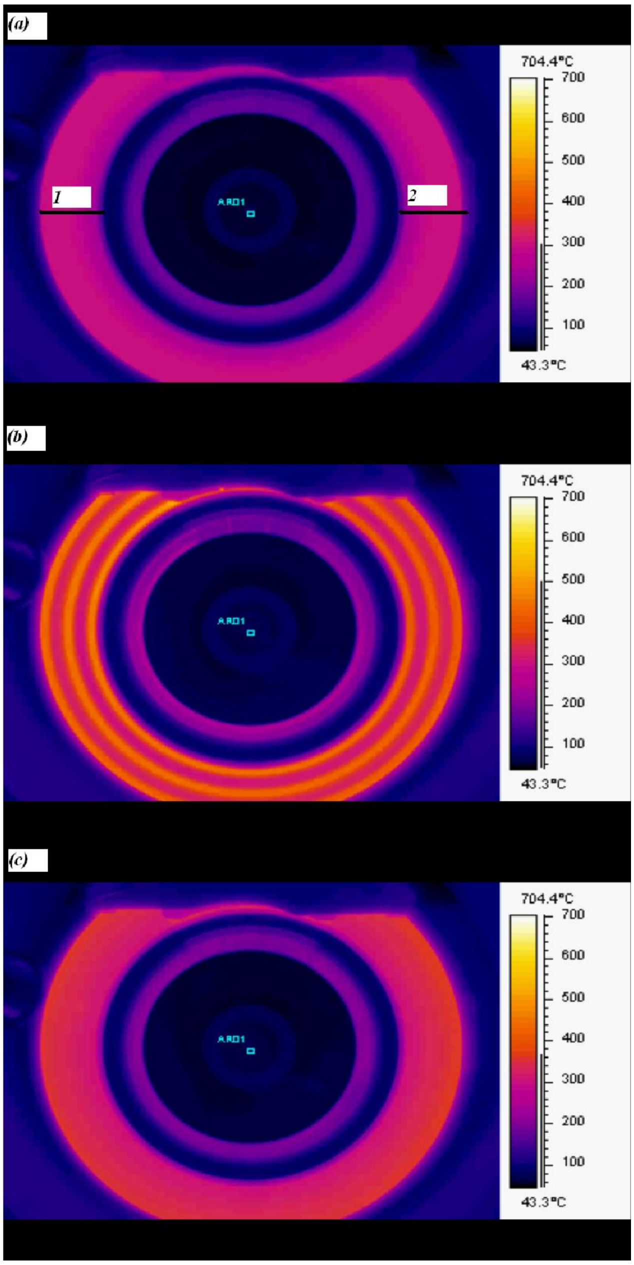

Figure 7 Thermal snapshots of the breaking: (a) thermography previous to the breaking, (b) thermography that evidences three radial heat spots and (c) uniform temperature distribution when the rotor goes to a constant angular velocity

A quantitative estimation of the values of temperatures in those rings is given in Figure 8 where the sizes of the rings can be estimated as 10 mm each one. Measurements of the sizes of these structures can be useful to estimate in a realistic way the ratio of the real area and the apparent contact area, $R = A_r/A_a$ [2]. In this case it has been estimated that R =0.50.

Figure 8 Temperature profile along the line 1 (indicated in Fig. 7(a)) in the instant of maximum surface temperature on the brake rotor (Fig. 7(b)). Notice the strong temperature increase respect to the temperature in between rings

Based on recent theoretical studies [2], it is possible to establish that, in this episode, this value of R yields the maximum temperature, T_{max}, because occurs a temperature increasing with a decreasing in the contact area ratio. This result could be useful to improve the design the compositions and the performance of the rotor and pads.

Moreover, when the temperature of the solid is spatially uniform it is possible to estimate the energy storage (loss) in the rotor during each breaking episode, it is given as [3]:

$$\dot{E} = mc\frac{dT}{dt}, \qquad (3)$$

where m is the mass of the rotor and c is the specific heat. Thus, the time derivative of T is proportional to such an energy. In Figure 9(a) it is shown the profile of the maximum surface temperature during a breaking episode and their plot of dT/dt as a function of time is given in Figure 9(b). From plot in Figure 9(b) it is clear that during breaking the rotor gains energy (positive values of dT/dt) in a smooth way due to the frictional contact but the rotor loss thermal energy in a discontinuous way, mainly through conduction and radiation mechanisms and after through convection because at high velocities this is the main mechanism of heat loss [3-7].

