NDT&E International 89 (2017) 74–80

Contents lists available at ScienceDirect

NDT&E International

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

High temperature EMAT design for scanning or fixed point operation on magnetite coated steel

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ARTICLE INFO

Keywords:
EMAT
High temperature
Thickness measurement
Magnetostriction

ABSTRACT

Bulk thickness measurements were performed at elevated temperatures on magnetite coated low carbon steel pipe and aluminium samples, using a permanent magnet electromagnetic acoustic transducer (EMAT). The design presented here exploits the non-contact nature of EMATs to allow continuous operation at elevated temperatures without physical coupling, sample preparation (in the form of oxide scale removal), or active cooling of the EMAT. A non-linear change in signal amplitude was recorded as the magnetite coated sample was heated in a furnace, whereas a steady decrease in amplitude was observed in aluminium. For a magnetite coated pipe sample, after a dwell time of 3 h, a SNR of 33.4 dB was measured at 450 °C, whilst a SNR of 33.0 dB was found at 25 °C. No significant EMAT performance loss was observed after one month of continuous exposure to 450 °C. EMAT-sample lift-off performance was investigated at elevated temperature on magnetite coated steel; a single-shot SNR of 31 dB for 3.0 mm lift-off was recorded at 450 °C, highlighting the suitability of this design for scanning or continuous fixed point inspection at high temperature.

1. Introduction

A variety of industrial metal components operate continuously at elevated temperatures, including pipelines, boilers and reactors, over a range of industries, most notably power generation, petrochemical and metal processing. Performing in-service nondestructive evaluation (NDE) without the need for plant shutdown provides numerous advantages, such as reduced risk from thermal cycling and a decrease in the shutdown period and associated costs. Notwithstanding the wealth of research dedicated to inspection and condition monitoring at high temperature, there are continued efforts towards advancement of current high temperature NDE techniques [1,2].

High temperature piezoelectric transducers have been shown to operate without active cooling at up 750 °C [1]; their use has been reported for thickness measurements [3] and monitoring of cracks [4]. Piezoelectric transducers typically employ high temperature piezoelectric materials [5–9] or waveguides as thermal buffers [3,10] to provide continuous operation at elevated temperatures. Their main drawback is maintaining physical coupling to the specimen, requiring solid coupling [1], brazing [11] or direct deposition of a piezoelectric material [12]. Issues can arise in long term use of solid coupling techniques, such as thermally induced cycling stress from a thermal expansion mismatch between the transducer and sample. Industrial applications of high temperature transducers may require scanning techniques for inspection of large component areas, but high temperature piezoelectric transducers are currently limited to inspection at a permanently installed location. Therefore, a transducer capable of operating at a fixed point or in a scanning mode may prove beneficial for some applications.

Laser based methods are non-contact and able to operate on samples at elevated temperatures [13,14], although laser techniques are usually expensive and can be dependent on surface condition. Development of magnetostrictive patch transducers (MPTs) has been of interest for high temperature inspection, however these methods also require physical coupling of the transducer to the sample [15].

EMATs have been employed in thickness measurements and defect detection at high temperatures due to their noncontact nature, although this requires active cooling of a permanent magnet [16,17] or the use of a bulky electromagnet [18,19], limiting their use in some industrial settings. Laser-EMAT systems have also been employed successfully for high temperature operation [20–22], often with a water-cooled EMAT receiver, as EMATs generally provide greater efficiency in detection [23].

In this work, a robust and compact high temperature EMAT was developed, with a view to overcome some disadvantages of currently available high temperature ultrasound transducers. The design applies the advantages of EMATs to facilitate continuous operation at elevated temperatures without physical coupling, sample preparation (in the

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http://dx.doi.org/10.1016/j.ndteint.2017.04.001
Received 6 October 2016; Received in revised form 28 March 2017; Accepted 11 April 2017
Available online 13 April 2017

form of oxide scale removal), or active cooling, for use on oxide coated steel pipelines. The vast majority of industrial ferritic steel pipelines which operate continuously for long periods over 200 °C in a reducing atmosphere tend to develop a thin, well-adhered oxide surface coating (magnetite), which has been shown to greatly enhance EMAT efficiency [24,25]. This study exploits this increase in EMAT efficiency on magnetite coated steel to generate high signal-to-noise ratio (SNR) signals at temperatures up to 450 °C.

EMATs use a combination of static and dynamic magnetic fields to generate and detect ultrasound waves principally through two mechanisms, the Lorentz force and magnetostriction [26]; the mechanism that operates or dominates depends upon the EMAT design, and the electrical and magnetic properties of the sample. Lorentz force describes the EMAT generation and detection mechanism which operates on electrically conducting samples. When an AC current is driven through a coil, an eddy current is generated within the electromagnetic skin depth of the sample, this interacts with the static magnetic field to produce a Lorentz force on the free conducting electrons. Momentum exchange between the electrons and the lattice via collision generates ultrasound within the sample. EMATs can detect ultrasound through the reciprocal process.

Previous research has shown that the magnetostriction mechanism operates on magnetite coated steel [24,25], which can greatly enhance EMAT sensitivity depending on a number of factors, including strength of the static magnetic field, degree of bonding between the oxide coating and steel substrate, coating thickness and composition. Subject to these factors, the magnetostriction mechanism is able to generate signals in the region of two orders of magnitude greater on magnetite coated steel, when compared to bare steel samples. This variation is attributed to the fundamental difference between the generation and detection of ultrasound via magnetostriction when a highly magnetostrictive oxide coating is present, compared to the contribution from both the Lorentz force and magnetostriction on bare steel. Fundamentally, the Lorentz force mechanism produces a surface force acting on a conductive sample, whilst the magnetostrictive mechanism produces a shear body force across the entire magnetostrictive coating thickness on magnetite coated samples.

