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Effects of induction heating process parameters on hardness profile of 4340 steel bearing shoulder using 2D axisymmetric model

Habib Hammi, Noureddine Barka, Abderrazak El Ouafi,
Mathematics, Computer and Engineering Department, University of Quebec at Rimouski,
Rimouski, Quebec, Canada

Abstract— The main of this work is to study the effects of machine parameters (Heating system) on 4340 bearing seating shoulder heated by induction process. This process is able to produce uniform hardness profile with compressive residual stresses favorable to prevent fatigue contact failure. This paper presents, first, 2D axisymmetric model developed by multi-physics commercial software. This model is used to analyze quantitatively the effects of machine parameters such as imposed current density, heating time, frequency, and some dimensional factors related to the part dimensions. The simulation results are advantageously exploited to quantify the effects of the parameters and the interactions between them. Finally, a sensitivity study is done to predict the temperatures and to create a model to follow. The obtained results are very beneficial to develop other geometries with the same approach.

Index Terms—**induction, bearing, shoulder, hardness profile, residual stresses, fatigue, model, current density, heating time, frequency, sensitivity study.**

List of symbols:

E = Electric field intensity.
D = Electric flux density.
H = Magnetic field intensity.
B = Magnetic flux density.
J = Conduction current density.
ρ^{cha} = Electric charge density.
∇U = gra, $\nabla \cdot U$ = diand $\nabla \times U$ = cu.
T = Temperature.
= Density of the metal.
c = Specific heat.
k = Thermal conductivity of the metal.
Q = Heat source density induced by eddy currents per unit time in a unit volume.
= Density.
= Specific heat capacity.
ANOVA = Analysis of variance.
FEM = Finite Element Method.
= x-axis gap between the coil and the bearing (mm).
= y-axis gap between the coil and the bearing (mm).
= Heating time.
= Imposed current density.

I. INTRODUCTION

The bearing seating is a part that is used to allow motion transfer between shaft and housing in a mechanical composition. To maintain a good life performance of the bearing, it is required to apply induction heating with extremely accurate parameters. When applied correctly, induction heating could improve wear resistance and enhance contact fatigue life. This treatment creates a very hard surface layer on steels by converting an as-cast ferrite and pearlite microstructure into hard martensitic phase.

Until now, it is still very difficult to understand entire effects of the process parameters on the temperature and on hardness profile. In fact, it is very complex to establish the relationship between temperature profile and machine parameters such as geometrical dimensions (mm), heating time (s) and the density of the initial current in the coil (A · m) [1], [2], [3]. Adding to that, there is no study that shows if one parameter affects the results more or less than another. This type of study, called sensitivity study, based on analysis of variance (ANOVA), is a collection of statistical tools that analyses the difference between parameters effects. The ANOVA study gives path to understanding the effect size of each multi-physical parameter, and also, to reducing errors and time loses on calculations.

During 1831, English scientist Michael Faraday discovered that a current can be produced in a part by exposing it to a dynamic electromagnetic field. He then established the Faraday induction law [7]. Some years later, exactly in 1851, French scientist Leon Foucault discovered induced currents, and called them Foucault Currents. And during 1878, he proved that those currents are responsible for heating parts by Joule Effects. This discovery lead to the start of the induction heating industry and made researchers studies this field very closely. Calculation of the temperature distribution after induction heating process was done by Baker in 1958. Dodd and Deeds did the same study on an infinite cylinder in 1967. But, in 1974, Donea was the first to use FEM (Finite Element Method) and 2D axisymmetric model to calculate the magnetic vector intensity during induction heating process. Davis and Simpson were the first to evaluate temperature profile versus machine parameters for several mechanical components in 1974. So, they calculated the effects of machine power and heating duration over temperature profile. In recent years, a number of investigations have been put forward dealing with modeling and simulation of fatigue behaviour of different components coupled to the used process parameters for induction hardening.

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In 2001, Kristoffersen and Vomacka showed in their investigation that the process parameters of induction hardening influence the residual stress-state of hardened parts to a great extent. They varied the process parameters of induction hardening to give a constant hardness penetration depth. In 2011, Barka presented a sensitivity study using a Comsol 3D model simulation for spur gear heated by induction process. The developed model is exploited to study the sensitivity of the final temperatures to the variation of simulation parameters and some geometrical factors. And finally, the sensitivity of hardness profile with the machine parameters variation is investigated using various statistical tools applied to the obtained results.

