Available online at www.sciencedirect.com
ScienceDirect
NDT&E International 41 (2008) 217–222
NDT&E international
www.elsevier.com/locate/ndteint

Experimental study of ultrasound propagation at a liquid–solid composite interface for inspection of liquid–metal cooled nuclear reactors

C. Lesueur[a], J. Moysan[a,*], G. Corneloup[a], F. Baque[b]

[a]*Laboratoire de Caractérisation Non Destructive (LCND), Université de la Méditerranée, IUT GMP, Avenue Gaston Berger, 13625 Aix-en-Provence cedex, France*
[b]*CEA/Cadarache DTN/STPA/LTTS, 13108 Saint-Paul-lez-Durance cedex, France*

Received 7 August 2006; received in revised form 8 September 2007; accepted 24 September 2007
Available online 31 October 2007

Abstract

The influence of unfilled cavities at a liquid–solid interface on ultrasound propagation is investigated. This kind of interface exists only when the surface is rough and the liquid is non-wetting. Normally incident compression waves are used. Possible modelling approaches are discussed, showing that no model is able to efficiently describe this kind of interface. We demonstrate that wave transmission drops dramatically. It is suggested that the incoming ultrasonic energy induces the growth and the coalescence of the vapour phase contained in the unfilled cavities under ultrasound field. A major result of this paper is to provide proof that difficult experiments in metal–liquid can be replaced by easier experiments in water.

Keywords: Ultrasonics; Interface; Wetting; Liquid–metal; Lead–bismuth

1. Introduction

The operation of nuclear power plants requires periodic in-service inspection in order to periodically verify the reliability of the reactor structures. In monitoring liquid–metal cooled nuclear reactors, possible solution for the next nuclear power generation, inspection and maintenance problems are encountered due to opaque and hot environment. Non-destructive techniques such as ultrasound are well suited in handling these kinds of inspections. However, there are some difficulties in use since high temperature submergible transducers are required [1]. Above all, a good acoustic coupling between the transducer and the liquid and even between the liquid and the material to be inspected is required. Experience acquired with liquid sodium shows that the resulting ultrasound signals are often unstable and weak.

The current explanation for these weak signal amplitudes is a poor contact between the liquid and the surface of the transducer or the surface of the material to be inspected. The liquid–solid interface is termed ''composite'': i.e. partly liquid–solid and partly liquid–vapour. This kind of interface is the result of the interaction between two physico-chemical properties of the interfaces: wetting and roughness. Wetting is the ability of a liquid to spread on a solid surface. It is defined by a contact angle θ_y depending on solid–liquid interfacial energy (γ_{SL}) and also depending on solid–vapour (γ_{SV}) and liquid–vapour (γ_{LV}) interfacial energies through the Young equation (1) [2]:

$$\cos \theta_y = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}. \tag{1}$$

A composite interface is obtained when the studied liquid is non-wetting and when the surface of the solid has a certain degree of roughness. Liquid does not take on the actual shape of the irregularities of the surface and vapour pockets at a micrometric scale exist between the liquid and the solid (Fig. 1) [2].

*Corresponding author. Tel.: +33 4 42 93 90 52; fax: +33 4 42 93 90 84.
E-mail address: moysan@iut.univ-aix.fr (J. Moysan).

0963-8695/$ - see front matter
doi:10.1016/j.ndteint.2007.09.003

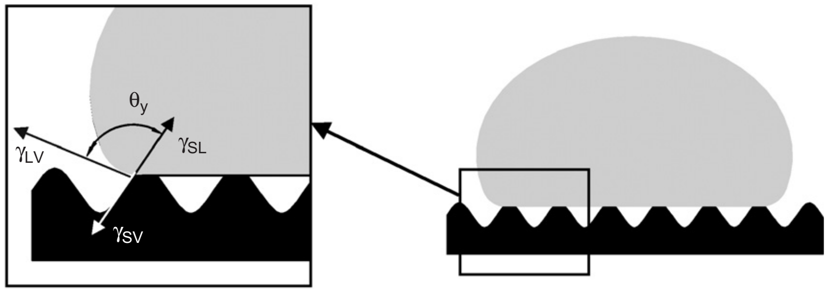

Fig. 1. Composite interface.

