Science Front Publishers *Journal for Foundations and Applications of Physics*, **3 (2), (2016)**
(sciencefront.org) **ISSN 2394-3688**

Non-Destructive Investigation of Bulk Residual Stress in Automobile Brake Pads with its Service Life

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(Received 12 July 2016, Accepted 28 August 2016, Published 11 September 2016)

Abstract

Automobile brake systems transform kinetic energy into heat for the purpose of speed control. During this operation, rapid heating and cooling cycles cause the formation of residual stress in the brake pad backing plate. In this study, the relation between residual stress magnitude and the operation period is investigated to predict the service life of brake pads. Residual stresses are calculated related to longitudinal ultrasonic wave velocity variations which are measured non-destructively using cost effective and accurate immersion ultrasonic technique. Finally, a mathematical model is developed to predict residual stress in brake pad backing plates related to operation period.

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***Keywords*:** Ultrasonic waves; brake pads; residual stress; operation period

1. Introduction

Brake systems are the most important safety parts of automobiles. During the continuous process of the energy cycle, an automobile's speed is reduced, in the case of no applied force, by the friction of air with automobile surface and road surface with tires that convert kinetic energy into heat energy. In order to control the speed of an automobile, mechanical systems are required to speed up that energy conversion. Brake system in automobiles converts the energy of motion into heat energy by applying an opposing force. The opposite force that accomplishes rapid deceleration is friction force.

Brake systems contain contacting parts which are pads and rotors. Pads are pressed on the moving rotor to apply friction force. Harder the pressure applied by the pads higher the friction force applied in the opposite direction of the momentum. During the contact of pads and rotor, kinetic energy is converted into heat and some of that heat is stored in pad and rotor parts of the brake system. As a result of the heat input, temperatures of these parts rapidly increase to high values. On the other hand, atmospheric temperature is very little when compared to the temperature increase in brake system parts and heat rapidly transfers into the air. This cycle is repeated many times during the operation of a vehicle and rapid heating and cooling periods have harmful effects on these parts of brake systems.

Brake pad backing plates are made of ductile materials such as steel and residual stresses are formed as a result of heating and cooling cycles. It is not expected to have high magnitude of residual stress within a ductile material. Residual stress stored in these materials acts as an additional load during the braking process and failures can be occurred. Destruction of a single brake pad cannot have a catastrophic effect, but it is not a desired situation. Studies on residual stress is expected to inform manufacturers and automobile owners about damage limits of these critical parts.

Thermal effects on brake system parts were investigated by various researchers. For this purpose, numerical simulations [1-5] and experimental analyses [6-8] were performed. These studies showed that temperature changes during the braking process affect the service life and material performance of brake system components. Residual stress is the main reason of corruptions occurred within the brake system components and it is a result of rapid heating and cooling cycles [9-13]. Residual stress analyses proved that plastic deformations occur within brake discs during the operation, however, residual stress formation in brake pads have never been investigated.

Longitudinal ultrasonic waves were previously used for non-destructive evaluation of residual stress [14-16]. Ultrasonic waves were also used with the pulse-echo technique by Uzun and Bilge [17] to investigate bulk residual stress in welded steel plates. Another method to transmit ultrasonic waves into materials is immersion technique which is also used for bulk residual stress measurement in steel materials [18-19]. Previous studies showed that high-frequency ultrasonic sound waves are capable of determination of bulk residual stress within a specific volume of materials.

It is a proven fact that mechanical processes at braking systems have damaging effects. Mechanical processes cause rapid temperature changes at brake pads and residual stresses can be formed in the backing plate of these parts. Formation of stress has an effect on fatigue and fracture that can cause catastrophic failures [20-21]. Previous studies focused on damages in brake discs, but brake pads have been neglected [22-25]. In this study, the relation between operation period of brake pads and residual stress are investigated in order to predict service life. Non-destructive immersion technique is used to determine residual stress in brake pad backing plates for cost-effective and rapid investigation.

2. Methodology

In order to investigate operation life of brake pads, bulk residual stress in backing plate of brake pads is determined using longitudinal ultrasonic waves. For this purpose, brake pads at different operation periods are used. Ultrasonic wave velocity measurements are performed using immersion ultrasonic technique. A correlation between ultrasonic wave velocity variations and stress is developed based on the acoustoelastic effect. After the calibration process, ultrasonic wave velocity measurements are performed at each brake pad sample to calculate residual stress.