It is very important to study the effect of each parameter of the heating process and to find a relation between them. This leads to a better understand of the multi-physical environment of the simulation and of the whole process, knowing the degree of importance of each parameter and its thumbnail on the results. So after that, we could conclude which parameter is good to be changed and which one doesn't affect the results. The degree of importance, or so called effect size leads us to better sharpen the parameters and to create the best environment to have the desirable results [6].

In this work, a 2D-axisymetric model of a 4340 steel bearing seating was designed. Using COMSOL multi-physics, as the best multi-physic software, induction heating process was applied to the shoulder. In the first place, the parameters were chosen to have martensitic temperature as a result. To have good results, flux concentrators were added, they are two pieces that anneal the edge effect of the induced currents [8]. This assured the transformation and the creation of the hardened martensitic layer. In the second place, the simulation was repeated changing each parameter apart to understand the effect of each parameter on the temperature and hardness profile. Finally, multi-changing parametric study was done. This study consists of changing all the parameters in the same time and analyzing the results versus parameters matrix. A prediction model is proposed from the results of the sensitivity results. The predicted results and the simulated ones are then compared to see if the prediction is precise or not. This gave a prediction model to exploit during the future works.

II. SIMULATION MODEL AND FORMULATIONS

The model is composed, of a 25 mm diameter bearing seating shoulder with major diameter of 33 mm and minor diameter of 25 mm. The part is enrolled with a 26.7 mm coil (Fig. 1). The materials in which are made the piece and the coil are respectively 4340 steel and copper.

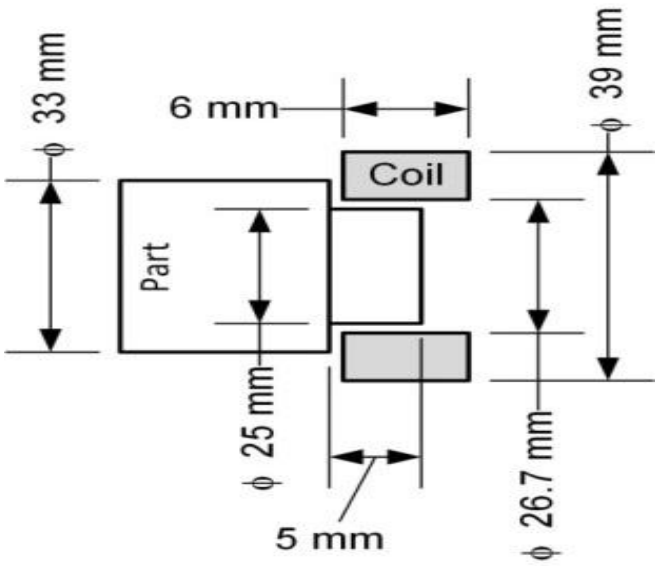

Fig. 1. Bearing seating and coil dimensions

A. Mathematical modeling of the electromagnetic field

To calculate electromagnetic field, it is imperative to be able to solve Maxwell's equations, for general time-varying electromagnetic fields. Maxwell's equation in differential form can be written as.

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (1)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (2)$$

$$\nabla \cdot B = 0 \quad (3)$$

$$\nabla \cdot D = \rho^{charge} \quad (4)$$

Where E is electric field intensity, D is electric flux density, H is magnetic field intensity, B is magnetic flux density, J is conduction current density, and ρ^{char} is electric charge density. Special symbols like and ∇ are popular in vector algebra and are useful to shorten an expression of particular differential operation without having to carry out the details, $\nabla U = grad$, $\nabla \cdot U = di$ and $\nabla \times U = cur$.

B. Mathematical modeling of the thermal processes

In this part, we used the Fourier equation as it is written in this form.

$$c\gamma \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = \dot{Q} \quad (5)$$

Where T is temperature, is the density of the metal, c is the specific heat, k is the thermal conductivity of the metal and Q is the heat source density induced by eddy currents per unit time in a unit volume. So the system to be solved is given by:

$$j\omega\sigma(T)A + \nabla \times (\mu^{-1}\nabla \times A) = 0 \quad (6)$$

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$$\rho C_p \frac{\partial T}{\partial t} - \nabla . k \nabla T = Q(T, A) \qquad (7)$$

Where is the density, is the specific heat capacity.

C. Space discretization (Mesh calculation)

This work is done using the finite element method to obtain an approximate solution for the calculation of the equations. Space discretization is a very important aspect of FEM analysis [4]. FEM discretization, also called mesh generation (Fig.2) was done in COMSOL and a convergence study was held to find the best mesh size that gives the most suitable results (Fig. 3).

