

## The Use of Non Linear Harmonic Analysis of Material Magnetic Response for Monitoring Fatigue in Austenitic Steels

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### ABSTRACT

The irreversible austenite to martensite phase transformation in some stainless steels under plastic deformation changes the steel's ferromagnetic content and hence magnetic properties. In this paper we report on a study of the non-linear harmonic analysis of the magnetic response of 304L and 321 stainless steels under cyclic fatigue. The results indicate that dynamic reverse magnetostriction and magnetomechanical effects observed in the 1<sup>st</sup> and 3<sup>rd</sup> harmonics of the materials magnetic response may provide valuable insight into the material fatigue state over a wide temperature range. Good agreement is achieved between the observed experimental data and modelled response. The paper concludes that, whilst the observed strong temperature dependence of austenite to martensite phase transformation hinders use of the steel's magnetic response as a direct measure of fatigue damage accumulation at plant operating temperatures, the information contained in the cyclic magnetic response may provide indirect evidence of the accumulated fatigue history.

### INTRODUCTION

Non-destructive methods of detecting and monitoring microscopic material damage in operating plant, if proven and validated for site use, could allow the early detection of unexpected degradation threatening plant safety and availability prior to the formation of macroscopic fatigue cracks. A number of studies [1-4] of potential non destructive methods of monitoring fatigue damage accumulation in austenitic steels have been performed in recent years. Some of the most promising methods have been those designed to monitor the changes in material magnetic and electrical properties during the fatigue process. In some unstabilised and metastable austenitic steels, a change in magnetic properties results from an irreversible austenite to martensite phase transformation during plastic deformation, so increasing the ferromagnetic content. Electrical conductivity changes also occur due the increased dislocation density resulting from plastic deformation.

The driving force for the austenite to martensite phase transformation, and hence the amount of ferromagnetic phase generated during fatigue, is strongly dependent on the material composition, metallurgical state, temperature and loading conditions. Niffenegger et al [3,4] have studied various magnetic methods for monitoring fatigue damage accumulation in commercial austenitic steels and concluded that, for specific testing conditions, a good correlation exists between the amount of martensite and the number of fatigue cycles. However material and operating specific calibration curves have to be evaluated in order to allow reliable component operating lifetime predictions.

In our current studies, an electromagnetic Non Linear Harmonic Analysis (NLHA) system is being assessed for monitoring fatigue damage accumulation in austenitic steels in operating power plant. A particular feature of this system is its ability to monitor the harmonics of the material magnetic response continuously during fatigue cycling at different temperatures. Early results from these studies [5] focused on electromagnetic fatigue monitoring at room temperature in 321 stainless steel plate. These revealed features in the cyclic magnetic response which were interpreted in terms of Jiles' [6] theory of the magnetomechanical effect.

In this paper, electromagnetic NLHA fatigue monitoring results obtained on 304L stainless steel plate between room temperature and 300C are presented, and a comparison made with earlier 321 data and modelling predictions of the material and sensor response during cyclic fatigue.

### NDE FATIGUE MONITORING FACILITY

Tests were performed in an electromagnetic NDE fatigue monitoring facility described previously [5] comprising the NLHA system, fatigue testing machine and an encircling electromagnetic sensor (concentric transmitter and receiver coils). The NLHA system is based on a prototype system used by The University of Hanover in the 5<sup>th</sup> Framework GRETE Project [1]. A pure sinusoidally varying electric current (at 800Hz in these studies) passed through the transmitter coil surrounding the fatigue specimen generates a sinusoidally varying magnetic field in the specimen. The specimen non-linear magnetic response to the applied field is detected in the form of the amplitude and phases of the 1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> harmonics of the signal induced in the receiver coils. The frequency of the sinusoidal current was selected to ensure full penetration (large skin depth) of the magnetic field into the fatigue specimen.

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Strain controlled (saw tooth waveform) fatigue tests were conducted at a constant total strain range of 0.8% ( $\pm 0.4\%$ ). A fatigue cycle frequency of 0.2 Hz was used to minimise heating of the fatigue specimens. Continuous monitoring (at sampling frequency of  $\sim 200\text{Hz}$ ) of the magnetic response of the specimen within the sensor coils was performed during cyclic fatiguing, with simultaneous recording of the stress and strain outputs from the fatigue testing machine. Variation of peak 1<sup>st</sup> and 3<sup>rd</sup> harmonic amplitudes and phases with number of fatigue, and variation of the 1<sup>st</sup> and 3<sup>rd</sup> harmonic amplitudes and phases during each fatigue cycle were then output. Heater coils attached to the specimen grips and surrounded with insulating wool enabled the specimen temperature to be controlled over a wide temperature range, whilst keeping the sensor temperature below 90°C.

