**CMMT(MN)049**

# Elevated Temperature Modulus Measurements using the Impulse Excitation Technique (IET)

This Measurement Note discusses the application and relevance of the Impulse Excitation Technique for measuring the variation of modulus of metallic materials over a temperature range relevant to warm and hot metalworking. Results are presented for an aluminium alloy, a 316 stainless steel and nickel-based superalloy. The materials were chosen to represent the requirements of the major ferrous and non-ferrous metal processing sectors.

Although most metalworking operations involve large scale plastic deformation, many of the finite element (FE) models developed to model the processes require thermo-elastic-plastic analyses which incorporate heat transfer, deformation and elastic effects. The elevated temperature elastic modulus is a significant parameter in these calculations. There are also a number of special cases where elastic effects are particularly important, for example when examining the development of residual stresses and springback in sheet metalworking processes and for modelling the performance of the tool or roll, contact and lubrication at the tool/workpiece interface.

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# Introduction

There is not a wealth of information in the literature on the variation of elastic modulus with temperature. Data is available in a number of handbooks, but often only over a limited temperature range. Also, much of the fundamental work on the elastic properties has focused on pure metals and only a limited number of materials [1-3] and there is relatively little information in the literature on modulus measurement methods at elevated temperatures for engineering alloys.

Fig. 1 shows the typical variation of modulus with temperature for a range of metals [1].

At the temperatures involved in hot metalworking, accurate measurement of modulus from conventional mechanical tests is difficult, mainly due to the problems associated with strain measurement. Dynamic modulus methods, which are based on the speed of stress waves in solids, offer a solution and the techniques can be used to measure the variation of elastic modulus over a wide temperature range, although the issue of dynamic vs static values for modulus remains.

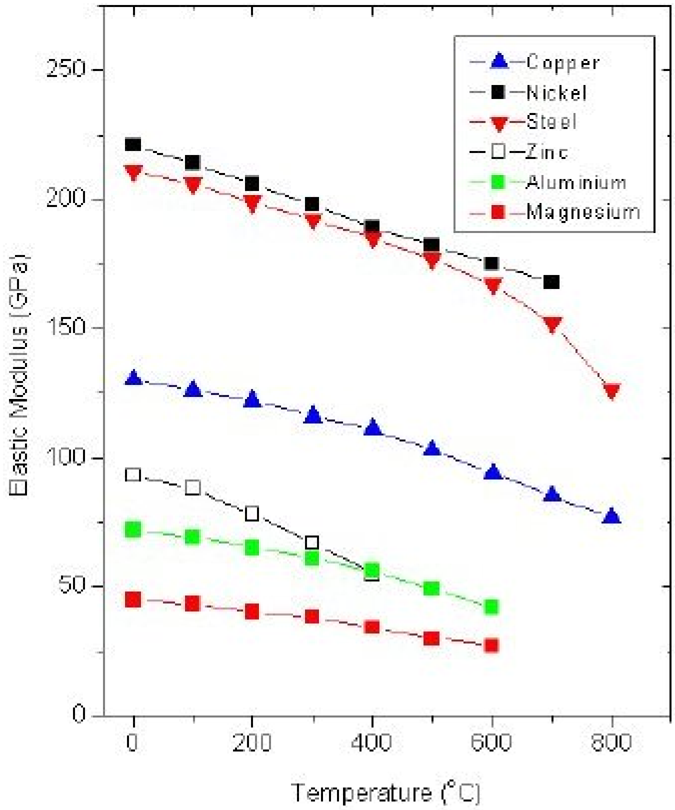


**Figure 1: Variation of modulus with temperature for a variety of metals [1].**

# Dynamic Modulus Methods

A variety of dynamic modulus methods are available including:

- Flexural resonance methods
- Ultrasonic wave propagation
- Impulse excitation technique (IET)

The most commonly used methods for metals are the resonance techniques. The dynamic methods are relatively quick and simple and involve small elastic strains and high strain rates. Some can be readily modified to enable high temperature measurements. In the present work at NPL, tests have been carried out on a variety of materials using the Impulse Excitation Technique (IET), which is described in some detail below.