D. Convergence study

Convergence study was done in the simulation to find the mesh size that suits the most and gives the best results. When drawing the temperature versus mesh size plot, it starts by being horizontally stable and constant and after that increases starting from a mesh size bigger than 0.5 mm. This 0.5 mm represents the mesh size used in the simulation. The chosen mesh size gives insurance about the exactitude of the results. As the mesh is refined, the FEM solution should approach the analytical solution of the mathematical model. This attribute is obviously necessary to instill confidence in FEM results from the standpoint of mathematics.

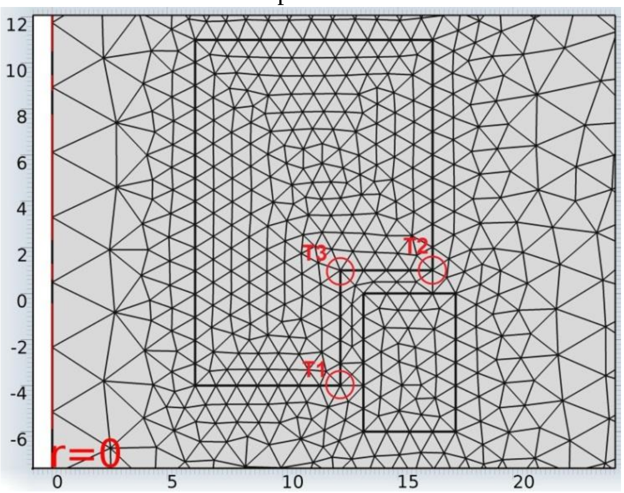

Fig. 2. Space discretization (mesh) in COMSOL

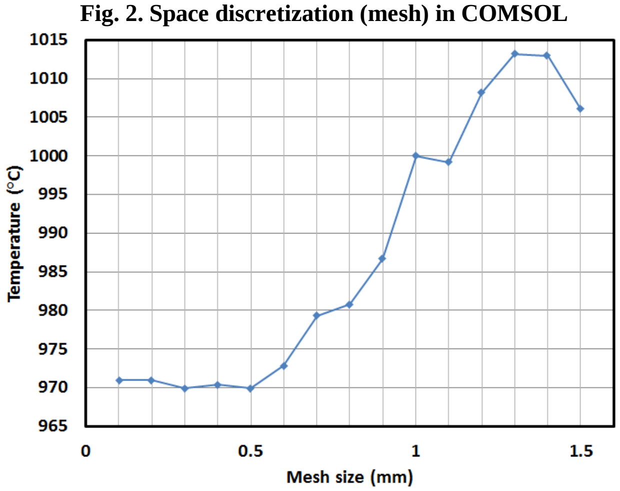

Fig. 3. T versus mesh size

E. Coupling of electromagnetic and thermal problem (Two-step approach)

One of the major features of induction heating computation deals with the fact that both the electromagnetic and heat transfer phenomena are tightly coupled thanks to the interrelated nature of the material properties. First, specific heat, thermal conductivity, and electric resistivity are functions of the temperature. On the second hand, magnetic permeability is a function of magnetic field intensity, temperature, and frequency.

F. Primary results

After establishing the most suitable mesh size for the simulation, and after designing the work piece and the coil, simulation was done, or it should be called a primary simulation. It is called primary, because it doesn't give the wanted results. The results are shown in Fig. 4. The temperature profile is not uniform and the distribution isn't equal along the edges. One of the best ways to make a uniform temperature profile is to use the flux concentrator. Those pieces are made in the same 4340 steel to have the same material properties as the work piece. When the flux concentrators are used, they created uniformity, annealing the edge effects, as if the shoulder has bigger dimensions. This can be seen in Fig. 5. It is saw that the heat spread all over the bearing edges.

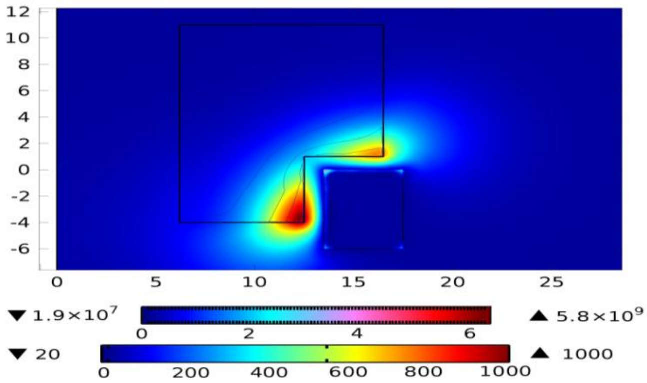

Fig. 4. Temperature distribution (°C) [0,1000] and total induced current (A · m) [1.9x10^7 ,5.8x10^9] without flux concentrators.