**MATERIALS**

The 304 material, procured as bars of 25.4 mm diameter, and 1000 mm long, had a chemical composition given in Table 1. Fatigue specimens were machined from each bar and then solution annealed for 30 minutes at 1050°C in vacuum.

**Table 1** Chemical Composition of Materials by Analysis (wt%)

Material	C	S	P	Si	Mn	Ni	Cr
321	0.020	0.027	0.030	0.49	1.88	9.75	17.25

Material	Cu	Ti	Co	N
321	0.44	0.14	0.13	0.025

**EXPERIMENTAL RESULTS**

The variation of the peak cyclic 1<sup>st</sup> harmonic amplitude within each fatigue cycle with increasing number of fatigue cycles at room temperature is presented in Figure 1. After an initial slight reduction during the first 500 fatigue cycles, the 1<sup>st</sup> harmonic amplitude observed in the 304L specimen increases continuously with increasing numbers of fatigue cycles. However the increases are an order of magnitude smaller than in those previously observed [5] in a 321 specimen at room temperature. A similarly weak 1<sup>st</sup> harmonic phase change in the 304L specimen compared with 321 specimen is also observed. This difference is consistent with previous studies [3,4] and reflects the much lower amount of martensite produced in 304L steel than in 321 steel during cyclic fatigue.

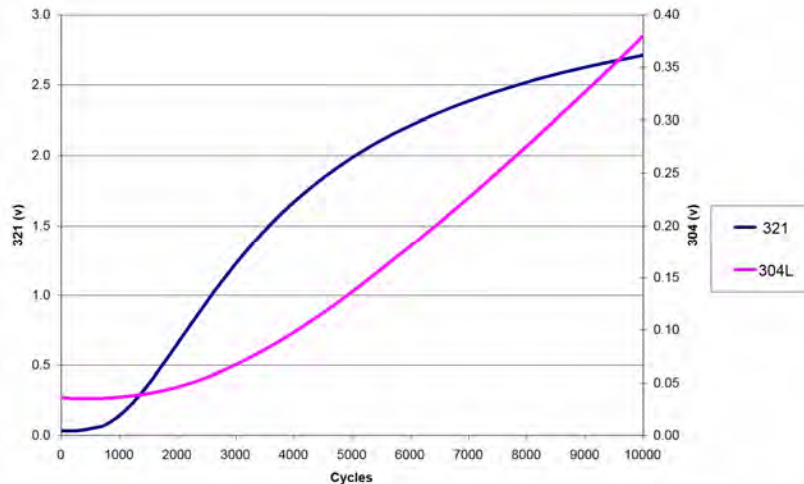


Fig.1. 304L and 321 ss 1<sup>st</sup> harmonic amplitude v number of fatigue cycles at RT

In Figure 2, the measured variations in the peak 1<sup>st</sup> harmonic amplitude signal of a 304L specimen temperature cycled between room temperature, 150C and 300C during fatigue cycling up to 9000 cycles are presented. Following each temperature shift, fatigue cycling and electromagnetic monitoring only recommenced after the system and specimen temperature had stabilised. Distinct step changes in peak harmonic signals followed each temperature shift which is

caused primarily by the temperature dependence of the transmitter coil resistivity. The subsequent variations in these signals with increasing number of fatigue cycles were temperature dependent, with the largest changes occurring at room temperature. Again this strong temperature dependence is consistent with previous studies [3,4].