2.1. Experimental Setup

Nine different brake pads, at different operation periods, are provided by Renault MAIS Turkey. Operation periods are determined in terms of distance travelled. One of these brake pads is unused brand new which is used to determined ultrasonic wave velocity at no stress state. Backing plate of these pads are made of carbon steel Q235 with Young's modulus of 200 GPa [26], the yield strength of 245 MPa and tensile strength of 438 MPa [27].

Precise ultrasonic wave velocity measurements are performed using immersion ultrasonic system. This well-known and widely used technique transmits ultrasonic waves to the material through thewater.Three waveforms, which occur during the travel of longitudinal ultrasonic waves within an immersion system, are illustrated in Figure 1which are the initial pulse with highest amplitude on the left, the surface echo, and the back-wall echo. Measurement of the time gap between two echoes from the surface and the back-wall of the material (t_2) allows calculation of ultrasonic wave velocity.

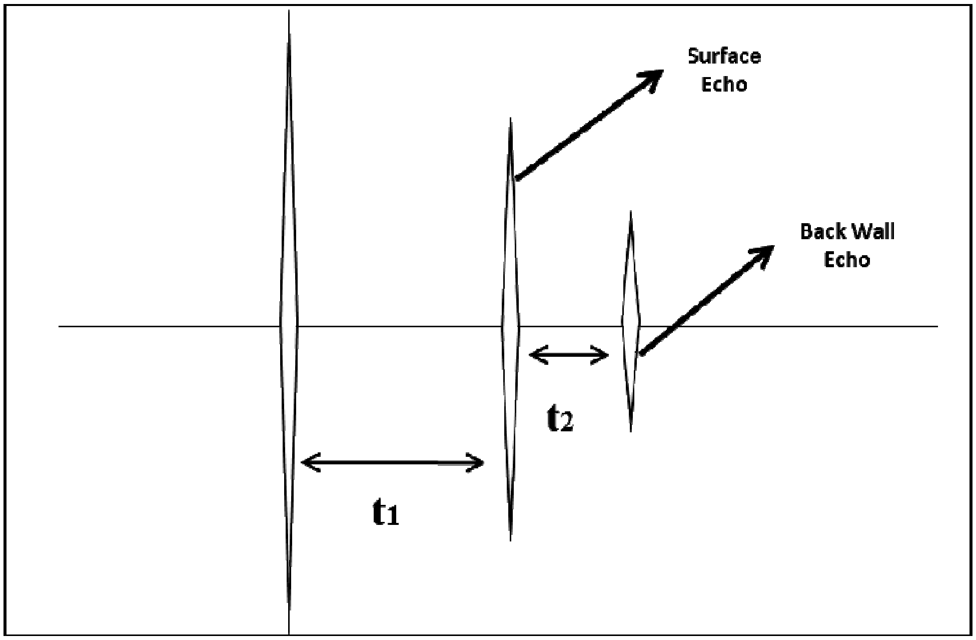

Figure 1. Schematic illustration of the immersion ultrasonic system wave propagation

2.2. Acoustoelastic Effect

Continuum defines the medium in which ultrasonic waves propagate and structural parameters can be related to properties of an equivalent continuous medium [19]. Variations in the elastic structure of continuum and velocity of waves in the medium are determined by the acoustoelastic theory. Hughes and Kelly [28]studied the relation between stress and wave propagation usingMurnaghan's[29] theory of finite deformations and third-order terms for energy.D. Vangi [30] also correlated time of flight of ultrasonic waves with monoaxial stress and obtained a linear relation.

In the case of longitudinal waves that propagate and oscillate in the same direction, relation between ultrasonic wave velocity and stress can be simplified and defined with Equation 1 where $\partial\sigma$ is stress change from a reference level, L_{22} is acoustoelastic constant, V_{22} is longitudinal wave velocity, and V_{22}^{0} is longitudinal wave velocity at axial zero stress.

$$\frac{\partial V_{22}/V_{22}^{0}}{\partial\sigma} = L_{22} \qquad (1)$$

Pulse-echo ultrasonic technique for non-destructive investigation provides bulk stress through the thickness of a material. Ultrasonic waves travel through different sections of a material and they are exposed to different stress zones during their movement. There can be tensional and compressive stress regions through the thickness, and results provide a combined effect of these regions on ultrasonic waves. These different stress zones affect the velocity of ultrasonic waves. Accordingly, an average stress value through the thickness of the material is obtained at each measurement point. Measured stresses in this study are bulk stresses and they are correlated with ultrasonic wave velocity variations.