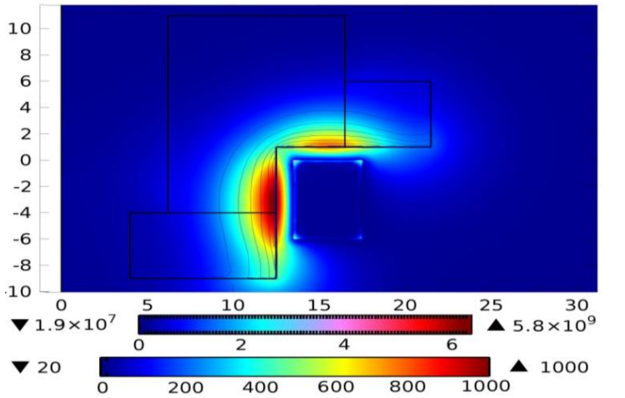

Fig. 5. Temperature distribution (°C) [0,1000] and total induced current (A · m) [1.9x10^7 ,5.8x10^9] using flux concentrators.

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III. PARAMETRIC EFFECTS

In this part, a parametric study was done to understand the effect size of each parameter on the temperature and hardness profile. The gap between the work piece and the coil was changed along x-axis and y-axis. The variation was done between 0.5, 1, and 1.5 mm. After that, the heat duration, was changed from 0.4 to 0.6 s with a 0.1 s step. And finally, was varied with ± 5%. The two temperatures are determined at two locations as showed in Fig. 2. These temperatures (T1 and T2) allow the characterization of the heated profile. The study of T3 was avoided due to the weakness of the heat in the corner. That gave very low temperature and so little variations.

A. *Effect of x-axis gap (Gx)*

The change of the position along x-axis affected the temperatures of the 2 points, specially the T1. It is seen from the curve that when the gap went from 0.5 mm to 1 mm, the temperature decreased with about 765 °C and when the gap changed from 1 mm to 1.5 mm, the temperature of T1 varied by nearly 328 °C. This difference is due to the fact that the farer the coil is from the work piece; the less heated the piece is. T2 didn't change nearly not at all comparing to T1 because of the absence of the x-axis abscise effect. The best conclusion is that any change in the coil position over the x-axis affects T1 the most. A variation of about ± 50% in x-axis gap, gives nearly ± 50% change in T1, the same variation generates approximately ± 5% variation in T2 (Fig. 6).

B. *Effect of y-axis gap (Gy)*

Due to its geometrical disposition, the effect of changes over y-axis affected the T2 the most. It is understood from the curve (Fig. 7) that the temperature decreased of about 523 °C when the gap went from 0.5 to 1 mm and of about 285 °C when the gap went from 1 to 1.5 mm. T1 didn't change nearly not at all comparing to T2 because of the absence of the y-axis abscise effect. A variation of about ± 50% in y-axis gap, gives nearly ± 0.2% change in T1, the same variation generates approximately ± 50% variation in T2 (Fig. 7). It is obvious that the effects of x-axis gap and y-axis gap variations on T1 and T2 respectively are inversed.

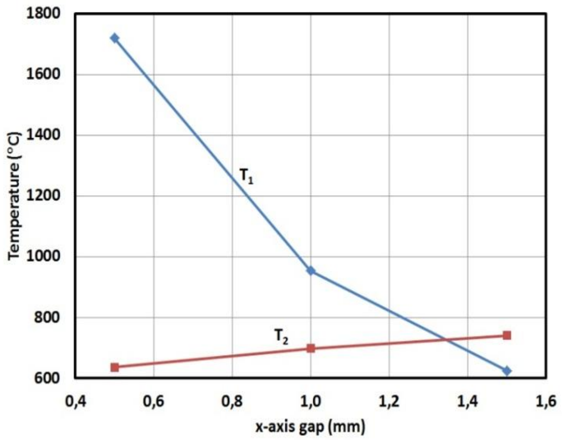

Fig. 6. T1 and T2, versus x-axis gap.

