DETERMINATION OF THE ELASTIC MODULI OF MATERIALS AT HIGH TEMPERATURES BY MEANS OF A NON-CONTACT SENSOR.

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Abstract. The determination of the elastic moduli of materials by means of the measurement of the frequencies of the elastic modes has become a celebrated technique (pulse excitation technique). Its non-destructive character and its ease of use in almost all circumstances make it very attractive for research as well as industrial environments. This work describes the state of the art and reports on the development of a non-contact laser-based sensor to detect the elastic deformations of materials even at temperatures up to 1200°C.

1. Introduction

The knowledge of the elastic constants such as the Young's modulus, the shear modulus and Poisson's ratio of engineering materials is indispensable for design and construction purposes. The most common techniques to determine the elastic properties are
1. Static bending
2. Ultrasonic method
3. Resonance method
4. Impulse excitation technique

The use of the first three techniques at high temperature introduces several technical and practical complications. The impulse excitation technique, on the other hand, allows non-contact measurement of elastic waves in materials even at a remote distance. In this study, it is shown that the potentialities of this technique can be enlarged by optical detection of the elastic waves and this opens new opportunities for high temperature materials characterisation and quality control.

2. Impulse excitation technique

A macroscopic but elastic distortion in a material will propagate by means of elastic waves. The typical frequencies of these waves lie between 0.1 Hz and 100 kHz. Once elastic waves are created, they are subject to several damping mechanisms which depend strongly on materials properties. Depending on the shape of the specimens, however, some modes can persist longer as standing waves with frequencies which are related to the dimensions and material properties of the specimen. The standing wave mode with the lowest frequency, the so-called fundamental or ground mode, has the largest amplitude and is consequently most suited for detection.
The wave equation of elastic waves in a material are solutions of a fourth-order differential equation which depend on the boundary conditions (i.e. the shape of the specimen) in a very complicated way. Therefore, the dependence of the frequencies of the elastic modes on materials properties such as the elastic moduli, density etc.... has theoretically been determined for some specific simple geometries like rods and bars only. Consequently, most of the test specimens have preferably this particular shape. Although every elastic mode contains physical information about the material under investigation, the knowledge of the frequency of the

ground mode suffices to determine the elastic constants. The results of theoretical calculations can be found in literature [1-6].
The transient technique by which elastic properties are obtained from elastic wave analysis is known as the Impulse Excitation Technique or the Dynamic Resonance Method. After a sample is struck mechanically, the material vibrations are captured by a sensor and converted into an electrical signal which can be analysed.
A short time after the impact, most of the transient and higher order elastic waves are dissipated and the ground mode is the remaining vibrational mode (see figure 1). Since the technique is focused on determining the frequency of the ground mode, spectral analysis as well as a time analysis of the vibrational modes are appropriate. The last technique is based on simply counting zero-passages of the remaining ground mode and is used in commercial instruments like the GrindoSonic. As soon as the frequency is deduced, elastic moduli can be calculated.

