Time of Crossing in Pulsed Eddy Current Signals

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Abstract. Signals picked up from pulsed eddy current systems used to evaluate aluminium specimen exhibit interesting trends among which are points of intersection in the time-voltage curves. This study investigated the relationship between these picked up signal trends observed in the presence of a specimen to those observed in its absence to establish if they could be used to gauge small (µm) differences in thickness around a nominal thickness in thin aluminium sheets. Six aluminium specimen sheets, all at a temperature of 30 °C, and with thicknesses varied between 0.5 mm and 3 mm in steps of 0.5 mm, were used in the study. The locus of the signal picked up in the presence of a specimen always reached steady state conditions at a later time than that of the signal picked up in the absence of a specimen resulting in a time of crossing observed for each specimen thickness. This TOC was used to establish a relationship between time and the specimen thickness. The established relationship could be used to gauge differences in thickness around a nominal thickness in thin aluminium sheets.

1. Introduction

Pulsed eddy currents (PEC) have been considered for non-destructive evaluation of various materials as far back as the 1950s [1]. Since pulsed waves are made up of a continuum of sinusoidal waves of various frequencies, they contain information that can only be acquired by the use of many sinusoidal scans of conventional eddy currents (CEC) [2]. Circulating (eddy) currents are generated in bulk materials that are in close proximity with time varying magnetic fields as postulated in Maxwell's equations. These fields, when generated as a result of a controlled electric current flowing through a coil (drive-coil) of known dimensions, can generate predictable eddy currents within an aluminium bulk material of known thickness. The effect of the generate eddy currents picked up by another coil (pick-up coil) results in a current signal within the pick-up coil that depicts the bulk characteristics of the aluminium specimen. It is this locus of the pick-up coil signal that is observed and investigated in this study.

Crossing points have been observed in picked up pulse eddy current signals by various researchers. One search example is the lift off point of intersection (LOI). The term "lift-off" refers to the distance between the coil probe and the evaluated specimen. Figure 1 gives an example of LOI first observed by Waidelich and Haung [3]. In their investigations, they concluded that at a specific time, during a cycle of the pickup signal, there will be found a crossing point for any parameter in the system, such as lift-off, thickness of the specimen, conductivity of the specimen and permeability of the specimen. The LOI in figure 1 was obtained by carrying out experiments with all other parameters held constant while the distance between the probe and the specimen were varied in steps of 1 mm [4]. This point of intersection points to the fact that at the time of its happening, the effect of lift off is effectively eliminated. By time gating and collecting information on thickness, Giguere et el [5], effectively used LOI to characterise material loss. LOI has also been used, to map out corrosion in a specimen [6], to detect cracks under material fasteners [7] and to quantify defects and mark defect locations in multi-layered specimen [8].

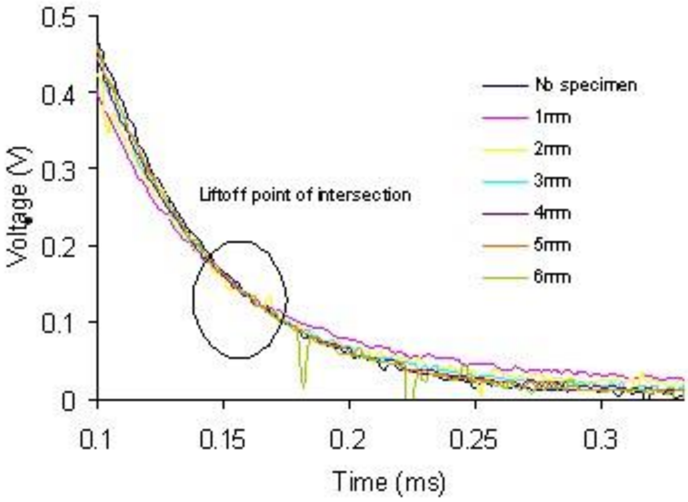

Figure 1. Lift-off point of intersection obtained with data collected with lift-off varied in steps of 1 mm.

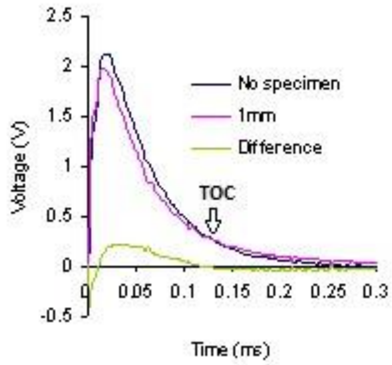

Figure 2. Pick-up coil signal.