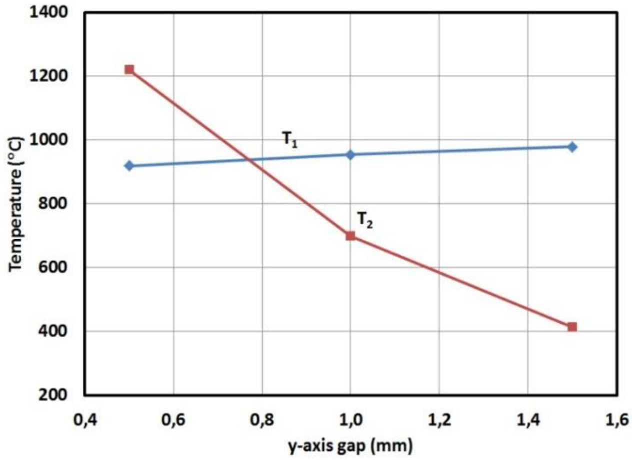

Fig. 7. T1 and T2 versus y-axis gap.

C. *Effect of heating time ( )*

The variation affected T1 and T2 nearly equally, because is a parameter that affects all the simulation and all the process. It is a parameter that is present in the time-dependent solver. The increase in gave nearly a constant change in the temperature, 0.1 s increase for gave nearly 90 °C increase in T1, and nearly 60 °C increase in T2. A variation of about ± 20% in , gives nearly ± 10% change in T1, the same variation generates approximately ± 9% variation in T2 (Fig. 8).

D. *Effect of imposed current density ( )*

Changes in affected equally T1 and T2. An increase of 5% in from -5% to gives increases of 72°C in T1 and 62 °C in T2. Nearly the same numbers of degrees °C were increased during the change from to +5%. has a linear effect. A variation of about ± 5% in , gives nearly ± 10% change in T1, the same variation generates approximately ± 9% variation in T2 (Fig.9).

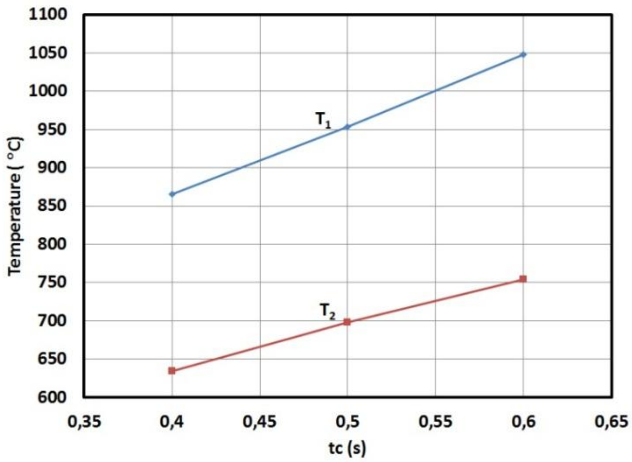

Fig. 8. T1 and T2 versus .

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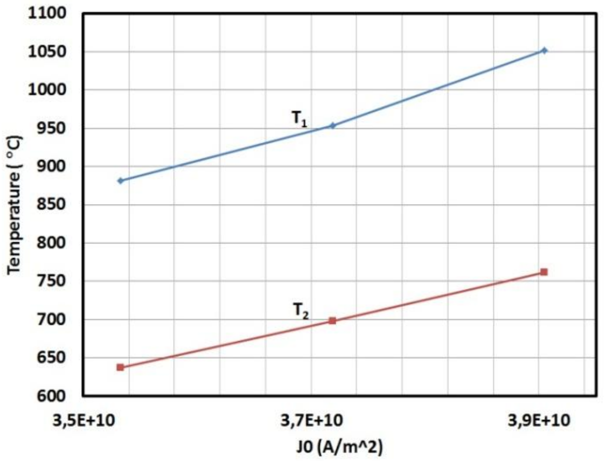

Fig. 9. T1 and T2 versus

The parameters for the sensitivity study are concluded from the parametric study. From Fig. 7, it is seen that T1 is closer to 1000 °C at around an x-axis gap equal to 0.95 mm and from Fig. 8, it is seen that T2 is closer to 1000 °C at around a y-axis gap equal to 0.75 mm. To better visualize the variations, see table I. The parameters are organized in 3 levels and are shown in table II.

Table I. Recapitulative table about temperatures variations versus factors variations

Factor	T1 variation	T2 variation
Gx (± 0.1mm)	± 50%	± 5%
Gy (± 0.1mm)	± 0.2%	± 50%
(± 0.1s)	± 10%	± 9%
(± 5%)	± 10%	± 9%

Where Gx, Gy, , and are respectively equal to x-axis gap, y-axis gap, , and .