No study of ultrasound propagation at this type of composite interface exists and furthermore it is difficult to predict the presence of this kind of interface for real rough surfaces (random roughness). We therefore create artificial holes and plots to obtain a precise description of the roughness at a micrometric scale. The liquid metal used is lead–bismuth which is a potential substitute for sodium as coolant fluid in the international project Generation IV Forum for the fourth generation nuclear reactor. The non-wetting phenomena are of the same order and ultrasound transmission will be affected in the same manner as in the sodium. In Section 2 we discuss the quasistatic approximation (QSA), the approach generally used to describe an imperfect interface. We explain the similarities and differences of our problem in comparison with works on partially contacting surfaces.

The aim of this work is to study the influence of the composite interface on ultrasound propagation in order to experimentally demonstrate that this kind of interface is responsible for in-service inspection problems in liquid–metal cooled nuclear reactors. The use of several samples with different liquid–vapour ratios allows us to quantify the influence of this factor on the transmitted ultrasound signal amplitude compared with a sample not having a composite interface (interface liquid–solid only).

2. Ultrasound transmission at a composite interface

2.1. *Quasistatic approximation and existence of contacts at the interface*

Our study presents some common points with numerous research works on the modelling of the transmission of ultrasounds through partially contacting interfaces. Most of these studies used the QSA to describe the interaction of ultrasounds with imperfect interfaces. The concept of surface stiffness to describe the contact was presented by Kendall and Tabor [3]. The most inclusive formulation of the QSA has been published by Baik and Thompson. They model the imperfect contacts as continuous distributions of springs along the interface plane [4]. The description of imperfect interfaces addresses various domains: the study of the contact conditions between two solids [5,6], the possible non-detection of cracks under compressive stresses [7], the bonding of adhesive joints [8]. Most studies neglect the interface thickness due to the low frequency regime but in case of an interface between a layer and a substrate Pecorari shows that there is a dependence of the interfacial stiffness on the layer thickness [9].

It is well known that at a solid–air interface almost all the wave is reflected. Two rough surfaces pressed together are in contact at the asperity peaks. QSA modelling assumes that the wavelength is large compared with the width of the gaps. In this low frequency regime Baik and Thompson showed that the reflection coefficient is then obtained from:

$$|R_{12}| = \left|\frac{Z_1 - Z_2 + \mathrm{i}\omega(Z_1 Z_2/K)}{Z_1 + Z_2 + \mathrm{i}\omega(Z_1 Z_2/K)}\right|, \tag{2}$$

where K is the stiffness per unit area of the interface and relates the discontinuity of the displacement components to the corresponding components of the stress applied, Z are the acoustic impedances of the solids, ω is the angular frequency of the wave.

The stiffness per unit area of an interface is given by the rate of change of nominal pressure (p_{nom}) with surface deflection (u) [10]:

$$K = -\frac{\mathrm{d}p_{\mathrm{nom}}}{\mathrm{d}u}. \tag{3}$$

The important term when considering a possible application of this kind of approach for our composite interface is the term u. In QSA modelling it corresponds to the separation of the mean lines of the two rough surfaces, in other terms the average interfacial separation. The question is to understand whether such a description can apply to our interface.

In this study, we decided to work on a model rough surface with cylindrical holes. For a given liquid–solid system, a composite interface is obtained when the average width of the cavities on the surface of the solid is much less than the capillary length ℓ of the liquid studied. The capillary length is defined as follows:

$$\ell = \sqrt{\frac{\gamma_{\mathrm{LV}}}{\rho g}}, \tag{4}$$

where γ_{LV} represents the energy of the liquid–vapour interface and ρ the density of the liquid. In the absence of pressure due to ultrasound, the pressures at the holes are: the hydrostatic pressure ΔP_{H} due to the liquid column