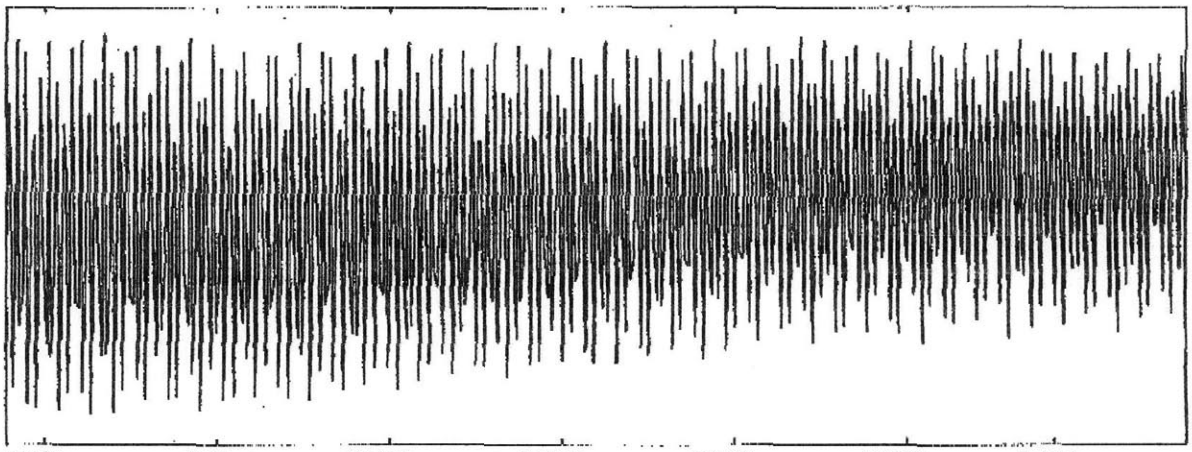

Figure 1.

A brass bar vibrating in its ground mode 0.05 seconds after excitation. The vibrations were captured by means of a Doppler interferometer. All vibrations except the ground mode are dissipated. The modulation of the exponential damping of the ground mode is probably a result of the motion of the centre of mass of the bar due to excitation.

All longitudinal and flexural (transverse) vibrational modes are related to Young's modulus. The torsional modes give information about shear modulus. In literature it is described in detail which procedures have to be followed and how test specimens have to be excited in order to activate the desired vibrational modes [7-13].
The power of the impulse excitation technique lies in the fact that the low-level stress which is applied to the material does not initiate non-linear or non-elastic phenomena. The stress itself is applied in a very short time interval (a pulse) and makes long-time interaction with the specimen as in traditional static techniques superfluous. The excitation creates a broad spectrum of vibrations including the ground mode, but without initialising inelastic distortions or motion of the centre of mass. Nevertheless, the excitation may cause practical problems, especially when the specimens are small or light (motion of the centre of mass!) or placed in a furnace but it is astonishing how easily the ground mode can be activated by even the lightest strike or tap.

3. Detection of elastic waves

The most crucial part of the impulse excitation technique is the sensor by which the elastic waves are captured. Preferably, detection should be performed without making contact to the sample. The most obvious non-contact sensor, considering the frequency range, is a microphone. Although useful in a very wide range, it is very sensitive for disturbance and noise from the environment. By using wave guides, the sound waves can be channelled. This technique is used to register the sound waves of a specimen at high temperature outside a furnace. The frequency of the ground mode of a bar of SiC as a function of temperature measured by this technique is shown in figure 2.

