

Induction hardening treatment and simulation for a grey cast iron used in engine cylinder liners

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Abstract. In this research, a technical study of induction hardening in a grey cast iron used in engine cylinder liners manufactured by LAVCO Ltda., a Colombian foundry company, was carried out. Metallurgical parameters such as austenitization temperature, cooling rate, and quenching severity were determined. These factors are exclusively dependent on chemical composition and initial microstructure of grey cast iron. Simulations of induction heating through finite elements method were performed and, the most appropriate experimental conditions to achieve the critical transformation temperature was evaluated to reach a proper surface hardening on the piece. Preliminary results revealed an excellent approximation between simulation and heating test performed with a full bridge inverter voltage adapted with local technology.

1. Introduction

Now metalworking industry in Colombia is going through a critical situation due to external factors such as the economic crisis that no occurs only in Colombia, if not worldwide, and other internal situations as poor development in the production processes innovation, low flexibility and diversification in the manufacture lines offered to the market [1]. Adding to this, inequality in the cost and excellent quality of foreign products inevitably leads to the purchase of imported raw materials [2]. LAVCO Ltda. requires expanding their business opportunities through the production of engine cylinder liners with improved properties to those already offers its customers. Engine cylinder liners are made from a grey cast iron, with acceptable mechanical properties for correct operation of the pistons in the engine. However, these properties must be improved to increase the half-life of the piece and avoid continuous replacements.

Grey cast irons are alloys of iron, carbon, and silicon, with flake graphite formed during solidification. This graphite is dispersed in a matrix whose microstructure is determined by the chemical composition and solidification process [3,4]. The induction hardening is a promising option in surface thermal treatment to improve mechanical properties such as hardness and wear resistance in auto parts for automotive industry [5,6]. The adoption of induction hardening can let to harden inside parts of the cylinders, representing an attractive option that would increase sales of the company, increasing competitiveness and representation in national and international markets.

Induction heating is a method wherein a magnetic field is generated via an electrical conductor (coil) on the workpiece, alternating current passes through the conductor, creating an alternating magnetic field that produces the Eddy current, this current dissipates energy as heat [7]. In comparison



to other conventional techniques, induction heating provides energy savings and other advantages, such as, easy automation and control, reducing the physical requirements for installation, the ability of self-monitoring and short operating times, among others. Temperature pattern generated for this process is especially affected by some variables like geometry and electric-magnetic properties of the workpiece, coupling distance and coil design, frequency selection and operating current and heating time [8,9]. For these reasons, COMSOL Multiphysics was used in this work to create a physical model that predicts the induction heating process in a grey cast iron through simulation and modelling by finite elements method. This modelling allows to select the heat treatment parameters to generate the minimum energy consumption for proper temperature distributions in the grey cast iron surface when a hardening process is performed, and thus achieve improved mechanical properties. Finally, results obtained in the heating process simulation were evaluated and compared with experimental results.

2. Experimental

2.1. Conventional quenching of grey cast iron

Initially, a chemical and microstructural characterization of the casting was realized using the optical emission spectrometry technique on an equipment Bruker brand, reference Q4 Tasman with arc spark under an argon atmosphere and a microscope OLYMPUS GX71 at 500X and 1000X respectively. Subsequently, a quenching heat treatment was applied, considering that its silicon content mainly influences the critical temperature range transformation in cast irons. The lowest temperature of the critical range for casting was estimated by the following expression [10]:

$$\text{Critical Temperature, } ^\circ\text{C} = 730 + 28.0(\% \text{Si}) - 25.0(\% \text{Mn}) \quad (1)$$

On the other hand, determination of quench severity (H) is another important factor in treatment control. Usually, for grey cast irons, a cooling oil is recommended instead of performed in water due to the good response observed on the hardness and a cracking reduction [11]. Therefore, a range of 50°C above the value obtained by the theoretical calculation was used for austenitizing temperature (870°C) and oil with vigorous agitation as a cooling medium on round bars of 25.4mm in diameter and 20mm in height.