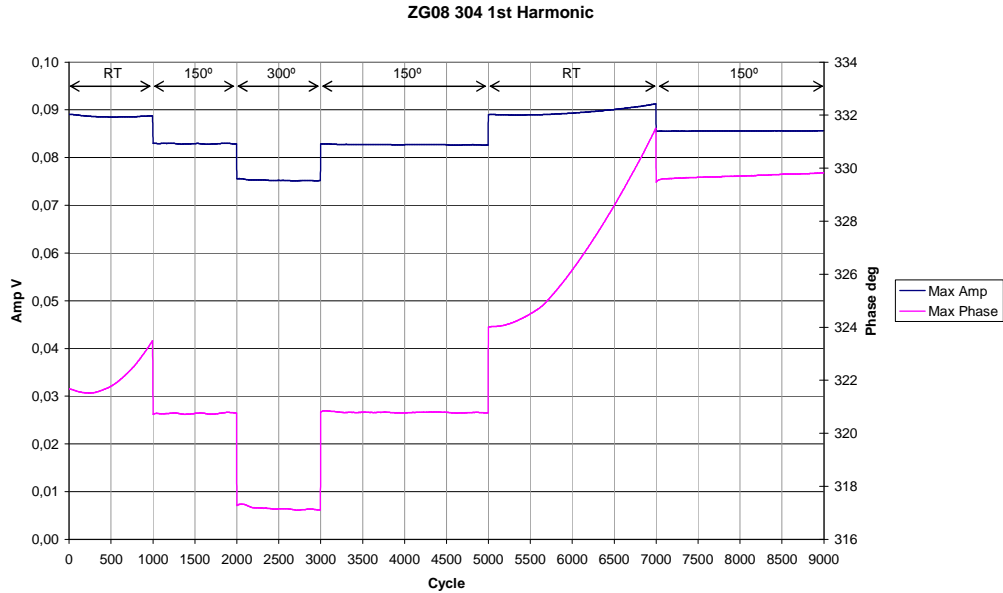


Fig 2. Variation of the maximum amplitudes and phases of the 1<sup>st</sup> harmonic signals from 304L specimen (RT to 300 °C,)

In Figs. 3 and 4, examples are presented of the cyclic variations in the amplitudes and phases of the 304L 1<sup>st</sup> and 3<sup>rd</sup> harmonic signals respectively correlated with the applied cyclic stresses and strains during continuous fatigue cycling at room temperature and 150C.

Initially, the cyclic variation of the 304 1<sup>st</sup> harmonic amplitude and phase signals closely follows the saw tooth strain variation (Fig. 3a) confirming an expected paramagnetic response of the unfatigued steel to the applied cyclic stress. With increased cycling, additional local minima appear at the peak tensile strains (Fig. 3b), which persist throughout the temperature and fatigue cycling test. These local minima are characteristic of the nonlinear magnetic response of the material as the ferromagnetic content increases during fatigue cycling.

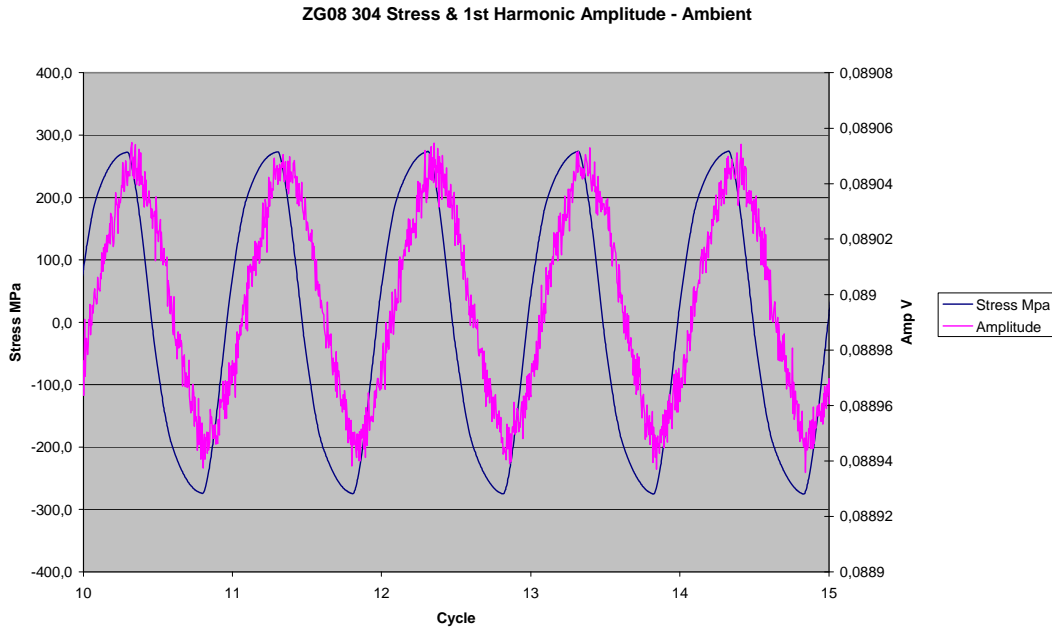


Fig.3a. 1<sup>st</sup> harmonic amplitude and stress of 304L specimen at RT from cycle 10