During the operation of the brake pad, thermal expansion and contraction occurred within the backing plate. After the thermal effect, some of the expanded sections cannot fully contract back to their rest state and this irregularity causes strains to remain within the material as residual stresses. For this purpose, the correlation between ultrasonic wave velocity and stress is determined in terms of thermal strains occurred during the expansion of materials. In this study, the relation that expresses thermal stress is used for calculation of stress state in terms of temperature changes (ΔT). Thermal stress is determined using Equation 2 where the modulus of elasticity (E) and thermal expansion coefficient (α) of brake pad backing plate are determined as 200 GPa and 15.9 $^{o}C^{-1}$, respectively.

$$\sigma = E\alpha(\Delta T) \tag{2}$$

3. Results

Acoustoelastic constant, the correlation between ultrasonic wave velocity and stress, is determined by measurement of ultrasonic wave velocity variations at stress stages. For this purpose, a single, unused and stress-free brake pad is used. The temperature of this brake pad is increased gradually, at each temperature step thermal strains formed within the backing plate and ultrasonic wave velocity measured at each step. Finally, the relation between stress and wave velocity variation provided acoustoelastic constant, which is found to be -0.00018938 Mpa^{-1} as illustrated in Figure 2.

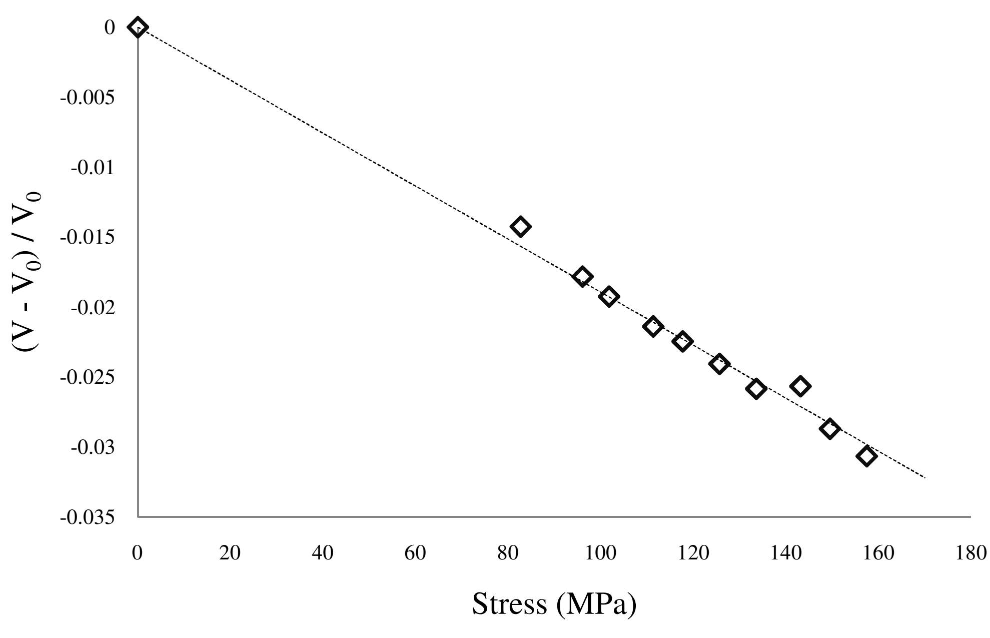

Figure 2. Brake pad backing plate stress and velocity change

The relation between ultrasonic wave velocity variations and stress show that ultrasonic wave velocity decreases linearly with increasing stress. This linear relation is determined in Equation 3 where σ is stress, V is ultrasonic wave velocity, V_0 is stress-free ultrasonic wave velocity and L is acoustoelastic constant.

$$\Delta\sigma = \frac{\Delta V}{V_0} L \tag{3}$$

Ultrasonic wave velocity measurements are performed in 6 measurement points of each brake pad as illustrated in Figure 3. Centre of the brake pad is selected for measurement because at that part of the brake pads backing plate thickness is homogeneous. Average of 6 measurements in a brake pad is used to determine residual stress state.

