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Measurements of the Thermal Expansion Coefficient of 1Cr18Ni9Ti Stainless Steel with a Laser Scanning Microdisplacement Detection Technique[1]

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A laser scanning microdisplacement detection system has been developed to measure the thermal expansion coefficient of materials over the range from room temperature to 1200 K. The measurement apparatus consists of a dynamic heating device, a microdisplacement detection system, and a microcomputer-based high-speed data acquisition system. The specimen is dynamically heated from room temperature to 1200 K by passing a large electrical current through it. The thermal expansion of the specimen is detected by the laser detection system, which records the shift of Fraunhofer diffraction fringes with a photodetector. Measurements of the mean linear thermal expansion coefficient of 1Cr18Ni9Ti stainless steel in the range of 300–1200 K are described. The results are compared with other reported values of the thermal expansion coefficient. The maximum deviation between them is about 2.3% at the highest temperature, 1200 K.

KEY WORDS: dynamic heating; high temperature; laser application technique; thermal expansion coefficient.

1. INTRODUCTION

Generally, optical interferometric techniques can be used for accurate measurements of the thermal expansion coefficient in both low-temperature and high-temperature ranges [1–4]. But in optical interferometric techniques, the specimen must be specially prepared to meet some strict requirements, such as flatness, parallelism, and high reflectivity of the

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specimen, etc., and a sophisticated interferometric system is needed. This is why it is seldom used for industrial measurements. Recently, we have developed a laser scanning microdisplacement detection technique for the purpose of measuring the thermal expansion of electroconductive solids from room temperature to 1200 K with an accuracy sufficient for industrial applications. This involves rapidly heating the specimen from room temperature to the desired high temperature by the passage of electrical current through it and simultaneously measuring the specimen temperature with a thermocouple and recording the shift in the Fraunhofer diffraction pattern produced by a laser/slit system.

2. MEASUREMENT APPARATUS

The measurement apparatus consists of (i) a large current power supply, (ii) a laser diffraction microdisplacement detection system, and (iii) a microcomputer-based data acquisition system. A functional diagram of the measurement system is presented in Fig. 1.

2.1. Dynamic Heating System

The heating apparatus is a large current output thyristor (voltage, 12 V; current, 1000 A). The power output can be controlled either manually

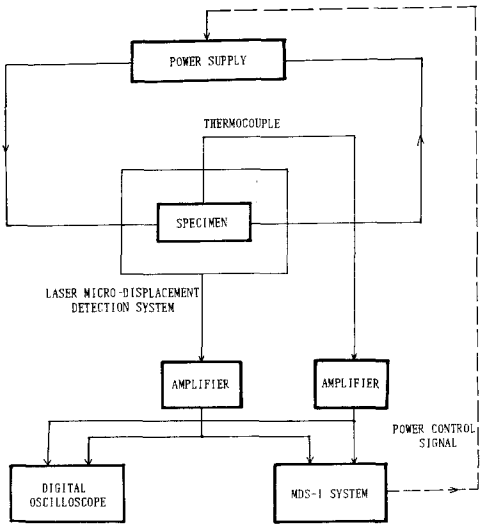

Fig. 1. Functional diagram of the dynamic heating system for the measurement of thermal expansion of electrically conducting solids.

or by a D/A output of the data acquisition system. So it is easy to set the heating rate of the specimen.

2.2. Specimen

A photograph of the specimen, which was fabricated from 1Cr18Ni9Ti stainless steel (2×6 mm; middle section length, 200 mm), is shown in Fig. 2. Two specially designed extensometers were attached to the center portion of the specimen. Each extensometer consists of two flexible arms and two rigid arms containing four pin rods with conically pointed ends to facilitate mounting to the sides of the specimen (see Fig. 3). So when the specimen expands, the extensometer does not constrain its expansion. A shaving blade is fixed on one rigid arm of each extensometer to form a slit between the edges of the blades, through which the laser beam is passed to produce a diffraction pattern. The specimen is fixed at the upper end and free at the lower end, which allows it to expand freely as shown in Fig. 4.

2.3. Laser Diffraction Microdisplacement Detection Technique

With Fraunhofer diffraction by a slit, the intensity of the diffraction pattern received at a sufficient distance L from the slit can be expressed as [5]

$$I = I_0 \frac{\sin^2(\pi b \sin \phi/\lambda)}{(\pi b \sin \phi/\lambda)^2} \tag{1}$$

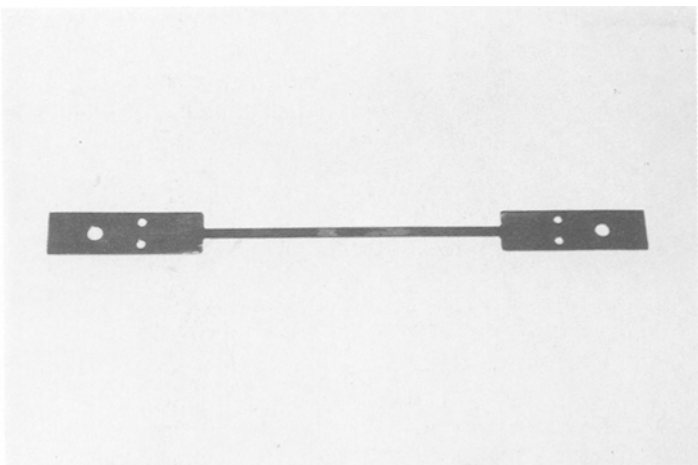

Fig. 2. Photograph of the specimen used in the present experiment.