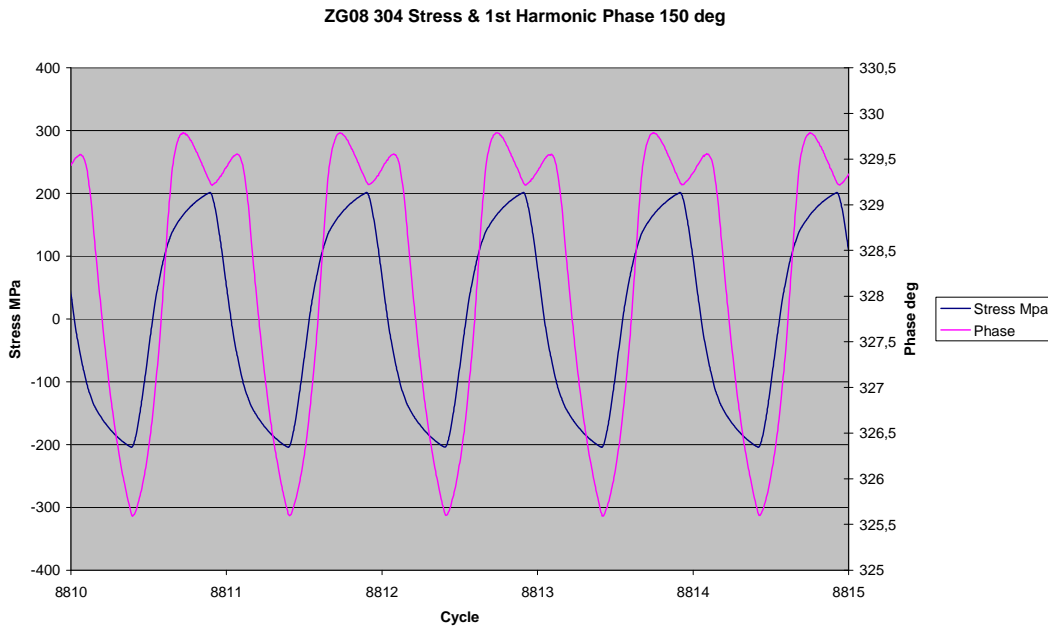


Fig.3b. 1<sup>st</sup> harmonic phase and stress of 304L specimen at 150°C from cycle 8810

The 304L 3<sup>rd</sup> harmonic amplitude signals are negligible or weak at the start of fatigue cycling but develop local minima in the amplitude signals at peak tensile and compressive strains which persist at all temperatures up to more than 5000 cycles (Fig. 4a). However, following continued cycling at room temperature above 5000 cycles only the local minima at peak tensile strain remains (Fig. 4b). Similar behaviour is observed in the 3<sup>rd</sup> harmonic phase signals.