Table II. Scratching parameters and their levels for the sensitivity study

Factors	Level 1	Level 2	Level 3
Gx (mm)	0.85	0.95	1.05
Gy (mm)	0.65	0.75	0.85
(s)	0.4	0.5	0.6
($\cdot 10^{10}$ A · m)	3.53	3.72	3.90

IV. SENSITIVITY STUDY

In this part, all the 4 parameters are changed simultaneously around the 3 scratching levels of table II to obtain an alternation, or a matrix of results [9]. From which, only one result is best suitable to create a uniform good martensitic heat profile. The parameters that are changed are, as said before, x-axis gap, y-axis gap, , and . This gave a simulation of $3^4 =$ combinations. The sensitivity study is performed by varying the parameters around the nominal level 2 set of values (Table II) (x-axis gap = 0.95 mm, y-axis gap = 0.75 mm, = 0.5 s, = $3.72 \cdot 10^{10}$ A · m). The variation is equal to ± 0.1 mm on x-axis gap and y-axis gap, ± 0.1 s on , and ± 5% on value. The simulation results were statistically analyzed using ANOVA study. This study was done to determine the percent contribution and the effect of each parameter over the temperature profile (Table III). Average affects graphs presented in Fig. 10, Fig. 11, and Fig. 12 shows that temperatures are affected by all the four parameters, but with different contributions, the 3 scratching levels are in X axis and temperature is in Y axis.

Table III. Percent contribution of each parameter variation over the temperatures

	X-axis gap (%)	Y-axis gap (%)	(%)	(%)	Error (%)
T	32	0	37	28	3
T	0	44	27	28	1
T	15	17	48	20	0

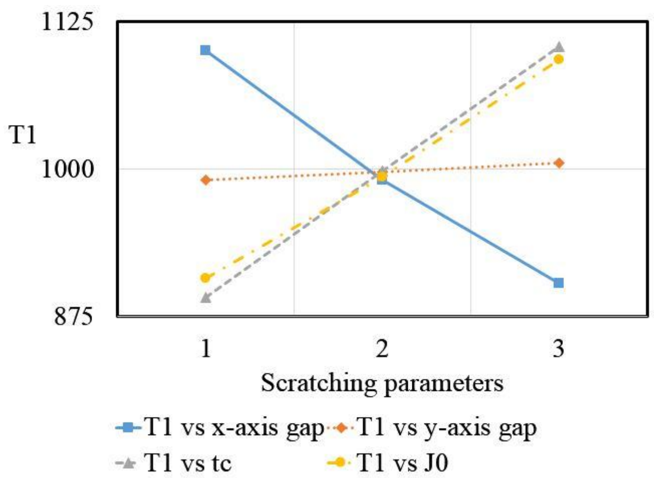

Fig. 10. Main effects of x-axis gap, y-axis gap, , and on T1(°C).

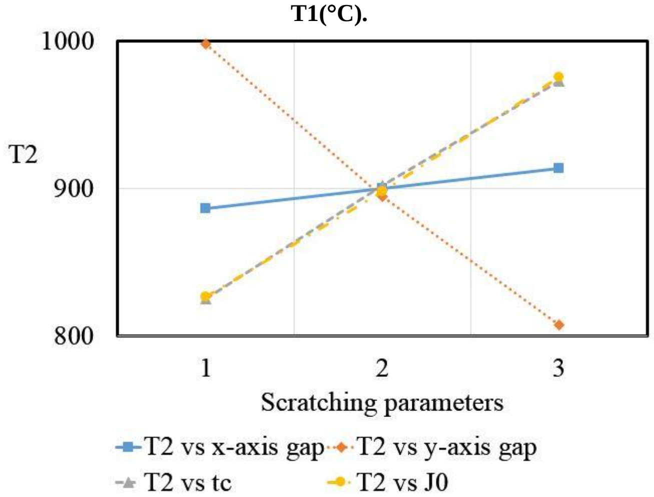

Fig. 11. Main effects of x-axis gap, y-axis gap, and on T2(°C).

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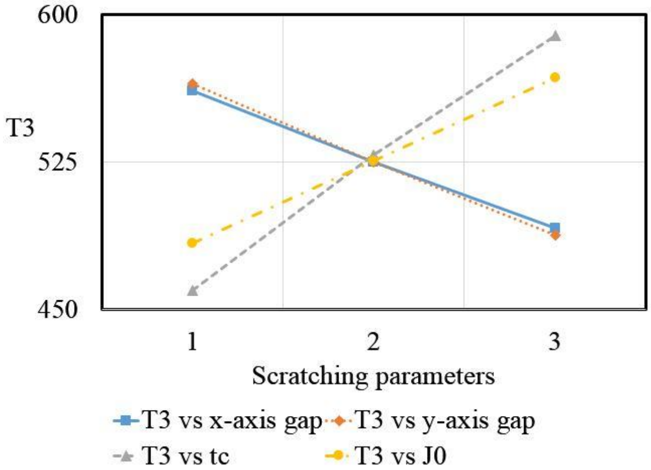

Fig. 12. Main effects of x-axis gap, y-axis gap, , and on T3(°C).