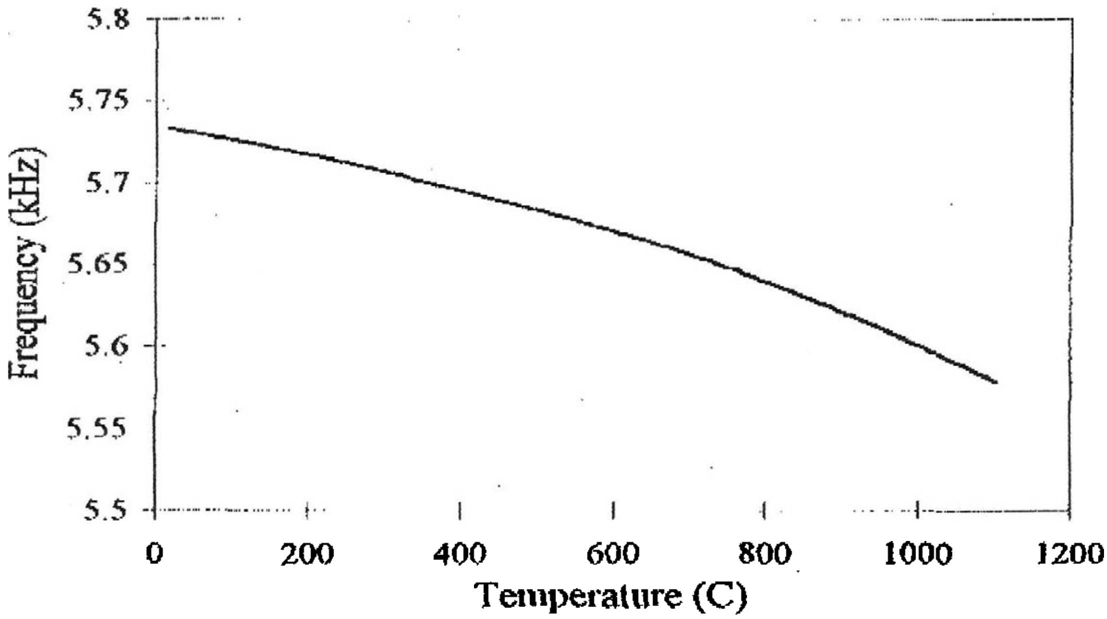

Figure 2

The frequency of the transversal elastic ground mode of a SiC bar between 20 and 1120 °C measured by means of a microphone at the end of a ceramic wave guide trough the walls of the furnace. The data were analysed with a GrindoSonic.

Piezo-electric sensors, on the other hand, make direct contact to the specimens and may disturb the elastic modes, altering the frequencies. But commonly this effect is negligible. For sufficiently massieve specimens these types of sensitive sensors have become the standard sensor for several applications.
As a conclusion, although the available sensors cover a very wide range of applications, measurements at high and low temperatures, in hostile environments, on small specimens, in vacuum, etc...can not be performed easily. Therefore, an optical sensor was developed.

4. Optical detection of elastic waves.

The detection of wave phenomena like ultra sound by means of optical techniques is a well established technique in solid state physics and materials research. This indicates that optical sensors are very suited too for the detection of elastic distortions in materials in the high and low temperature range and in very small specimens. Probably, it can replace the conventional sensors in some standard applications.