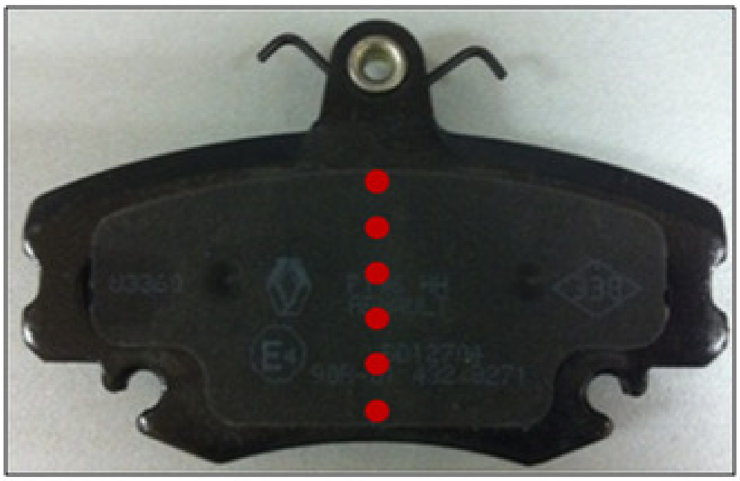

Figure 3. Illustration of brake pad and wave velocity measurement points

Measurements were analyzed in terms of standard deviation and averages. The maximum standard deviation in a brake pad sample is found to be 18.39 m/s while the minimum deviation is 2.59 m/s, which are less than 0.3 percent of the average ultrasonic wave velocity in that brake pad. Low standard deviation shows that ultrasonic wave velocity distribution within the steel backing plates is homogeneous. The ultrasonic wave velocities in terms of the operation period of brake pads are given in Figure 4. Wave velocity decreases with increasing operation period. R-square value states that experimental results fit the parabolic equation with 96.4 % accuracy. Ultrasonic wave velocity in stress-free unused brake pad is measured to be 6391.3 m/s. The operation period of service life ended brake pad is 48,000 km and ultrasonic wave velocity in this pad is 6153.6 m/s. According to the third order parabolic trend line, it is predicted that ultrasonic wave velocity stabilizes at a value around 6150 m/s, after 55,000 km of operation period.

Residual stresses increase with increasing operation period as illustrated in Figure 5. Distribution of residual stress is parabolic. It can be stated that at longer operation periods, the residual stress shift is expected to be decreased. After a period of 60,000 km, residual stress in a brake pads seem to be stabilized. It can be stated that, this is the maximum possible operation period of brake pads. After that period of operation, wear material of brake pads is expected to be exhausted. For the sake of safety, brake pads should be replaced after a period of 60,000 km.