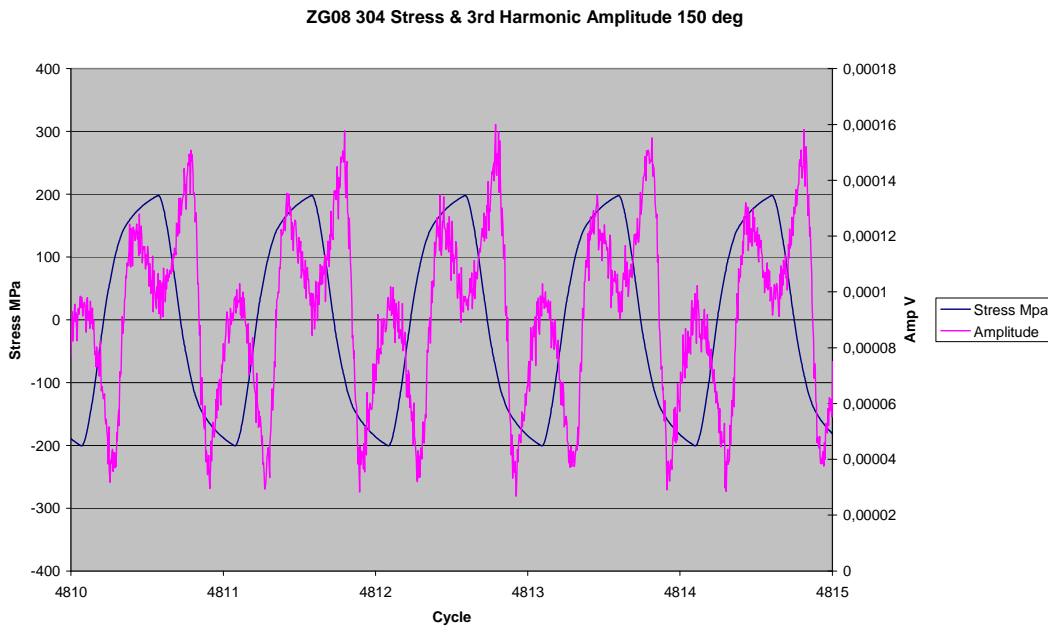


Fig.4a. 3<sup>rd</sup> harmonic amplitude and stress of 304L specimen at 150°C from cycle 4810

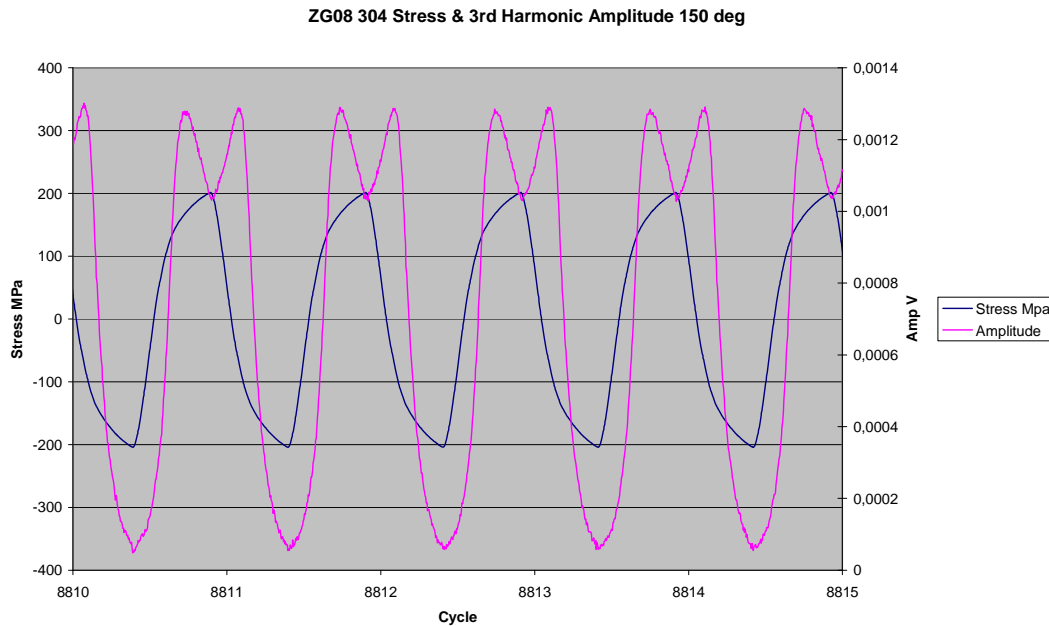


Fig. 4b. 3<sup>rd</sup> harmonic amplitude and stress of 304L specimen at 150°C from cycle 8810

The features in 3<sup>rd</sup> harmonic amplitude data in Figs 3 and 4 are consistent with those previously reported for 321 steel [5] and, as discussed later, are indicative of magnetic domain wall reorientation occurring at both peak tensile and compressive stress

In two subsequent tests, annealed 304L specimens were fatigued to failure at 150C and 250C, without initially being cycled for a period at room temperature. The variations in the peak 1<sup>st</sup> harmonic amplitudes and phases over the full test at 150C and 250C are presented in Figures 5 and 6 respectively. At both temperatures the magnitudes of the changes in 1<sup>st</sup> harmonic amplitudes and phases are small compared with those observed at room temperature. Step changes in the observed signals correlate well with small variations in the applied stress, with the exception of the step change observed after ~18000 cycles at 250C. At 150C, only the peak 1<sup>st</sup> harmonic phase signal shows a non linear variation with increasing number of fatigue cycles (Fig. 5). At 250C therefore there is no correlation between the measured peak 1<sup>st</sup> harmonic amplitude and phase response and accumulated number of fatigue cycles. The observed step change in the 1<sup>st</sup> harmonic amplitude and phase signals (Fig 6) at 18000 cycles may coincide with the onset of microcrack formation since the specimen subsequently failed after ~28000 cycles. However the evidence is weak.