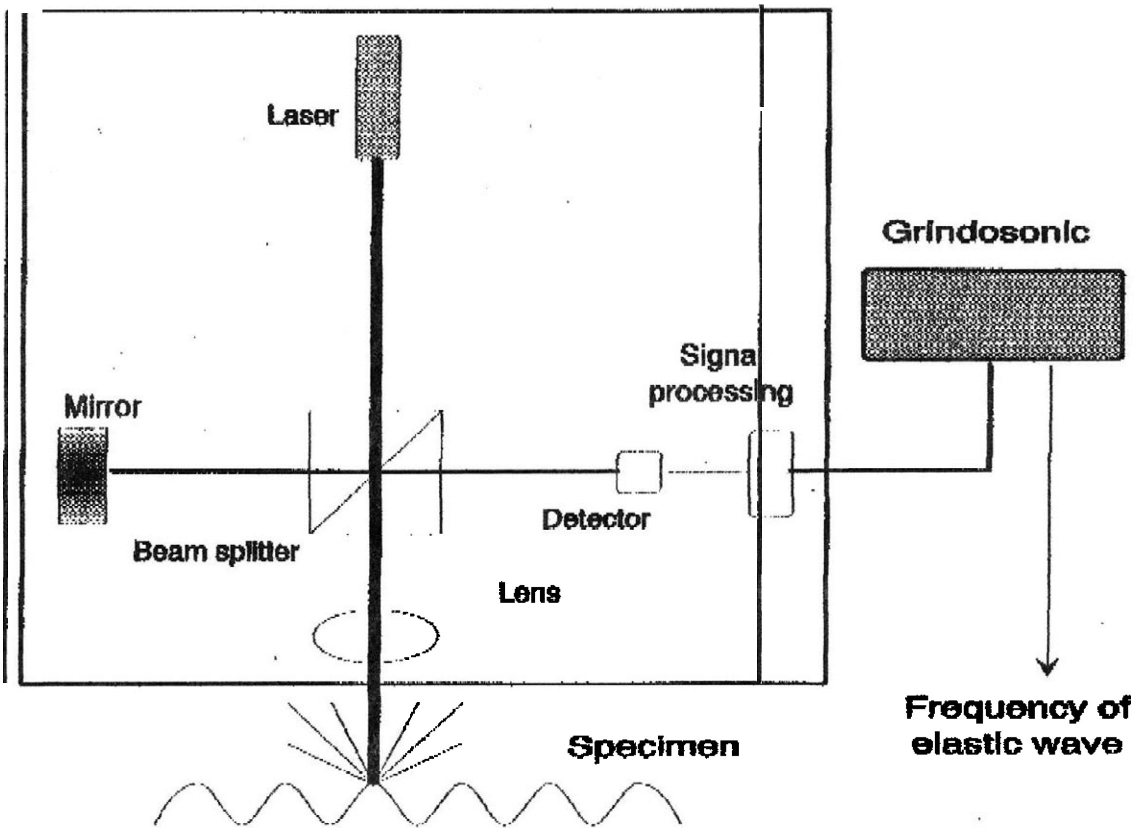

Figure 3

Principle of the detection of elastic waves in materials by means of an interferometric configuration (Michelson interferometer). The materials surface acts as a mirror in one of the arms of the interferometer. For details see text.

Optical techniques can be divided roughly into interferometric and non-interferometric techniques [14]. The practical problems which one encounters with any optical technique are vibrations of the setup, scattering due to rough surfaces, air turbulence in furnaces, interfering reflections on windows of furnaces and cryostats, etc... Actually, there is no unique optical detection technique which covers all applications
The configuration of an interferometric setup is shown in figure 3. All interferometric sensors are based on the principle that (commonly) a laserbeam is reflected on the vibrating materials surface (which acts as one of the mirrors in a Michelson interferometer) and interferes with the undisturbed laser beam. The elastic waves have essentially two effects on the reflected light: a phase modulation and a frequency shift. The information contained in this light is, after detection, processed by standard electronics. A description of the used techniques can be found briefly in reference 14. A detailed description of the sensor will be published elsewhere.
As a result of calculations and experimental evidence, we found that elastic waves with amplitudes of at least 100 nm can easily be detected. The setup was tested on several samples with rather smooth surface. The signal was analysed by a GrindoSonic apparatus. The testing of the sensor on samples with rough surface and on samples at high temperature (the aim is at least 1200° C) is still going on. The experimental configuration used for the high temperature measurement is shown in figure 4.

