A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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IDENTIFICATION OF STRUCTURAL DEFECTS OF METAL COMPOSITE CASTINGS WITH THE USE OF ELASTIC WAVES

IDENTYFIKACJA DEFEKTÓW STRUKTURY METALOWYCH ODLEWÓW KOMPOZYTOWYCH ZA POMOCĄ FAL SPRĘŻYSTYCH

The method of elastic wave propagation was applied to detect defects in composite castings (ingots). If a defect occurs, which is detected by the radiography, elastic wave propagation changes locally, i.e. causes disturbance of elastic wave propagation. Methods of signal analysis based on wavelet decomposition were used. Calculations related with wavelet analysis were made in the MATLAB environment using standard Wavelet Toolbox functions.

Keywords: acoustic emission, wavelet transform, quality of composite castings

Wykorzystano metodę badań bazującą na propagacji fal sprężystych do wykrywania wad odlewów kompozytowych. Poddano obserwacji lokalne zmiany propagacji fali sprężystej podczas analizowania defektów, których występowanie potwierdzono za pomocą defektoskopii radiologicznej. Zastosowano metody analizy sygnałów oparte na dekompozycji falkowej. Obliczenie transformat falkowych wykonano w środowisku MATLAB z wykorzystaniem standardowych funkcji Wavelet Toolbox.

1. Introduction

The elastic wave is formed when the energy of intermolecular bonds is released, which is caused by strains, cracks, phase transitions and other phenomena. The accumulated energy is released at the place where original structural bonds of the material get disarranged. If an external reason appears and changes the state of elastic energy acquired in operation, deformation processes originate in one or many areas of the material. During these processes, part of the accumulated energy can be emitted in the form of elastic waves. These elastic waves emitted by the source propagate throughout the volume of material and are subject to all processes associated with wave propagation. These waves are connected with and depend on physical processes that take place inside and outside the material at nano-, micro- and macroscopic levels [1].

2. Experimental investigation

Three samples randomly chosen from a series of cast metal matrix composites were examined. The composites were reinforced with short carbon fibres in the form of felt. The reinforcement was saturated under a pressure of 30MPa with liquid aluminium alloy (AlSi11) with all the technological requirements duly maintained [2–4]. The cylindrical shape of samples was adopted (ø – 44mm, h – 6mm) as such shape guarantees the easiness of the casting process, mechanical working and of testing.

To define the quality of materials, the samples were subject to X-ray defectoscopic tests, which were carried out at the AR company in Szczecin by means of an Andrex CMA max 16 kV, max 160 mA defectoscope. The parameters of the sample exposure were as follows: current [I]: 4 mA, voltage [U]: 80 kV, time of exposure : 2 min.

To check the methods used to detect structural defects in the composite castings, forced elastic wave signals in the form of acoustic emission signals were compared. Acoustic emission (stress wave emission) is understood as the propagation of elastic wave forced by an external stimulus.

The Hsu-Nielsen method was applied as the forcing medium. This method, utilizing the propagation of wave generated as a result of graphite break, is also used to calibrate a measurement path. The acoustic source is created by breaking a graphite pencil-lead covered

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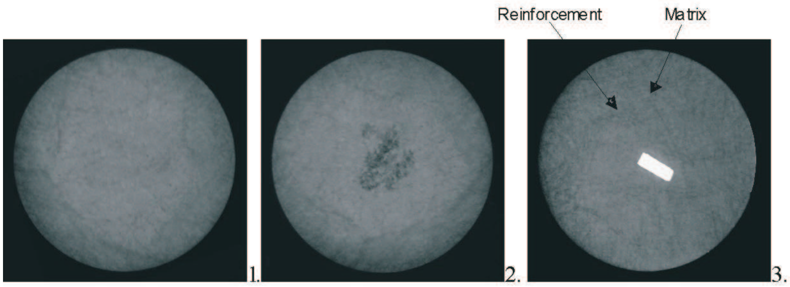

Fig. 1. Radiogram: sample No 1 – showing the structure of composite casting without defects detectable by means of X-ray defectoscopy; sample No 2 – showing insufficient saturation of the reinforcing structure with liquid metal of silumin warp, so called porosity; sample No 3 – an alien body seen in the central part of the casting. The chemical composition was determined on the basis of X-ray analysis [3]. (Dimensions of sample: diameter – 44 mm, height– 6 mm)