It is also observed that that throughout the 250C fatigue test the observed 1<sup>st</sup> harmonic amplitude follows closely the applied strain sawtooth waveform within each cycle, whilst the 3rd harmonic amplitude does not vary significantly throughout the test. The 150C and 250C tests results demonstrate that a paramagnetic response persists to high numbers of fatigue cycles at high temperatures, confirming again the strong temperature dependence of the austenite-to-martensite phase transformation. It is interesting to note that 304L specimens fatigued first at room temperature (see Figure 2) continue to display non-linear response at high temperature as result of the stability of the martensite phase at these temperatures. This may lead to a means of indirectly monitoring fatigue damage accumulation

One is led to conclude therefore that if the dominant fatigue damage process occurring in operating plant occurs at these high temperatures, then a measurement of the magnitude (1<sup>st</sup> harmonic amplitude) of the material's ferromagnetic magnetic response alone will not provide an effective fatigue monitoring method. Monitoring of the phase amplitude is more promising. If, however, component fatigue occurs primarily during temperature cycling to lower temperatures (at plant start-up and shutdown), the accumulated amount of martensite phase produced as a result of these lower temperature excursions may provide a valuable indicator of fatigue damage accumulation.

The change in the shape of cyclic magnetic response during individual fatigue cycles with increasing number of fatigue cycles may provide a better measure of fatigue damage accumulation than measurement of 1<sup>st</sup> or 3<sup>rd</sup> harmonic amplitudes and phase. To be able to make use of these features it is necessary to have a stronger theoretical understanding of the processes involved. Progress in this area is described below.

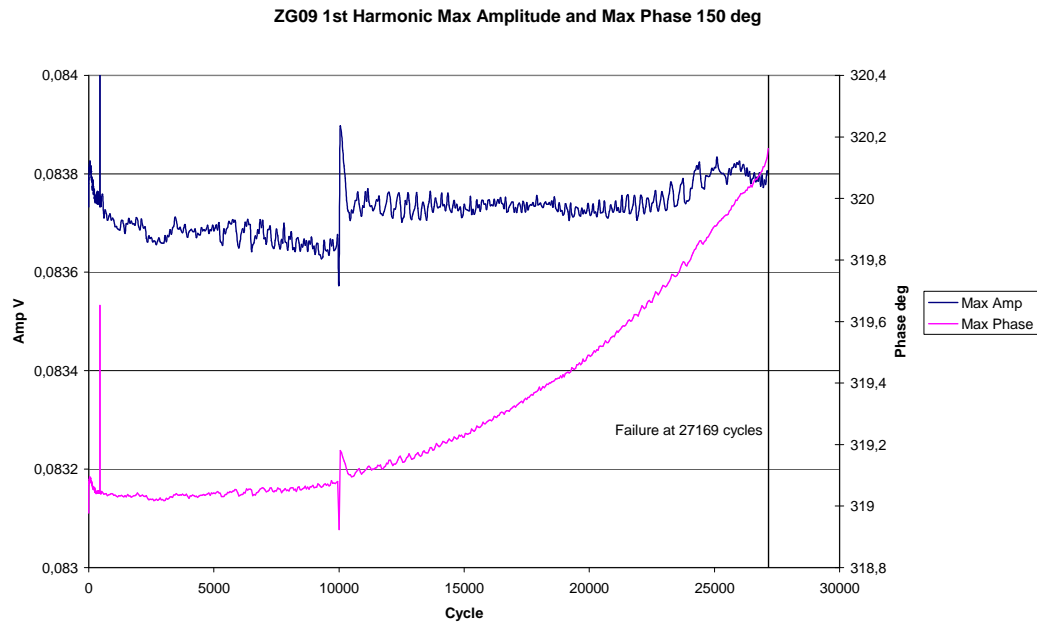


Fig. 5. Variation of the maximum amplitudes and phases of the 1<sup>st</sup> harmonic signals from specimen ZG09 at 150°C