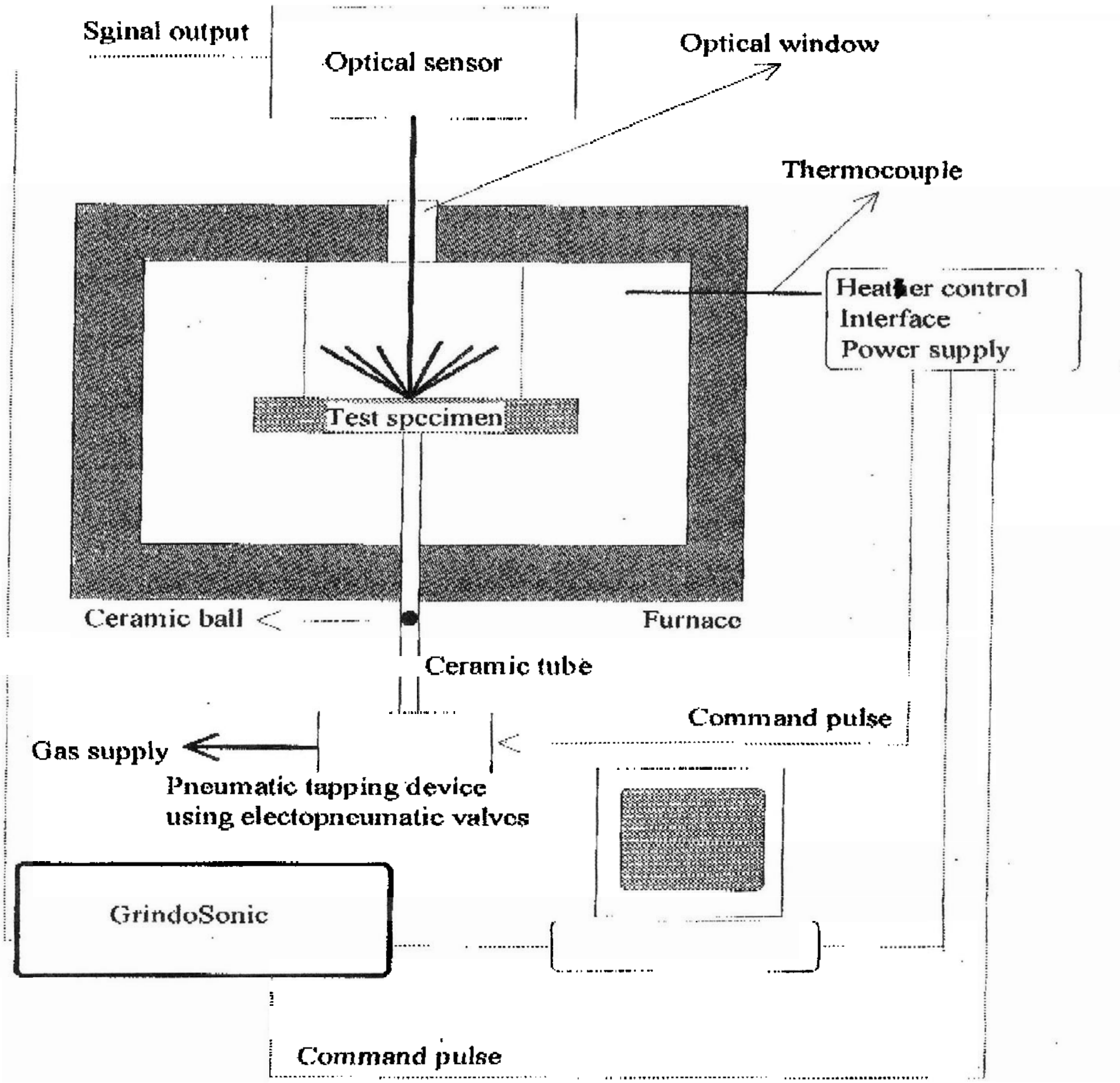

Figure 4

Schematic presentation of a setup to determine the elastic properties of materials at high temperatures. The wave analysis is performed by means of a GirndoSonic apparatus. The excitation of the specimen occurs by a small ceramic ball which is pneumatically projected against the bottom side of the test specimen. The specimen itself is is hanging freely in two stainless steel wires at the fundamental transverse nodal points. Each measurement sequence, including the temperatur control of the furnace and the electropneumatic valves is computer controlled. The elastic muduli can be measured automatically at increasing and decreasing temperatures.

References

[1]. B. Kardashev, S. Kustov, A.Lebedev and S. Nikanorov, J.Mech. behavoir of Materials Vol. 4 no.3 (1993), 225

[1]. F. Förster, Zeit.für Metallkunde 29 (4) (1937), 109

[2]. S. Spinner and W.E. Tefft, Proc. ASTM vol61 (1961), 1229

[3]. W.E. Tefft. J.of Research NBS Vol 64B(4) (1932), 237

[4]. G. Pickett, Proc.Am.Soc.Testing-Mats Vol.45 (1945), 846

[5] R.M. Davies, Philosophical Magazine Vol. 25 (1938) 364

[6]. R. Wagel and H. Walther, Physics Vol.6 (1935), 141

[7]. ASTM C215-85

[8]. ASTM C623-71

[9]. ASTM E111-82

[10]. ASTM C848-78

[11]. ASTM C747-74

[12]. A. Wolfenden et al. J.of Testing and EvaluationVol 17,1 (1989), 2

[13]. K. Heritage, C. Frisby and A. Wolfenden Rev.Sci.Instrum 59(6) (1988), 973

[14] J.P. Monchalin, IEEE transactions *on* UFFC Vol.5 (1986), 485