2.2. Modelling and simulation of induction heating

After preliminary testing of conventional quenching, modeling and simulation of the heating process was performed using COMSOL Multiphysics. As conductor (coil) "Copper [solid, annealed (12 micron GS)]" was used and to model the alloy "AAR Grade C steel casting wheels" was employed, the parameters of the alloy were selected to coincide with the LAVCO engine cylinder liner. At this stage, several numerical simulations for heating of cylinder manufactured by the company, and further a Jominy test piece made of the same cast iron and a copper coil of 13 turns with a diameter of 5mm were used for comparison of experimental results performed in the induction heating prototype adapted using technology locally.

2.3. Induction heating of grey cast iron

Induction heating was carried out with an electric system consisting of the following components: a rectifier; responsible for receiving the alternating current from the mains and transform it to DC, which was used in the inverter power circuit. Full bridge inverter; which it provides an alternating signal with a frequency and amplitude determined to the coil. Finally, the series RLC resonant load that allowed the heating of the workpiece that is located within the coil.

3. Results

3.1. Characterization and conventional quench of grey cast iron

The chemical composition of the grey cast iron reveals small amounts of alloying elements (Cr, Ni, Mo, and Mn), which could positively influence on the hardenability [12] (see Table 1). The presence of these elements generates different effects on the hardening process. For example, silicon content between 0.6 and 3.0% causes displacement on the phase transformation curves [13]. Additions of 1 to 2-wt% of nickel or copper are effective in increasing the hardened layer [14]. Moreover, the presence of chromium and molybdenum improve the mechanical strength of the parts in the case of products with simple, such as cylinder liners, piston rings, among other sections, due to the formation of chromium carbides and molybdenum [15].

Table 1. The chemical composition of the grey cast iron in weight percent.

Element	C	Si	Mn	Cu	Cr	S	Ni	P	Mo
Grey cast iron [wt%]	3.87	2.72	0.39	0.281	0.2	0.15	0.097	0.074	0.025

The sample studied has a pearlite matrix with steatite (ternary eutectic cementite, iron phosphide, and ferrite), see Figure 1(a). These morphological characteristics could provide rapid austenitic, which is beneficial in the thermal hardening treatment [16]. Conventional quenching was performed and the micrograph shown in Figure 1(b) was obtained, which reveals a typical microstructure of a typical hypereutectic grey cast iron, mainly composed of martensitic (fine needle-like structure) together with a small amount of retained austenite (white shade) and undissolved flake graphite [17]. This shown that it is possible to make a suitable quench procedure of the material, giving a final hardness of 54 HRC, exceeding the initial hardness of the sample (23 HRC). Finally, it can be inferred that hardening heat treatment is technically feasible to obtain engine cylinder liners with improved mechanical strength.

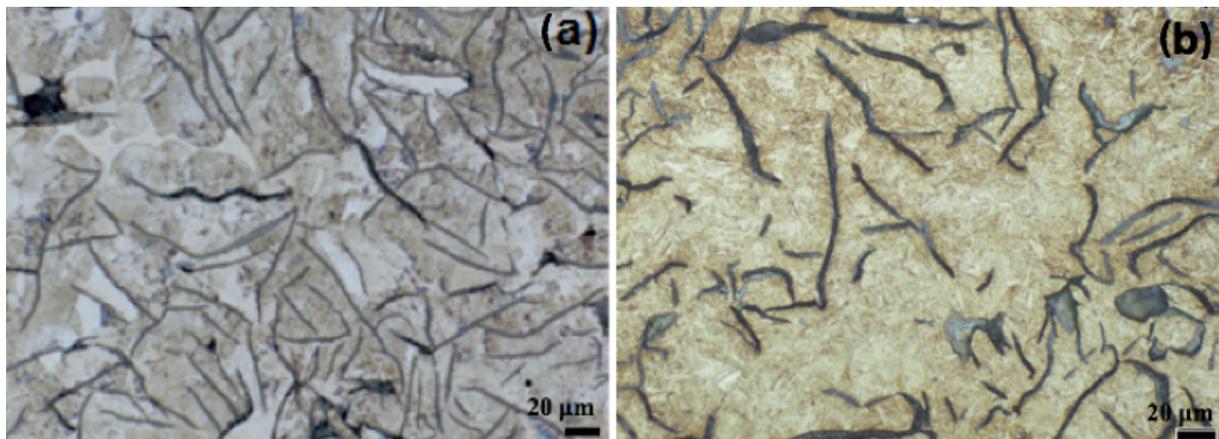


Figure 1. Optical micrographs of the grey cast iron with a chemical etching (2% nital solution) to 500X. Before quenching, (a), and after treatment, (b).