Figure 2 shows the crossing point between the signal received in the absence of a specimen and that received in its presence now referred to as the TOC. The exponential nature of the discharge locus of the pickup coil signals in figure 2, suggests a difference in time constant in the decaying pick up coil voltage signals received in the absence of the specimen and that received in its presence. The PEC system can be modelled as an electric circuit model and this was developed in the Matlab and Simulink environment [4]. The system is an interaction between three subsystems: the drive coil, the pickup coil and the specimen. The system is represented by a set of energy storage parameters that were lumped together and reduced to a single resistance in series with an inductor for each of the sub systems. The lumped parameters R_s and L_s for a specimen with a thickness, y are expressed as [4]*:*

$$R_s = \frac{\rho_{s1} l_{ed}}{\delta(t)\left(\dfrac{1}{\exp\left(-y/\delta(t)\right)} - 1\right) r_0 \ln\dfrac{r_2}{r_1}} \tag{1}$$

$$L_s = \frac{\mu_s \pi r_1^2}{2\left(\delta(t)\left(\exp\left(y/\delta(t)\right) - 1\right) + r_o \ln\dfrac{r_2}{r_1}\right)} \tag{2}$$

Since the presence of the signal changes the locus of the pickup coil signal, a closer look at the expressions stipulated to represent the specimen electrical properties, shows that the resistance and inductance of the specimen change with a change in the thickness, y, of the specimen but at the same time they are affected by the skin depth, δ (t), which is a function of time (t) [4]. This means that the time constant, τ of the decaying locus changes with time. Also the loci in figure 2 suggest the signal received in the absence of the specimen has a shorter time constant compared to that received in the presence of the 1 mm-thick specimen. The two signals will therefore always have a crossing point at a time referred to as the time of crossing (TOC). In this study, the TOC for different specimen thicknesses were investigated experimentally and by simulation, to establish whether small differences, to the order of microns, in thicknesses of a specimen can be determined from a Time-Thickness characteristic.

2. Experimental procedure

Figure 3 shows the experimental set up used in the study. A Sampo 1617 function generator, with an internal resistance of 50 Ω, was connected through a signal conditioning circuit to the eddy current reflection probe. The probe was placed on the tested specimen and the voltage signal across the pickup circuit was collected using a PC30FA, 11 channel data collection card, with an input range of -5 to +5 volts and an input impedance of 500 MΩ and data were stored on a desk top computer.

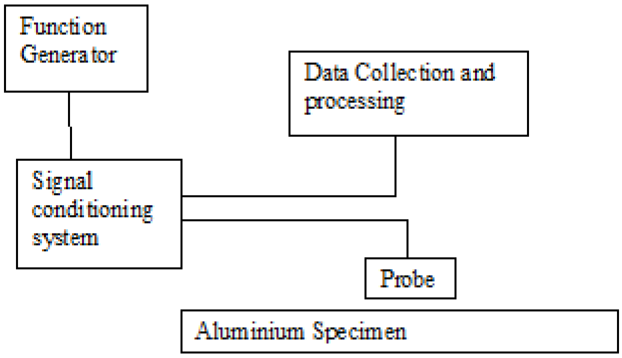

Figure 3. Block diagram of experimental set up.

In order to analyse the data presented for the time of crossing at 30°C, pick-up coil signals were collected for aluminium specimens of different thicknesses that varied from 0.5 to 3 mm in steps of 0.5 mm. Figure 2 is an example of the pick-up coil signal collected by the PC30FA data collection card. An example of the difference signal obtained by subtracting the signal received in the presence of a specimen from that received in the absence of the specimen (the reference signal) is included in the diagram. Difference signals were obtained for each of the specimen thicknesses. Data for each specimen was processed to obtain four different points of crossing for each specimen thickness, under similar conditions were recorded in a table.

Since variations in specimen thickness to the order of µm were not easily emulated in the experimental setup, a simulation study of the pulsed eddy current system modeled in Matlab and Simulink environment [4] was used. The results of the simulation study carried out at a specimen nominal thickness of 2 mm were recorded in table.