## Impulse Excitation Technique

The Impulse Excitation Technique (IET) involves the excitation of a testpiece by a small mechanical impulse and subsequent analysis of the fundamental resonant frequency of flexural vibration via a piezo-electric transducer in contact with the testpiece [4-8]. In the present work the testpieces were supported at the nodes of resonance in a furnace and struck by small ruby balls dropped down a guide tube to hit the centre of the testpiece.

The equation used to calculate modulus [4] is:

$$E = 0.9465 \frac{m}{w} f^2 \left(\frac{L}{t}\right)^3 T_1$$

where $m$ is the mass of the testpiece, $w$, $L$ and $t$ are the dimensions, $f$ is the fundamental resonant frequency for flexural vibration and $T_1$ is a shape factor, which for a **rectangular bar** is:

$$T_1 = 1 + 6.585\left(\frac{t}{L}\right)^2$$

The mass and dimensions of the testpiece were measured prior to testing, and measurements of the resonant frequency were taken at intervals of 100°C during both the heating and cooling cycle, with the specimen held at temperature for 10 minutes prior to taking the readings to ensure temperature uniformity. Three measurements were made at each temperature interval, and the mean frequency value used to calculate the elastic modulus. Results are presented in Figure 2a for the Aluminium 5052, Stainless 316 and Nimonic 901, plotted against the test temperature and normalised with respect to half the melting temperature in Figure 2b.

The theoretical errors in measurement of modulus by dynamic methods are small, of the order of ±1%. An important limitation of the technique is caused by internal damping, which causes a loss of signal as the temperature increases. The phenomenon occurs in all materials including metals and ceramics, but it is difficult to predict when this will occur. There are several mechanisms which result in damping associated with the movement of dislocations, viscous sliding between grains, point defects and thermoelastic effects. In the present work, no measurements could be made above 550°C for the aluminium alloy, and above 920°C and 1160°C for the Stainless and Nimonic specimens respectively.The approach of the temperature limit could be observed on the frequency analyser display as a broadening in the peak of the fundamental frequency accompanied by a sharp reduction in amplitude.