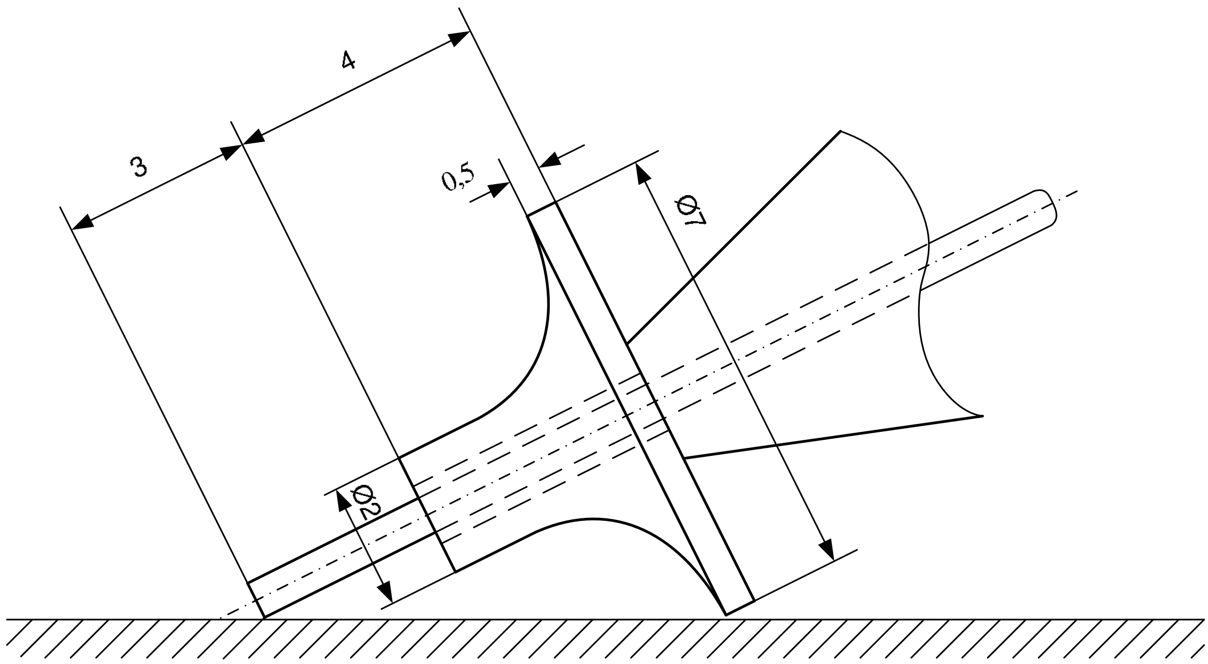

Fig. 2. Dimensions of the Hsu-Nielsen's calibrating head [3]

by an appropriately adapted tip. The pencil-lead diameter and hardness are, respectively, 0.5mm and 2H. The head, from which the pencil-lead is pulled out by three millimetres, ensures that the same angle exists at each break and, consequently, the same elastic wave is generated (acoustic emission). The measurement of the signal received from the graphite break guarantees repeatable calibration of the measurement path. This method is preferred at non-destructive measurements and was accepted as a standard in Western Europe and the USA [5–6]. The head is made of any polymer material. The general design of the head is shown in Figure 2.

The pencil-lead is broken on the same surface at a distance of 20mm from a transducer. The signal duration is very short, so the spectrum of the registered wave renders approximately the transducer amplitude characteristic along with the entire measurement path of signal transmission.

The form of the propagated wave depends on the material features of the medium. When the elastic wave encounters irregularities in the medium such as porosity or contaminants in the casting structure (Figure 1), basic parameters of the wave change. These parameters are: amplitude, phase, or time of passing through the tested material. The source signal resulting from breaking the graphite pencil-lead for a non-defective sample is shown in Figure 3a.

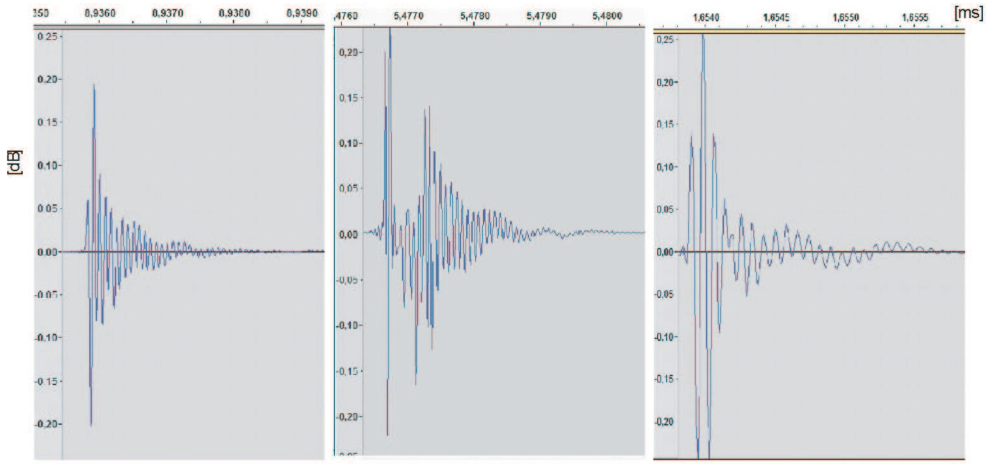

Fig. 3. The source signal for: a) sample without defects; b) sample with porosity; c) sample with an alien body (excitation of elastic wave with the Hsu-Nielsen method)