3. Results and Discussion

3.1. Results

Figures 4 and 5 show graphical representations of the difference signals obtained from the experiments

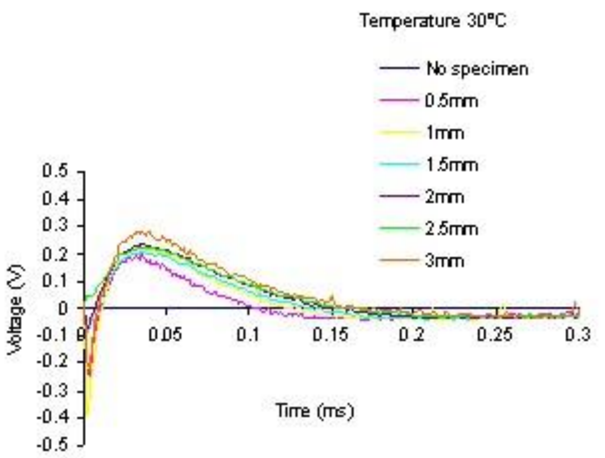

Figure 4. Difference signals**.**

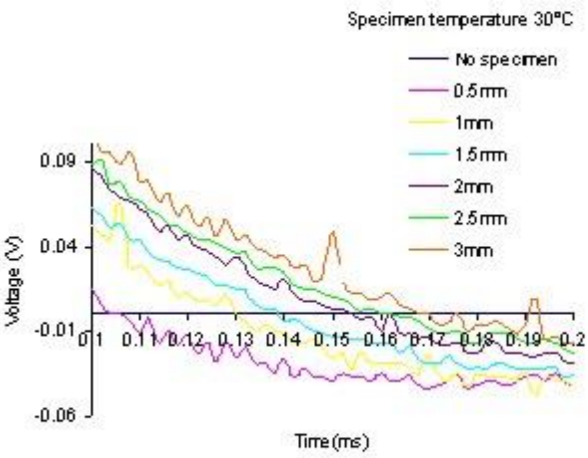

Figure 5. Zero Crossing is Time of crossing (TOC).

and Table 1 the averages calculated from the experimental data collected for the TOC at the specified specimen thicknesses.

Table 1. Averaging Time of crossing for the specimen thickness considered in the experiment.

Thickness (mm)	t1 (ms)	t2 (ms)	t3 (ms)	t4 (ms)	**tave (ms)**
0.5	0.098	0.098	0.102	0.102	0.1
1.0	0.118	0.118	0.118	0.122	0.119
1.5	0.132	0.136	0.134	0.138	0.135
2.0	0.136	0.142	0.14	0.14	0.14
2.5	0.152	0.156	0.158	0.162	0.157
3.0	0.168	0.17	0.172	0.17	0.17

Figure 6 shows the plot corresponding to the relationship between TOC and the thickness of the specimen (Time-Thickness characteristic). The 4th order polynomial included in the diagram was found to be the best trend that fitted the data.

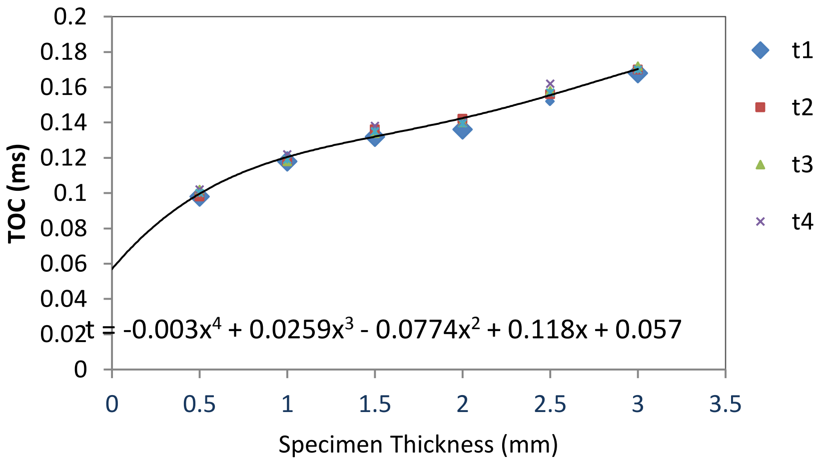

Figure 5. Experimental results: Thickness versus Time of Crossing (TOC).

Table 2 is a record of the simulated differences in TOC and their corresponding differences in specimen thickness at a nominal thickness of 2 mm.

