NDT&E International 68 (2014) 73–77

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

High temperature thickness measurements of stainless steel and low carbon steel using electromagnetic acoustic transducers

S.E. Burrows*, Y. Fan, S. Dixon

Department of Physics, University of Warwick, Coventry CV4 7AL, UK

ARTICLE INFO

Article history:
Received 7 May 2014
Received in revised form
16 July 2014
Accepted 30 July 2014
Available online 19 August 2014

Keywords:
Laser ultrasound
Electromagnetic acoustic transducer (EMAT)
High temperature

ABSTRACT

Thickness measurements were made on steel pipe at high temperatures using a non-contact water-cooled EMAT (electromagnetic acoustic transducer) and also a laser-EMAT system where a portable Nd:YAG laser with a fibre optic cable was used to generate ultrasound on a sample, and a water-cooled coil-wound EMAT used to detect ultrasound. The set-up was designed so that the laser was fired through a hole in the centre of the EMAT, and a low pass 5 MHz filter employed to reduce the plasma noise. Back wall reflections were clearly visible at temperatures up to 900 °C on stainless and ferromagnetic low carbon steel, enabling wall thickness to be measured, taking into account thermal expansion of the sample. The water-cooled EMAT system can measure wall thickness on ferromagnetic low carbon steel at temperatures up to the Curie point; here, ultrasound generation is dependent on the magnetic state of the steel.

1. Introduction

Online monitoring of pipes and other surfaces at high temperature for wall thickness and other defects is the key to many industrial NDE (Non-destructive Evaluation) demands, such as the power generation and the nuclear industry. The ability to monitor plant structure without shutting down has important economic considerations, and a method of high temperature monitoring is highly desirable. Previous systems which have been proposed for use at raised temperatures include a pulsed electromagnet for both generating and detecting ultrasound which is effective up to 250 °C on ferromagnetic low carbon steel [1], and a laser-EMAT system which can generate shear waveforms successfully at temperatures up to the Curie point of ferromagnetic low carbon steel [2]. Laser interferometry has successfully been used for ultrasonic thickness measurements on various steel grades at temperatures up to 1200 °C [3], although this is a relatively expensive form of NDT. Other methods have concentrated on high temperature piezoelectric transducers [4]; these incorporate piezoelectrics such as bismuth titanate which, has a Curie temperature (T_c) of 675 °C and can operate at temperatures up to 500 °C [5]. This piezoelectric has been to shown to operate well on pipes at elevated temperature when either deposited directly as a film [6], brazed [7] or screen printed onto shim and attached with couplant [8]. A disadvantage of bismuth titanate is its low piezoelectric coefficient compared with other materials such as PZT which, has a high coupling coefficient but a low Curie point (T_c) of 200 °C; PZT can be used as a transducer for high temperature NDT when mounted on a waveguide [9,10] which allows the PZT element to remain below its Curie point, although dispersion can occur in the waveguide. Single crystal lithium niobate is reported to work as a transducer at temperatures up to 1000 °C [11] and also has the advantage of a good matching thermal coefficient of expansion with stainless steel. The main drawback of using piezoelectric transducers is lack of a suitable high temperature couplant; while some couplants can withstand elevated temperatures for short periods of time (e.g. Pyrogel 100 from Diagnostic Sonar, ZGM paste from GE Inspection Technologies), it is difficult to source a couplant that can be used as a permanent bond for long term monitoring. A permanent high temperature couplant needs to have good transducer coupling, suitable thermal coefficient of expansion to match both test piece and transducer, and strong bonding to both test piece and transducer that can withstand thermal cycling. To avoid the problems caused by high temperature coupling, a non-contact method of generating and detecting ultrasound will be used for this work.

A non-contacting EMAT will generate ultrasound in a ferromagnetic sample such as low carbon steel using both Lorentz and magnetostrictive mechanisms, the Lorentz mechanism being dominant on bare steel at room temperature [12,13]. A third mechanism due to magnetisation force will not be relevant here due to the configuration of the EMATs, since the contribution arising from the magnetisation force is dependent on the angle of incidence of the bias magnetisation [14].

* Corresponding author. Tel.: +44 2476 574116.
E-mail address: s.e.burrows@warwick.ac.uk (S.E. Burrows).

http://dx.doi.org/10.1016/j.ndteint.2014.07.009

It is known that as the temperature of the sample rises, the Lorentz mechanism remains dominant until T_c of steel is reached (770 °C for a low carbon steel), when the magnetostrictive mechanism becomes more efficient [15]. Previously this has been thought due to a thin ferromagnetic oxide layer on the sample surface, the surface being cooler than the bulk of the material [16,17]. This layer concentrates the magnetic field, increasing generation efficiency. Recent studies also show that rearrangement of the magnetic moments from ordered domains to a disordered state at a magnetic phase transition lowers the magnetostrictive constant. This ferromagnetic to paramagnetic transition is accompanied by large changes in the efficiency of electromagnetic ultrasound generation leading to the use of EMATs as a method of studying phase transitions in magnetic alloys [18].