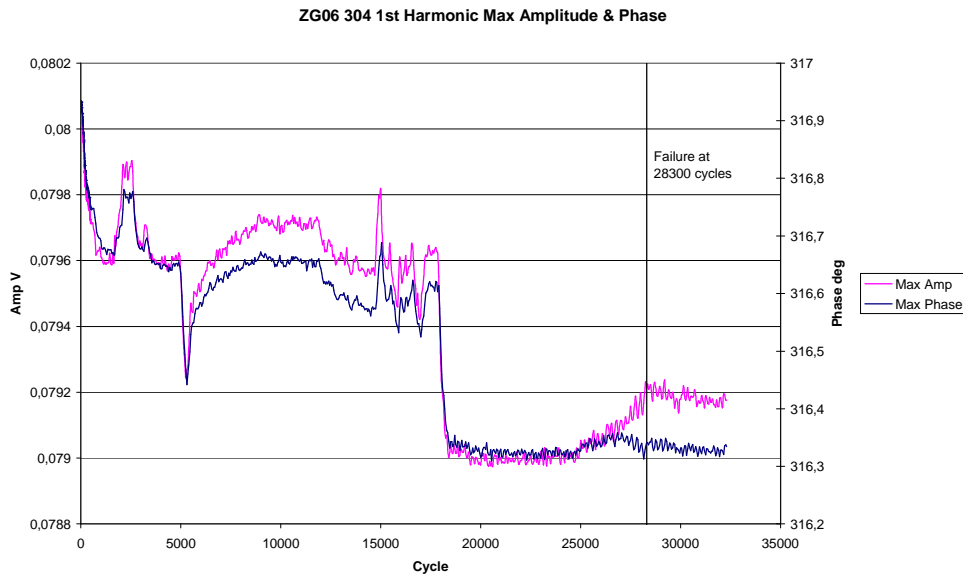


Fig. 6. Variation of the maximum amplitudes and phases of the 1<sup>st</sup> harmonic signals from specimen ZG06 at 250°C

MODEL OF MAGNETOMECHANICAL RESPONSE DURING CYCLIC FATIGUE

The observed variation in magnetisation is similar in character to that observed in other experiments in the literature [7, 8] in which the variation is attributed to the inverse magnetostriction effect. A fundamental aspect of the inverse magnetostriction effect is that, at high applied stresses, the reorientation of magnetic domains takes place so as to cause the magnetisation to move towards the anhysteretic magnetisation for the prevailing magnetomotive force. Equations for relating the magnitude and sign of the magnetostriction effect to the unstressed magnetisation and the applied stress have been given by Jiles [6]. The magnitude and sign of the effect are characterised by one or more magnetostriction coefficients, which are stress-dependent.

The tendency for the magnetisation to decrease slightly at high tensile stress has been noted by Jiles [6]. This arises from a reversal in the slope of the magnetostriction curve at high magnetisation (caused by high tensile stress) and reflects a tendency for the domain orientation in one direction to saturate at a certain level for the amount of the ferromagnetic phase present. With a further increase in stress, domain unpinning during plastic slip tends to dominate, and the magnetisation decreases slightly. Note that at high compressive stress, the magnetisation level is significantly lower, and so there is no saturation effect.

To aid in understanding the inverse magnetostriction effect in the fatigued specimen, a simple numerical model of the stress-dependent magnetisation was produced, using an EXCEL spreadsheet. This model was based on the stress-dependent magnetisation relation in Reference 6 Equation 22, namely:

$$\frac{dM}{dW} = \frac{1}{\xi} (M_{an} - M) + c \frac{dM_{an}}{dW}, \quad (1)$$

where:

$M$  is the magnetisation,

$W$  is the elastic energy,

$\xi$  is a constant with the dimensions of stress,

$M_{an}$  is the anhysteretic magnetisation, and

$c$  is a domain mobility constant.