3.2. Modelling and simulation of induction heating for a grey cast iron

Initially, equations that model the magnetic induction process and Eddy current generation by Maxwell's equations and Ohm's law for the electric field were determined [9] to prepare the model in COMSOL Multiphysics. Using sinusoidal harmonic excitations, Ampere's Law and conductive and capacitive effects of the material where currents are induced, the following expression is obtained:

$$j\omega\sigma^* \vec{A} + \vec{\nabla} \times (\mu^{-1} \vec{B}) = \vec{J}_e \quad (2)$$

Where \vec{A} is the vector potential; $\vec{B} = \nabla \times \vec{A}$, magnetic field; \vec{J}_e , current density produced by external sources; ω , frequency of the harmonic excitation; $\sigma^* = \sigma + j\omega\epsilon$, complex electrical conductivity of the material and μ , magnetic permeability of the material [18]. Boundary conditions are determinate by hybrid conditions, which Neumann ($\vec{J}_{surface} = \mu^{-1} \hat{n} \times \vec{B}$) and Dirichlet ($\hat{n} \times \vec{A} = 0$) boundary conditions are combined. Furthermore, heat transfer is determinate by the first law of thermodynamics, which study case can be written as follows [19]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (3)$$

Where T is temperature; \vec{u} , velocity vector; Q , heat produced by heat sources different to viscous sources; ρ , density; C_p , heat capacity at constant pressure and k , thermal conductivity of the material. Boundary conditions of heat transfer correspond to the thermal insulation on the boundary [$-\hat{n} \cdot (-k \nabla T) = 0$] and heat conduction conditions between the materials [11]. Electromagnetic and thermodynamic equations are coupled via electromagnetic power equation associated with Eddy currents induced in the material, which corresponds to a heat source as follows:

$$Q = \sigma \omega |\vec{A}|^2 \quad (4)$$

Figure 2(a) shown a cross section of engine cylinder liner and parametric mesh multiform implemented for calculations and Figure 2(b) shows the temperature as a function of radial position for different time (in seconds). In 3s a maximum temperature of 800°C is obtained, which decays with increasing distance from the centre. This result is consistent with the expected temperatures for phase transformation required for induction hardening in LAVCO cylinders.

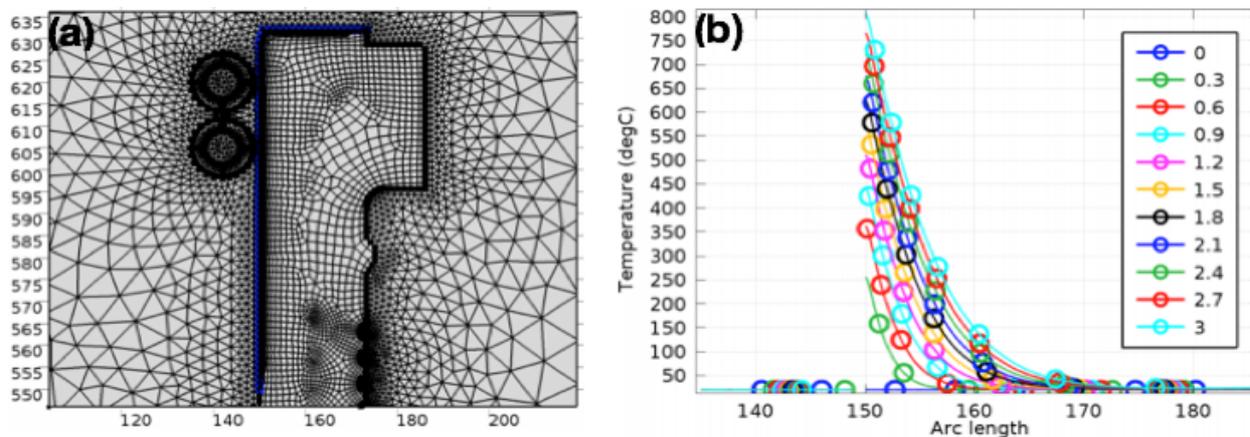


Figure 2. Cross section of LAVCO engine cylinder liner and meshing for the model, (a), and temperature distribution for different radial positions (abscissas, in millimetres), (b).