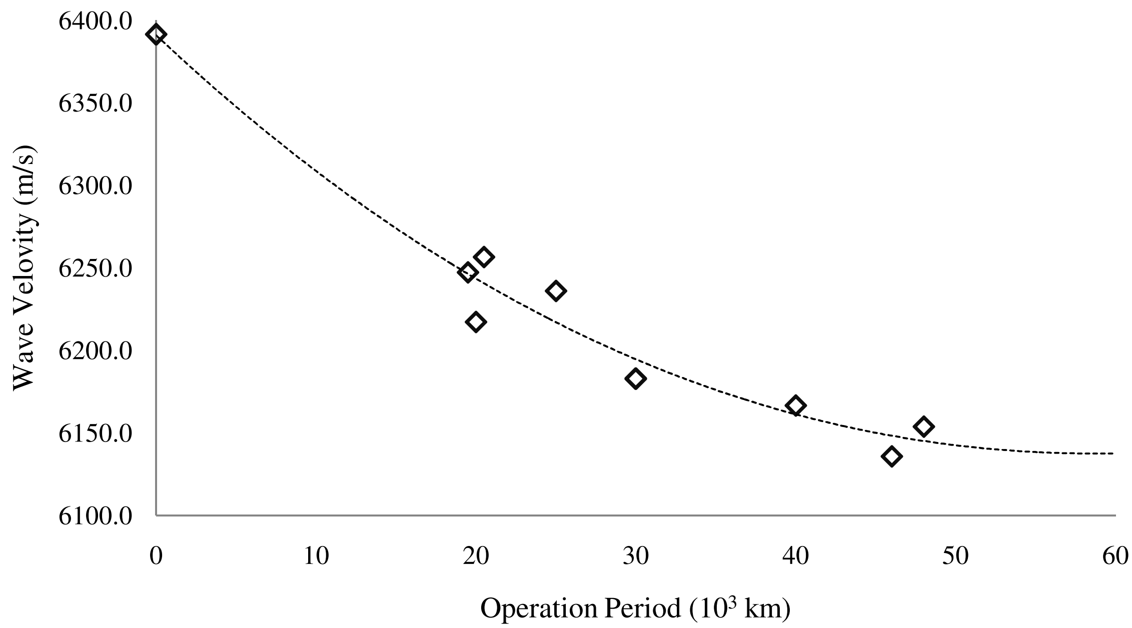

Figure 4. Ultrasonic wave velocity related to operation period

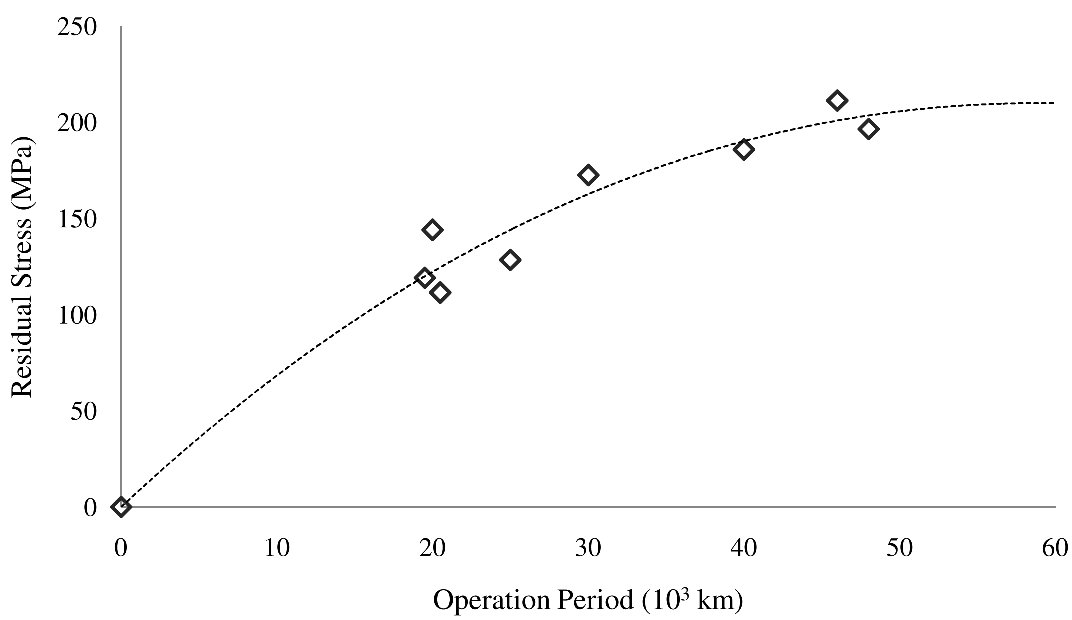

Figure 5. Residual stress related to operation period

The third order parabolic distribution of residual stress is given in Equation 4.

$$\sigma = ax^3 + bx^2 + cx \qquad (4)$$

In this equation, σ represents bulk residual stress in the brake pad, x representsthe distance travelled by a vehicle and a, b and c are constants. For this series of the brake pads,a is 0.0001MPa m^{-3}, b is -0.0755MPa m^{-2} and c is 7.5716 MPa m^{-1}. By the way, prediction of residual stress related to operation period of this type of brake pads is possible. This model also allows determination of the operation period of a brake pad after ultrasonic measurement of the bulk residual stress.

4. Conclusion

Investigation of residual stress has a vital importance because it has effects on fatigue and fracture that can cause catastrophic damages. Rapid heating and cooling cycles during the operation of brake pads cause the formation of residual stresses in the backing plate that affects service life. In this study, the service life of automobile brake pads is investigated in terms of residual stress. Immersion ultrasonic technique proved its capability on being an efficient and cost effective method to give information about operation period of brake pads. It is observed that residual stress increases with increasing operation period and tends to stabilize after 50,000 km. Wear material of brake pads seem to be exhausted after this period of usage and accordingly it can be stated that residual stress in brake pad backing plates exceeds 200 MPa at the end of their service life.

The parabolic trend obtained using the experimental data of residual stress provides a mathematical model which allows prediction of the operation period of a brake pad according to the measured residual stress. This kind of prediction is of high importance for the automobile industry, especially for vital safety parts.

The ultrasonic technique provides an alternative method for non-destructive investigation of residual stress. This previously accepted method is applied for prediction of the service life of automobile brake pads, but this method has some restrictions. Accurate measurement of thickness is an issue that should be accomplished in order to determine residual stress precisely. Wear material remained on the brake pad backing plates prevented that. In order to eliminate this restriction, thickness of a single stress-free sample accepted to be the same for all brake pads of the same brand which is measured accurately using precious thickness measurement device on the wear material free part of the sample.

Acknowledgements

The present study has been supported by Renault MAIS Turkey. M. I. Aybar, General Manager of Renault MAIS Turkey, provided nine set of brake pads which were used for different operation periods. The authors acknowledge this support.

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