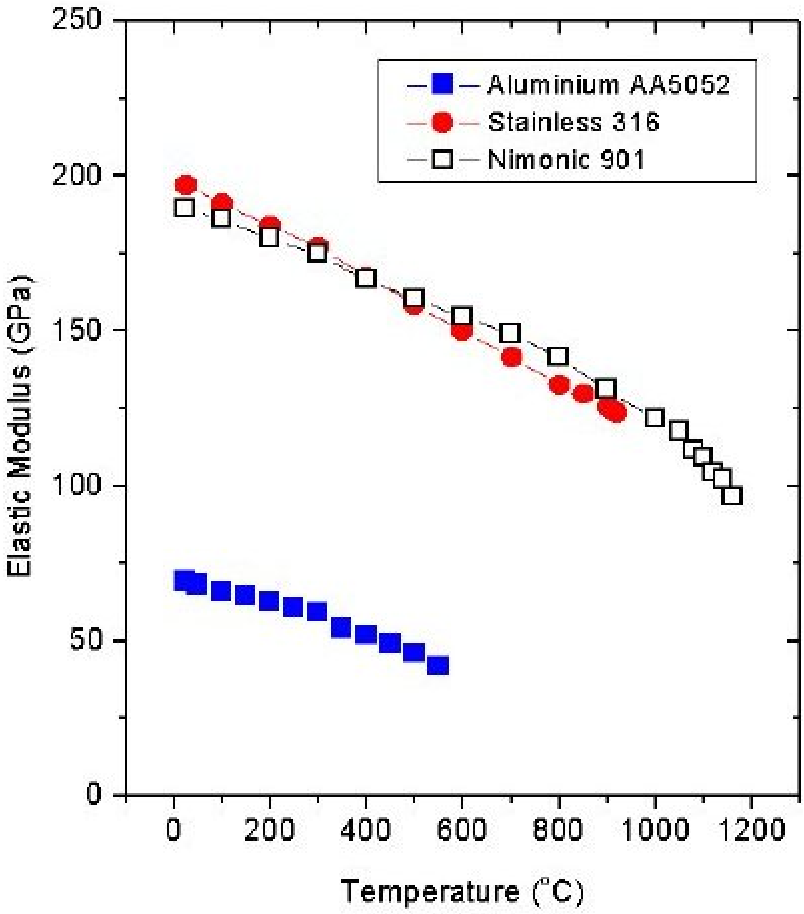


**Figure 2a: Variation of modulus with temperature**

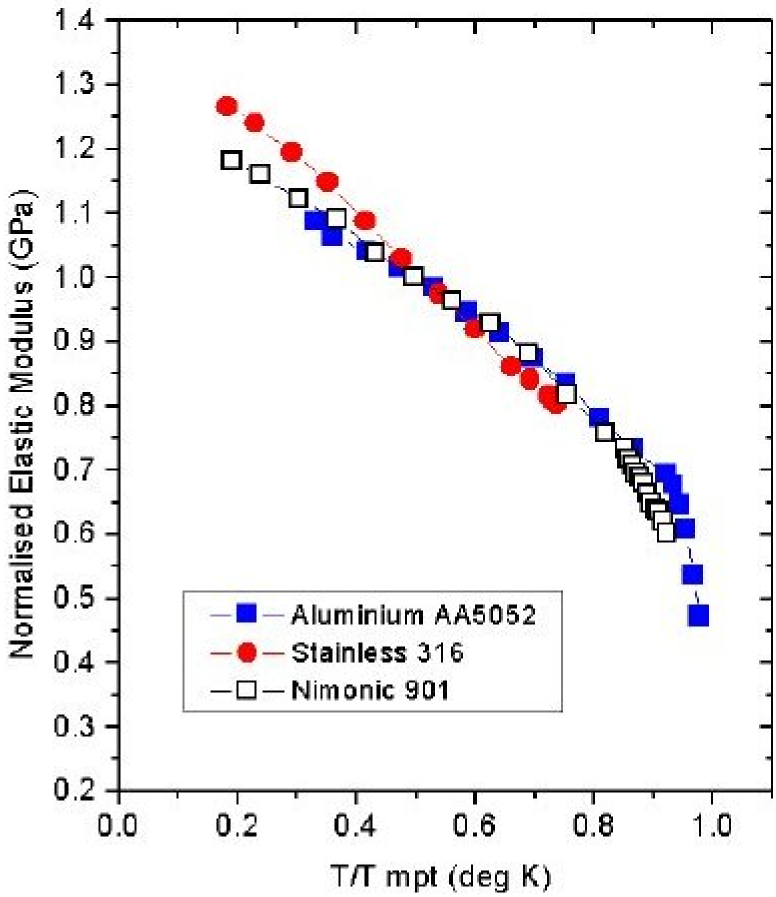


**Figure 2b: Normalised data**

The variation of modulus is non-linear and the slope begins to fall rapidly at higher temperatures, approaching the solidus. The modulus of a material is a function of the elastic behaviour of the constituent phases, and the distinct changes in slope which have been observed at specific temperatures in some materials [9] can be linked clearly to changes in microstructure.

# Summary

- Results from work at NPL support the utility of the impulse excitation technique for measuring the modulus of a variety of engineering alloys over the temperature range relative to warm and hot metalworking.
- The normalised modulus values were similar for the 3 materials examined.
- The dynamic modulus measurements showed excellent repeatability, with a typical uncertainty of ±1%. Dynamic methods have the advantage of being quick and simple, but the issue regarding the relevance of dynamic vs static measurements has still not been fully addressed.
- The dynamic modulus techniques could be applied equally to the tool and die materials to generate input data to FE models.

# Acknowledgement

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