The effect of x-axis gap and y-axis gap respectively on T2 and T1 is non-existent (0%). The x-axis gap affects T1 the most after that T3 (32% and 15%). The y-axis gap affects T2 and then T3 (44% and 17%). The effect of is greater than the effect of over the T1 and T3, 37 % > 28 % and 48 % > 20 %. The effects of x-axis gap and y-axis gap on T3 are nearly equal, 15 % compared to 17 %. Induced current density and heating duration have both nearly linear effects on all the three temperatures, this is represented in gray interrupted line and yellow semi-interrupted line in Fig.10, Fig.11, and Fig.12. With the increase of x-axis gap and y-axis gap, T1, T2, and T3 decrease. This is due to proximity effects and to the decrease in the electromagnetic field intensity. The small values of T3 are due to the fact that the point 3 is farer form the inductor compared with the point 1 and point 2. Due to this geometrical constraint, the point 3 will always receive less beamed power and thus less induced current density. The little size effect of over T2 can be explained by the fact that the coil is so close to the bearing along y-axis gap causing that the majority of the effect was manipulated by y-axis gap (44%).

A. Linear regression study and prediction model

In this study, data are implemented and used to find out the equations that best describe the relation between responses and parameters. The exactitude of the results is listed in Table IV. The prediction model established using a statistical software called Minitab gives equations that link T1, T2, and T3 from one side and x-axis gap, y-axis gap, ,and from another side. All the 3 equations are listed below. The equations are implemented using the temperature data to plot the temperature profiles and compare them to the simulated temperature profiles. To better understand the exactitude of the results, residual and delta formulas were calculated using T1, T2, and T3. The simulation results are nearly similar to the predicted results. After that, the predicted temperature is compared to the simulated temperature. This gave a tendency line that has a slope nearly equal to 1.

From Table IV, it is seen that the predicted model is very accurate since all the predicted values of are greater than 96%.

Table IV. Summary of the model performances

	Standard deviation (s)	(Predicted) (%)
T_1	26.5919	96.25
T_2	16.8883	97.75
T_3	5.89725	99.35

The final equations that give the expression of each temperature versus machine parameters are represented below.

It's important to mention that those equations are written and used without units because they link different physical entities that do not have the same units in the SI.

$$T_1 = -503.37 - 987499 \cdot G_x + 70125.4 \cdot G_y + \quad (8)$$

$$T_2 = -376.32 + 133563 \cdot G_x - 953452 \cdot G_y + \quad (9)$$

$$T_3 = -18.61 - 351583 \cdot G_x - 385602 \cdot G_y + 6\cdot \quad (10)$$

Where Gx, Gy, , and are respectively equal to x-axis gap, y-axis gap, ,and .

The third point has a predicted temperature that is nearly equal to the simulated one because of the little temperature variation in the corner due to the geometrical concerns. The coordinates of red points are simulated temperature in the X axis and predicted temperature in the Y axis. The blue line represents the tendency of the cloud of points. This tendency is represented by the lines which have slopes equal to 0.968, 0.981, and 0.994 for , , and , which are nearly equal to 1 (11), (12), and (13). The predicted temperatures and the simulated ones are close enough to say that this model is good to predict behavior and temperature. Especially around 1000 C, there is a very low error rate equal to some degrees (≤ 21).

The temperatures and are around 1000 thanks to the flux concentrators and edge effects. The variation is less than 4%. Shows lower values comparing to the 2 others temperatures because the point is farer from the coil due to the geometrical issue.

$$T_{1_{Predicted}} = 32.3 + 0.968\ T_{1_{Simulated}} \quad (11)$$

$$T_{2_{Predicted}} = 17.4 + 0.981\ T_{2_{Simulated}} \quad (12)$$

$$T_{3_{Predicted}} = 2.94 + 0.994\ T_{3_{Simulated}} \quad (13)$$

From Fig. 13, the predicted temperature T1 is equal to the simulated one around 900 °C to 1000 °C. For temperatures lower than 750 °C or greater than 1300 °C, the precision is lower and equality is lost. From Fig. 14, the predicted temperature T2 is equal to the simulated one around 800 °C to 1000 °C. For temperatures lower than 800 °C or greater than 1100 °C, the precision is lower and equality is lost. From Fig. 15, the predicted temperature T3 is equal to the simulated one from 425 °C to 650 °C. For temperatures lower than 400 °C or greater than 700 °C, the precision is lower and equality is lost.