Table 2. Simulated and calculated results for difference in Time of crossing, Δt, versus difference specimen thickness, Δx, at nominal thickness of 2 mm.

TOC Difference Δx (ms)	Thickness Difference Δx (μm)	
	Simulated	Calculated
0.00010	-4	- 4.3
0.00007	4	3.02

3.2. Discussion

Equation (1) is a possible representation of the trend lines for the graphical results shown in figure 6. It is a 4th order polynomial forecasted backward to include thicknesses below 0.5 mm. It shows that despite the fact that the time of crossing increases with increasing specimen thickness, it does not do so linearly. This could be attributed to the rather involved interaction between the electromagnetic effects of the three subsystems that make up the PEC system as discussed in the introduction.

3.2.1. Time constants and amplitudes.

Dividing the period of interest of the received Pickup Signal into sections, exponential trends were obtained for the varied specimen thicknesses. The start time of each section was set at 0 ms and results of the decaying voltage relationship for each signal $Ve^{-t/\tau}$ obtained for the various specimen thicknesses are shown in table 3.

Table 3. Time gated pickup coil signal ($Ve^{-t/\tau}$).

Thickness (mm)	Time gate 0 to 0.12 ms	Time gate 0.12 to 0.24 ms
0.0	$2.4756e^{-19535t}$	$0.2463e^{-20052t}$
0.5	$2.1231e^{-18096t}$	$0.2599e^{-14855t}$
1.0	$2.081e^{-18801t}$	$0.2358e^{-12983t}$
1.5	$2.1007e^{-19532t}$	$0.2113e^{-12134t}$
2.0	$2.1355e^{-19802t}$	$0.2052e^{-11963t}$

It is noted that as the signal decays toward a steady state value of zero volts, the values of the time constants in the two time gated sections considered are not the same. As predicted from the model, the resistance and inductance are function of the skin depth, δ (t) which varies with time. This could be the reason for the time changing time constant τ.

3.2.2. Time constants and amplitudes.

Equation (3) the relationship between the TOC and specimen thickness is not linear. However, it is possible to linearize the trend at a point by considering small changes about the point.

$$t = -0.003x^4 + 0.0259x^3 - 0.0774x^2 + 0.118x + 0.057 \quad (3)$$

At any point (x_0, t_0) on the curve shown in figure 6, there exist another point ($x_0 + \Delta x,\ t_0 + \Delta t$), due to a small change in thickness, Δ*x*. The resulting change in the time of crossing, *Δt,* is determined by considering the gradient at point (x_0, t_0) which is expressed as:

$$\Delta t = \left(\frac{dt(x)}{dx}\right)_{x_0} \Delta x \qquad (4)$$

Differentiating equation (1) and substituting for x at the nominal thickness x_0 give:

$$\Delta t = (-0.012x_0^3 + 0.0777x_0^2 - 0.1548x_0 + 0.118)\Delta x \qquad (5)$$

The small change in thickness, Δx can then be determined from a linear expression given in equation (6):

$$\Delta x = \Delta t/(-0.012x_0^3 + 0.0777x_0^2 - 0.1548x_0 + 0.118) \qquad (6)$$

Changes in TOC about a nominal thickness of 2 mm were obtained for 4 µm thickness differences in the specimen. The simulated changes were compared with those calculated using equation (6) and results are shown in table 2. Although these values are quite close, the differences between them could suggest that the 4 µm change in thickness was out of the range of the linearization used for the estimate. The results, however, could be used confidently in a colour coded scale as an alert for thickness differences within the 4 µm range about the 2 mm nominal thickness.

4. Conclusion

The PEC study carried out here suggests that a relationship between the TOC and varying specimen thickness, could be used to indicate differences in thickness of aluminium specimen of up to the order of microns. A closer look at the PEC system pickup coil signal trend showed that the time constant τ, of a signal received at a given specimen thickness, changed with increasing time within a period. This could be a possible reason for the nonlinearity of the TOC Time-Thickness characteristic. Although the relationship between the TOC and the specimen thickness is not linear, small changes about a nominal thickness could be estimated by using the differential solution of the actual relationship. The results could be used confidently in a colour coded scale as an alert for thickness differences within the 4 µm range about the 2 mm nominal thickness.

5. Acknowledgements

University of Zululand generously supported this research by providing time and financial assistance.

6. References

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