In Equation 1, the change in magnetisation with elastic energy (and hence stress) depends on the change in anhysteretic magnetisation with elastic energy, and also on the difference between the magnetisation and the anhysteretic magnetisation. The anhysteretic magnetisation itself depends on stress, which can be characterised as a stress-dependent term in the relation for the effective magneto-motive force causing the magnetisation,  $H_{eff}$ :

$$H_{eff} = H + \alpha M + \frac{3\sigma}{\mu_0} [M(\gamma(0) + \sigma\gamma'(0))],$$

where:

$H$  is the magneto-motive force arising from the current in the excitation coil,

$\alpha$  is the magnetisation self-coupling constant,

$\gamma(0)$  is the first order magnetostrictive constant at zero stress, and

$\gamma'(0)$  is the first derivative of the first order magnetostrictive constant at zero stress.

Values of the various parameters in Equations 1 and 2 used to calculate the magnetisation are given in Table 2 below.

Table 2. Constants used in calculation of magnetisation vs. stress

Parameter	Value
Magneto-motive force (excitation coil)	2544Am <sup>-1</sup>
First order magnetostrictive constant (at zero stress)	1.0*10 <sup>-18</sup> m <sup>2</sup> A <sup>-2</sup>
First derivative of first order magnetostrictive constant (at zero stress)	-3*10 <sup>-27</sup> m <sup>2</sup> A <sup>-2</sup> Pa <sup>-1</sup>
Magnetisation self coupling constant	0.001
Characteristic stress for difference term	5*10 <sup>7</sup> Pa
Domain mobility constant	0.1

These values of the constants in Table 2 are similar to those used by Jiles [6] in calculations for iron, though adjustments have been made to achieve a reasonable match to measured voltage response data, which corresponds to magnetisation. Plots of magnetisation and stress vs. time for one mechanical cycle are shown in Figure 7.

There is good agreement between the modeled variation of the magnetization and that of the measured 1<sup>st</sup> harmonic amplitudes and phases reported here. Further modeling studies are underway to predict the 3<sup>rd</sup> harmonic responses at different numbers of fatigue cycles and through each cycle.

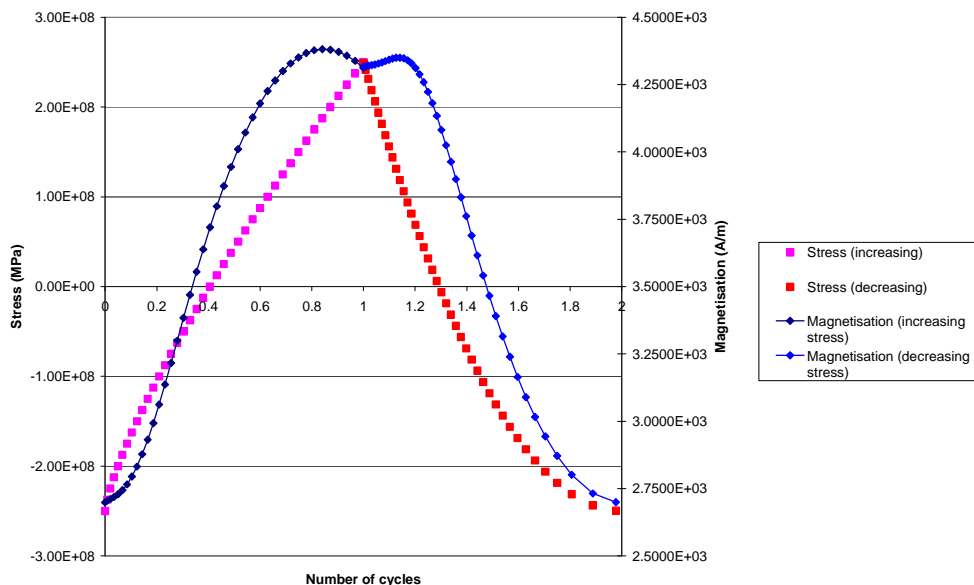


Fig.7. Calculated magnetisation, and stress vs. time, representing 1<sup>st</sup> harmonic at 9900 cycles

## CONCLUSIONS

The experimental data reported here on the magnetic response of 304L stainless steel during fatigue cycling provide useful insight into the changes in the materials magnetic properties which may be related to the accumulated fatigue damage. Further experimental and theoretical studies are underway. We conclude that whilst the observed strong temperature dependence of austenite to martensite phase transformation hinders use of the steels magnetic response as a direct measure of fatigue damage accumulation at plant operating temperatures, the information contained in the cyclic magnetic response may provide indirect evidence of the accumulated fatigue history

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