3.3. Heating of grey cast iron

For that, the full-bridge inverter works keeping load oscillation, it must produce commutations in synchronism with the oscillation, i.e., its switching frequency can be the same to the natural frequency of the load [20]. Preliminary assessments were performed with the local prototype. However, in this work only could make an evaluation of heating using a maximum current of 25A and a working frequency of 30kHz, due to the inconvenience of switching transistors used in the inverter circuit. Temperature profile obtained under these conditions in the simulation is presented in Figure 3. It can be seen that a maximum temperature of 93.8°C is reached on the surface of the specimen. Moreover, when the specimen under the same conditions model was heated, a surface temperature of 83°C was

obtained, which corresponds to 10.8°C less than the value expressed in the simulation. The overall efficiency of these systems is about 94% (near the resonance). The losses in the rectification stage can be assumed as 1% of the total efficiency. While remaining 5% may be related to inverter stage [21]. In our case, losses can be associated with an additional 5% to slight gap between the square voltage signal and the sinusoidal signal of the current, which did not allow the RLC load operated in the resonance frequency, consequently, less energy transfer was achieved. Despite this, the experimental results are very close to the values obtained from the physical model. For this reason, it is advisable to improve the prototype system of induction heating and deepen aspects concerning the type of piece, induction coil and operating conditions in the computational tool to have control and quality assurance in induction hardening of engine cylinder liners or any other piece.

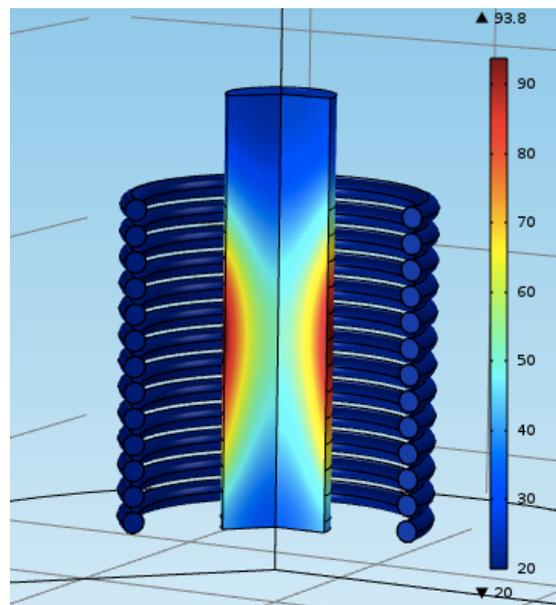


Figure 3. Temperature profile obtained in the cylindrical specimen.

4. Conclusions

Small amounts of alloying elements such as Cr, Ni, Mo and Mn in the cast iron have a positive influence on the hardenability. Additionally, the grey cast iron has a matrix of fine pearlite with steatite and graphite flakes with size, shape, and fair distribution, which allows a rapid austenitic.

The simulation study reveals that by employing moderate currents (90 and 500 A) at high frequencies (300 to 1000 kHz), the critical temperature profiles thinner but less uniform are obtained. However, to achieve a minimum power consumption, it was found that a minimum frequency of 150 kHz operation is necessary. The experimental results obtained in the specimen of 25.4mm (diameter) at low temperature, showed great similarity with the simulation.

The possibility of surficial hardening on these materials controlling the operating parameters, minimizing energy consumption and ensuring effective hardening depth, allow adding value to the quality of parts that require more precise specifications surface hardness. The deepening of this type of research will allow real solutions to the metalworking companies that are interested in improving the quality of their products.

Acknowledgments

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