When a sample is in the paramagnetic state, ultrasound generation by the Lorentz and particularly the magnetostriction mechanisms has poor efficiency, and therefore at temperatures above T_c EMATs are not suitable for generating ultrasound, although they can still detect. For the Lorentz generation mechanism, a current passing through a coil will generating a reciprocal Eddy current in the electromagnetic skin depth of the sample, which in turn interact with the bias magnetic field to produce a force F on the free electrons perpendicular to both the Eddy current and the bias magnetic field. Momentum exchange between the conduction electrons and the lattice by collision induces the phonon (ultrasound) in the sample. This force is proportional to the induced Eddy current density J and the bias magnetic flux density B

$$F = J \times B$$

The bias magnetic field is usually provided by the permanent in the EMAT, and because the bias magnetic flux density at the surface of the paramagnetic sample is significantly lower than that on the ferromagnetic sample, the Lorentz force component will be correspondingly lower, and the amplitude of any ultrasound signal will be weaker. The induced Eddy current will also interact with the dynamic magnetic field produced by the generation coil in the EMAT via the same Lorentz mechanism, and this is sometimes called the self-field generation mechanism [19]. For the magnetostriction generation mechanism, the energy coupling is dependent on a mechanical strain arising from ordered domains aligning with an applied magnetic field; in a paramagnetic sample, the domains are in a disordered state so no strain arises and therefore no ultrasound is generated.

EMATs can detect ultrasound through the reciprocal process of the generation mechanism, except it must rely on the bias magnetic field or the magnetostriction, for the self-field mechanism does not apply in this case. EMATs are more efficient at detection because of the inefficient momentum transfer from the conduction electrons to the lattice, due to the enormous difference in their mass. In detection, the EMAT actually acts as a velocity sensor [20], but the proof for this is not trivial.

For this study, a radially polarised shear wave EMAT was used to generate and detect ultrasound, for determining thickness measurements on ferritic and austenitic steel samples, at temperatures up to 900 °C. A second technique using laser generated ultrasound with a water cooled EMAT as detector was also deployed; the advantage of this method is that the EMAT design can be optimised for detection only, rather than a compromise being made on the EMAT design, as is the case when the same EMAT is used for both detection and generation. By using an EMAT as detector, the potential for greater sensitivity can be achieved compared with laser interferometry systems [3,21].

Laser ultrasound is a well established non-contact technique [22–24] which can generate shear, compression and surface waves on a variety of materials simultaneously. When used in the thermoelastic regime, a laser generates ultrasound through thermal expansion of the area illuminated by the laser spot; expansion is constrained by the surrounding cooler material and the stresses generated lead to a predominantly in-plane ultrasonic wave.

2. Experimental

2.1. Radially polarised shear wave EMAT

The EMAT utilised a coil design, constructed by wrapping a single layer of 0.08 mm diameter insulated copper wire as a spiral, placed under the centre of a 35 mm diameter NdFeB cylindrical permanent magnet. The magnet was held in a brass case with a water cooled fitting and the front of the EMAT coil protected by a thin titanium alloy face, separated from the coil by a 0.25 mm thick alumina spacer attached with Pelco high temperature ceramic paste. The coil was separated from the permanent magnet by 1.5 mm of alumina spacer, in order to reduce the Eddy currents induced in the magnet alloy. The EMAT was connected to a wideband pre-amplifier with a gain of approximately 60 dB. The pre-amplifier was connected to a digital oscilloscope, via a 5 MHz low pass filter to reduce plasma noise arising from the laser beam impact on the sample. The oscilloscope has an analogue bandwidth of 100 MHz, while the digitisation is done at 1 GS/s with 8-bits resolution. The data was stored on a computer for subsequent signal processing.

2.2. Laser-EMAT

The EMAT design was optimised for ultrasound detection by selecting the optimum diameter of the wire and the overall coil size used in the EMAT. As the number of turns increases, the inductance of the coil increases, and whilst at first glance this may appear to make the EMAT more sensitive, the increased inductance also limits the bandwidth of the transducer due to the finite input impedance of the amplifier. Here the coil was constructed by wrapping a single layer of 0.08 mm diameter insulated copper wire around a 4 mm diameter circle, and placed at the centre of a 35 mm overall diameter NdFeB permanent ring magnet, this permanent has an inside diameter of 4 mm, to allow the passage of the generation laser beam. The cylindrical magnet was held in a brass case with a water cooled fitting and the front of the EMAT coil is protected by a titanium alloy face, with alumina spacers as before. A schematic diagram of the EMAT construction is shown in Fig. 1. The Nd:YAG laser used has a typical pulse energy of 50 mJ at 1064 nm, and 10 ns pulse duration, coupled from the laser head to the sample via a fibre optic cable, operating in Q-switched mode at a pulse repetition frequency of 20 Hz. Using a fibre optic head enables good alignment through the centre hole of the magnet in the EMAT, whilst keeping the laser head remote from the hot sample. A schematic diagram of the set up is shown in Fig. 2.

A 316 stainless steel pipe sample of 70 mm diameter and 9 mm wall thickness was placed in a furnace and the temperature raised to the predetermined set point. After one hour at the specified temperature, to allow for the temperature of the sample to equilibrate, the door was opened and either the radial EMAT or the laser-EMAT system positioned, such that the sample-EMAT lift-off was < 0.5 mm. The sample surface temperature was also measured with a K-type thermocouple. Thickness measurements were taken over a range of temperatures between 25 °C and 900 °C. A ferromagnetic low carbon steel pipe, quenched and tempered, of 92 mm diameter and 10 mm wall thickness was also