Magnetite exhibits magnetostriction, a reversible property of magnetic materials with magnetocrystalline anisotropy, resulting in a strain on exposure to a magnetic field, termed Joule magnetostriction; the reverse is the Villari effect [27]. An alternating current applied through the coil generates a dynamic magnetic field, resulting in oscillating magnetostrictive strains within the coating which launch ultrasound waves into the bulk of the steel [28]. Magnetostriction is highly non-linear with change in the applied magnetic field, whereas the Lorentz force exhibits a linear relationship [29,30].

This paper presents a bulk shear wave EMAT design for pulse echo thickness measurements on industrial magnetite coated steel pipe and aluminium samples at temperatures up to 450 °C. The EMAT lift-off performance was investigated to evaluate the suitability for scanning inspections at high temperature.

2. High temperature EMAT

A radially polarized bulk shear wave EMAT (Sonemat, HWS2035-VC) was used, containing a spiral coil and a permanent magnet. A cross-sectional diagram of the high temperature EMAT design is shown in Fig. 1. The magnet is a high strength, high Curie point permanent magnet grade, that resists permanent demagnetization at higher temperatures; although it exhibits a lower magnetic flux density when heated. A static magnetic field, directed into the sample, is provided by a cubic magnet 25 mm in length, with a magnetic flux density of roughly 0.36 T at the surface of the magnet at ambient temperature. Similar to previous work [19], a hand wound spiral coil was encapsulated between two 0.5 mm thick alumina ceramic discs using 0.2 mm diameter bare copper wire; the front ceramic disc acts as a wear plate to protect the coil. The coil had 20 turns with a 0.2 mm spacing for the alumina ceramic adhesive, which functioned as electrical insulation. A 0.1 mm thick copper foil was placed between the magnet and coil, providing electromagnetic shielding [31] to reduce ultrasound generation within the magnet. The EMAT was housed in a stainless steel casing to provide electromagnetic and capacitive shielding of the EMAT, and to provide protection during measurements. To withstand elevated temperatures, a coaxial cable with ceramic as the inner insulator was used for connecting the EMAT to the pulser-receiver electronics.

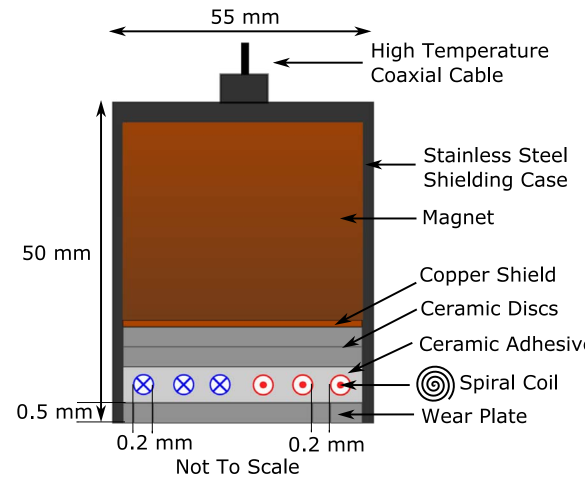

Fig. 1. Schematic cross-sectional view of the high temperature EMAT.

3. Experimental method

3.1. Experimental setup on magnetite coated steel

Two industrial magnetite coated low carbon steel pipe samples were used, termed sample A and B. The magnetite thickness was between 0.1 and 0.2 mm; this variation arises from the nature of growth of high temperature oxide scales in an industrial environment, where growth conditions can change due to a number factors, such as localized surface condition, temperature and composition. Average magnetite coating thickness was determined using a micrometer at a number of positions with and without the coating. Sample A had a stepped inner diameter, the maximum step at 6.8 mm and minimum step at 2.6 mm; both of these steps were tested to evaluate change in EMAT performance with sample thickness. Sample B had a uniform thickness of 6.8 mm. Both samples A and B had an outer pipe diameter of 150 mm.

The experimental setup of the pulse-echo bulk thickness measurement is illustrated in Fig. 2. A pulser-receiver unit (Sonemat, PR 5000) was used to provide a spike driving current pulse, at 450 V with a 100 ns pulse width, to excite the coil in generation, and wideband low-noise signal amplification in detection. A variable transformer was used, which allows one to change the voltage supply to the pulser-receiver, varying it from the mains supply voltage at ≈240 V. For example, with a variable setting at 100% the maximum driving current pulse was 28 A, whilst at 10% the maximum driving current pulse was

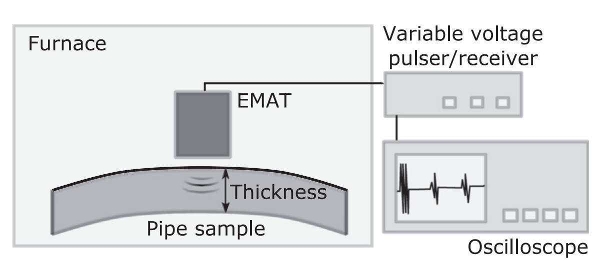

Fig. 2. Experimental set-up used to assess EMAT performance at high temperature.