Also, infrared thermography correctly revels that at high velocities (before and after a breaking episode) the temperature is slightly higher on the right hand side than on the left hand side. See Figure 10. It means that in a half revolution the rotor lost heat, by a convective mechanism, by around 10 ^{o}C. It can be concluded that in this latter case fins helps to cool efficiently the rotor.

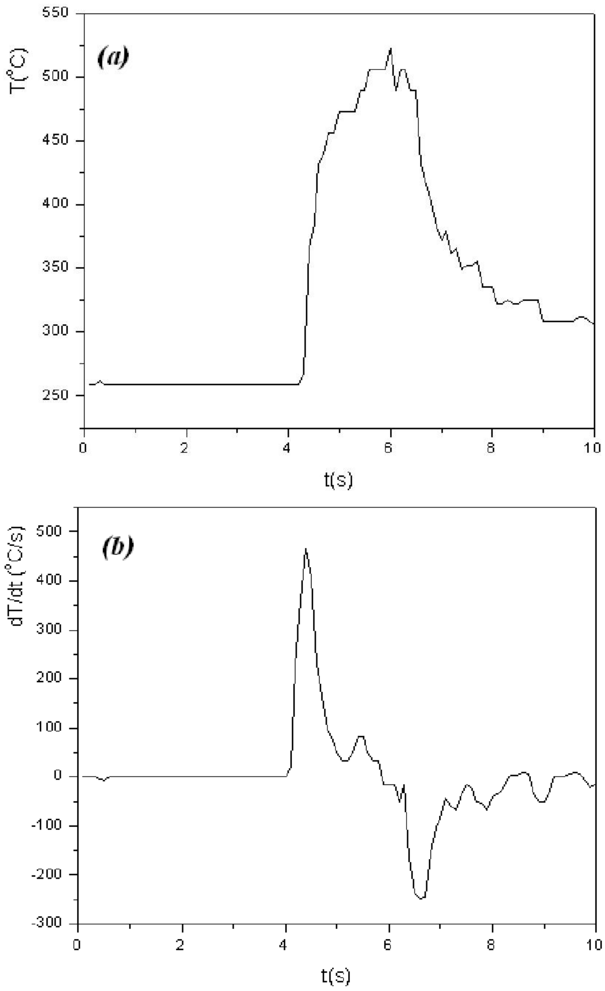

Figure 9 (a) Punctual change of the maximum temperature as a function of time during a braking episode. (b) Temporal derivative dT/dt for the profile given in (a). This quantity is proportional to the energy

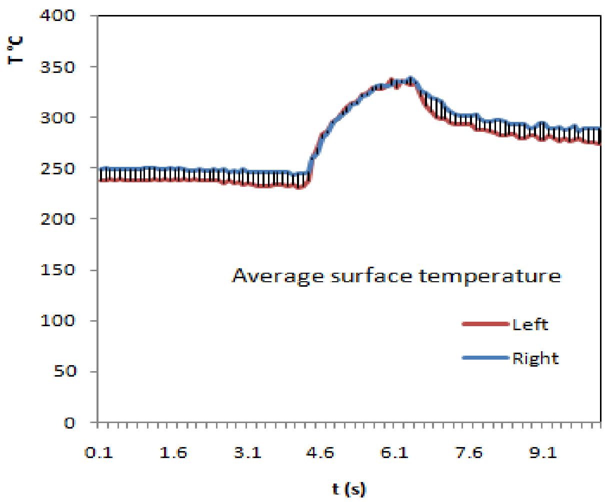

Figure 10 Time averaged surface temperatures on the left hand side (red) and

CONCLUSIONS

In this paper, we have shown that infrared thermography is a very useful tool to determine accurate spatial and temporal temperature profiles. These profiles allows us to obtain valuable information as the maxima temperatures in each breaking episode, the existence of hot rings, the gain and lost of heat and the importance of these events upon the compositional and mechanical properties. The overall results given here can used to improve the performance and to design of vented break rotors.

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