3. Selection of time-frequency analysis method

The most common method of signal analysis in diagnostic applications is the frequency analysis based on the Fourier transform. However, it does not enable locating momentary changes in the signal, i.e. locating the signals which originate from transitory processes [8–9]. Introducing a locating window defined as $w(t-b)$ to the Fourier transform, where b defines a shift of the window in time, we can define the Short Time Fourier Transform [10]:

$$S(b,f) = \int_{-\infty}^{+\infty} x(t) \cdot e^{-j2\pi ft} \cdot w(t-b)dt, \quad (1)$$

which is a generalised form of the Gabor transform [10]. The introduction of the locating window considerably improved the quality of results obtained from locating transient signals in relation to the traditional Fourier transform. However, the main restriction of the Short Time Fourier Transform is the constant window width which makes it difficult to analyse signals including components with considerably different frequencies. The next improvement of the signal analysis methods was the extension of the locating window features by adding a graduating parameter a, which enabled defining the analysing function as: $\psi\left(\frac{t-b}{a}\right)$. The function $\psi(t)$ can be generally any function described in an interval where it takes values different from zero [9]. It allows to select the analysing function to ensure the best possible mapping of the searched transitory process. On the basis of the above function, called the matrix (wavelet), base or main function, a two-dimensional function (wavelet transform) was defined:

$$WT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \cdot \psi\left(\frac{t-b}{a}\right)dt, \quad a,b \in R, a \neq 0 \quad (2)$$

where

$x(t)$ – analysed signal,

a– parameter defining frequency (scale),

b – parameter defining time (displacement).

A change in the parameter a leads to a change of the wavelet duration, i.e. wavelet frequency, while a change of the parameter b translates into a change of its localisation in the time domain. By varying these parameters we may optimise them for the required resolution in the time and frequency domains [9]. As the technology of microprocessors and their computing power has been improved in recent years, this method of signal analysis is gaining popularity [9], confirmed by works of authors representing a wide spectrum of science, from medicine to astrophysics to purely engineering applications [10–11].

Some publications present the results of signal analyses performed by means of another time-frequency method. The method, referred to as the Wigner-Ville transform, is defined as follows [8]:

$$W_x(t,f) = \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right) \cdot e^{-j2\pi f\tau}d\tau, \quad (3)$$

where $x*(t)$ is an imaginary signal conjugated with $x(t)$. However, with these assumptions, it is necessary to know the quantity $q_x(t,\tau) = x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right)$ in the entire interval for $\tau \in (-\infty; +\infty)$, which in practice may prove troublesome. That is why the expression $q_x(t,\tau)$ is replaced by its short-time version, which enables to define the so called pseudo Wigner-Wille distribution (PWVD) [8]:

$$PW_x(t,f) = \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right) \cdot w(\tau) \cdot e^{-j2\pi f\tau} d\tau \tag{4}$$

The Wigner-Ville transformation is generally used in signal analysis where the type of signal modulation is essential. Like the wavelet analysis, this kind of signal analysis offers the choice of an optimum resolution of time and frequency domains.

4. Summary

The Heisenberg uncertainty principle is fulfilled for the wavelet transform t, which enables testing the structure of the analyzed signal by means of energy distribution of its components. This principle reads that the signal energy described simultaneously in the time and frequency domains is concentrated around the point with the coordinates t and ξ, which determine the time coordinate and the mid-frequency band. The energy distribution in the time domain is determined by the wavelet span concentrated around the point t, whereas in the frequency domain it is determined by the span of the Fourier transform for the wavelet concentrated around the ξ point. The differences in the energy distribution in the time-scale coordinates open way to the pulse identification method. For the pulse signal, the energy distribution in the time-scale coordinates is different from that for other signals, e.g. for a harmonic signal [9]. The wavelet transforms were calculated in the MATLAB environment, where standard functions of Wavelet Toolbox were used. The result was a set of coefficients defining the similarity between a pulse for the standard composite material (sample 1 – without defects, see Fig. 1) and the same pulse for materials with casting defects (samples 2 and 3 in Fig. 1).