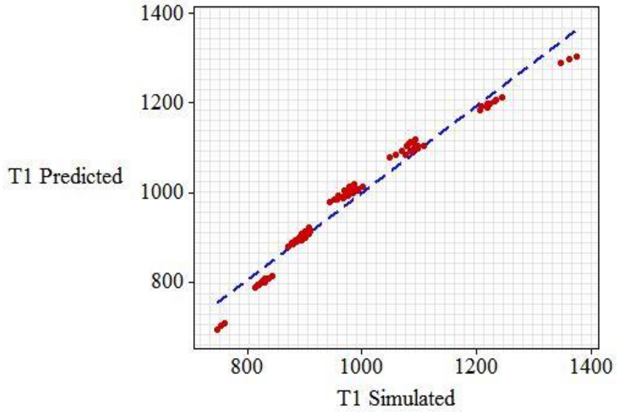

Fig. 13. Predicted(°C) vs simulated(°C).

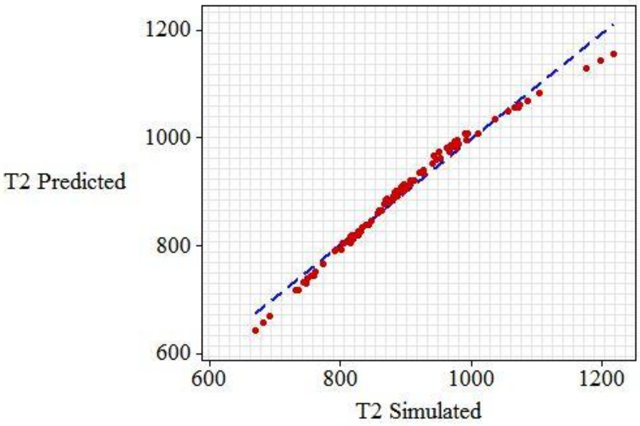

Fig. 14. Predicted(°C) vs simulated(°C).

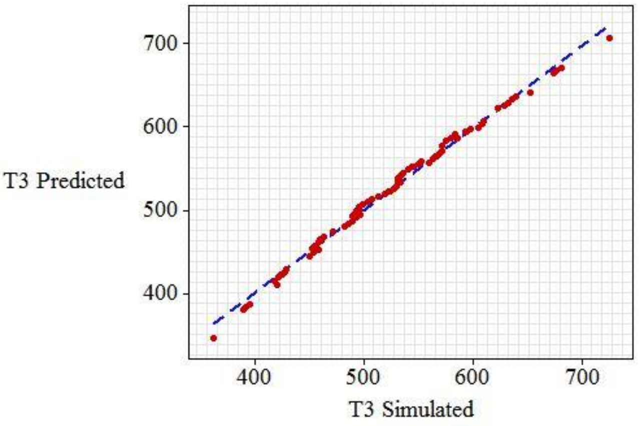

Fig. 15. Predicted(°C) vs simulated(°C).

V. CONCLUSION

In this work, a 2D axisymmetric model of an AISI 4340 alloy steel bearing seating was developed to study the parametric and sensitivity effect of machine parameters. A linear regression study was done to predict the behavior. The prediction showed that the predicted model and the simulated model have the same behavior. Those prediction models are used to predict the physical behavior. The results will be exploited in future researches. Bearing seating is a comparatively simple piece comparing to gears and splines, this gives some openings to future researches and works. The same approach could be used to predict temperature profile and hardness profile of other mechanical components.

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AUTHOR BIOGRAPHY

Habib Hammi is a research student at University of Quebec in Rimouski UQAR in Quebec in Canada. The main field of his research is the induction heating process applied to simple and geometrically complex mechanical components. He is also working to determine the effects of the induction heating parameters on hardness profiles for shoulders, gears and splines.

Barka, Noureddine is a professor in University of Quebec in Rimouski. His fields of research are induction heating and hardening, electromecanic system design and laser processes. He obtained his bachelor degree in 2001 from UQAR, his master degree in 2005

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from UQAR and his doctor degree in 2011 from ETS, Ecole de technologiesuperieure.

El OuafiAbderrazak is a professor in University of Quebec in Rimouski UQAR. He is the head of the master committee in UQAR, also member of the CRSNG-UQAR and the research laboratory LRP. His fields of research are computer assisted fabrication, precision engineering, mechanical fabrication and robotics. His is graduated from University of Laval as a Philosophiae Doctor in mechanical engineering.