By using the wavelet decomposition of signal analysis, we were able to determine clear differences between signals depending on the structure of tested castings. Figures 4 to 6 illustrate the results of calculations of the energy pulse of pencil-lead breaks by means of the constant signal wavelet transformation, where the signal originated consecutively from a sample without defects (Fig. 4), a sample with material porosity (Fig. 5) and a sample with an alien body (Fig. 6). The observed differences in pulse energy were clear. For instance, a particularly strong broad-banded response came from the sample with porosity, connected with overlapping of the forced wave with numerous reflections, damping, attenuation and dissipation of the wave inside the porosity.

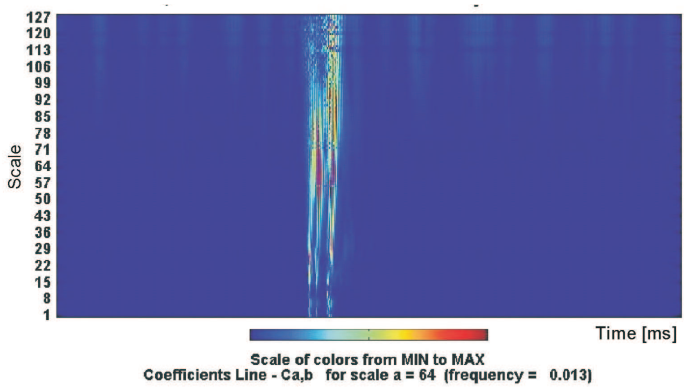

Fig. 4. The wavelet decomposition for sample 1 (denotations as in Fig. 1)

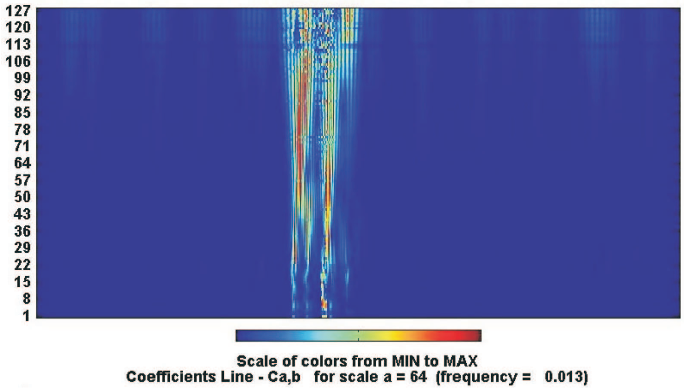

Fig. 5. The wavelet decomposition for sample 2 (denotations as in Fig. 1)

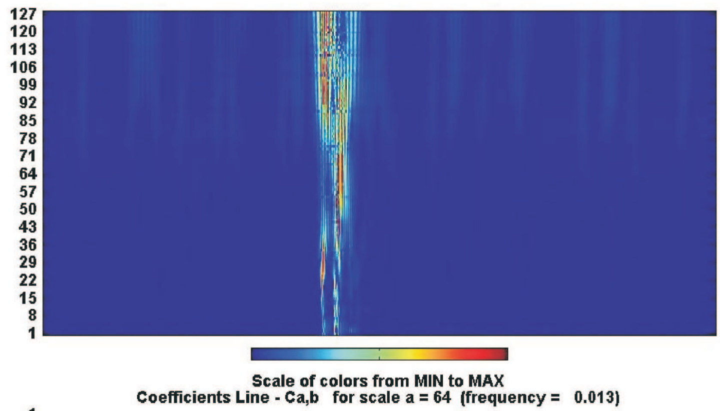

Fig. 6. The wavelet decomposition for sample 3 (denotations as in Fig. 1)

The constant wavelet transform seems to be particularly useful for analyses of internal processes of machine component material structures. These processes manifest themselves by non steady-state vibrations not only in the time domain. The area of the elementary window of analysis remains constant, because the time scale compression corresponds to an expansion of the frequency scale [9–10]. Although it is not directly the function of frequency, it can be interpreted as a two-dimensional analogy of the proportional spectrum. Therefore, the wavelet interpretation of the monitored signal offers a possibility of recognizing signal variability (dependent, *inter alia*, on material structure, e.g. defects such as porosity or an alien body in the casting structure) which enables the evaluation and simplification of the representation assigned to it.

5. Concluding Remarks

The proposed method of structure description, combined with X-ray radiography (Fig. 1) is an optimum diagnostic method. These authors continue research into applications of non-destructive measurement methods using elastic waves of the acoustic emission, concerning such issues as sizes of castings or ingots and the location of defects inside material structures. At present a patent application is being prepared, which describes in detail possibilities and methods of detecting and identifying defects in metallic composite materials.

6. Denotations

$w(t-b)$ – locating window of Fourier transform,
$\psi\left(\frac{t-b}{a}\right)$ – analyzing function,
$x(t)$ – analyzed signal,
a – frequency (scale coefficient) parameter,
b – time localization,
$x*(t)$ – imaginary signal conjugated with $x(t)$
t – time position of frequency band,
ξ – mean band frequency

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