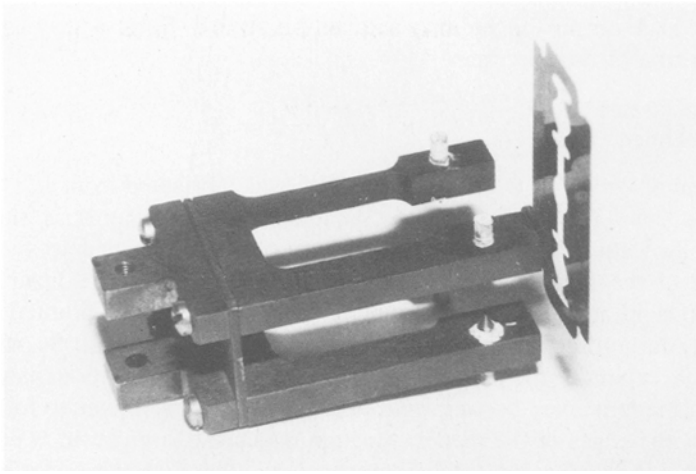

Fig. 3. Photograph of the specially designed extensometer used in the present experiment.

where I_0 is the intensity of the center of the diffraction pattern, λ is the wave length of the laser, ϕ is the diffraction angle, and b is the width of the slit.

At a fixed diffraction angle where the photodetector is located, the intensity received varies as a sinusoidal function with the variation of b. The output v of the photodetector can be expressed as

$$v = V(u) \sin^2 u \tag{2}$$

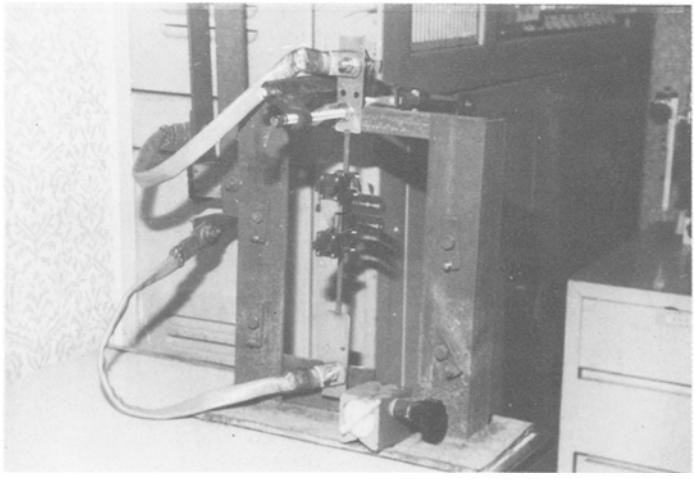

Fig. 4. Photograph of the specimen mounted on the support assembly.

where V is the amplitude and the phase of the fringe shift pattern is given by

$$u = \frac{\pi b \sin \phi}{\lambda} \tag{3}$$

In general,

$$u = k\pi \tag{4}$$

where k is the fringe order. Both the amplitude and the phase of Eq. (2) are a function of argument u, which, in turn, is a function of b.

From the combination of Eqs. (3) and (4), the width of the slit can be calculated by

$$b = \frac{k\lambda}{\sin \phi} \tag{5}$$

and the change in slit width by

$$\Delta b = (b_2 - b_1) = (k_2 - k_1)\frac{\lambda}{\sin \phi} = N\frac{\lambda}{\sin \phi} \tag{6}$$

where subscripts 1 and 2 denote the initial state and present state, respectively, and N is the number of fringes which have shifted across the photodetector. Consequently, by measuring the fringe number N, the variation of a slit's width Δb can be determined.

The arrangement of the laser microdisplacement detection system is schematically shown in Fig. 5.

2.4. Data Acquisition and Analysis

In the experiment, a He–Ne laser (7 mW) is used to illuminate the slit directly with a narrow beam (diameter, about 1.5 mm) and a diffraction

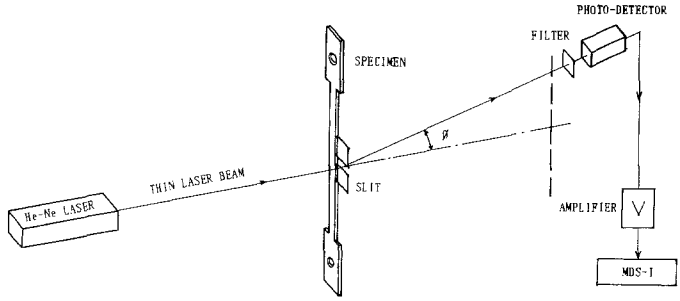

Fig. 5. Schematic diagram of the arrangement of the laser microdisplacement detection system.

pattern is produced. The optical fringe signal is converted into electrical current by a silicon photocell, which is located at a fixed diffraction angle ϕ (see Fig. 5). The current output (in the range of 1–10 nA) is amplified to the level of volts and then recorded by a data acquisition system. During controlled dynamic heating (heating rate in the range of 25–30 $K \cdot s^{-1}$), a fringe shift is produced by the expansion of the heated specimen.

The temperature of the specimen is measured with a thermocouple and recorded by the data acquisition system. The thermocouple (K type) is spot welded onto the surface of the specimen (diameter of the thermocouple is 0.05 mm to obtain a good thermal response).

The computer used in the data acquisition system is a MDS-I microcomputer. A fringe/temperature pair was sampled every 20 ms. The total recording time was 50 s (i.e., 2500 data pairs).

The mean linear thermal expansion coefficient $\bar{\alpha}$ in the temperature range $\Delta T = T - T_0$, can be computed from the following equation:

$$\bar{\alpha} = \frac{\lambda}{l_0 \sin \phi} \frac{N}{\Delta T} \tag{7}$$

where l_0 is the length of the specimen at reference temperature T_0 (20°C in the present work). Therefore, individual values for $\bar{\alpha}$ may be determined from the fringe number N observed at each recorded temperature. In the present work, final values for $\bar{\alpha}$ were determined by fitting a polynomial

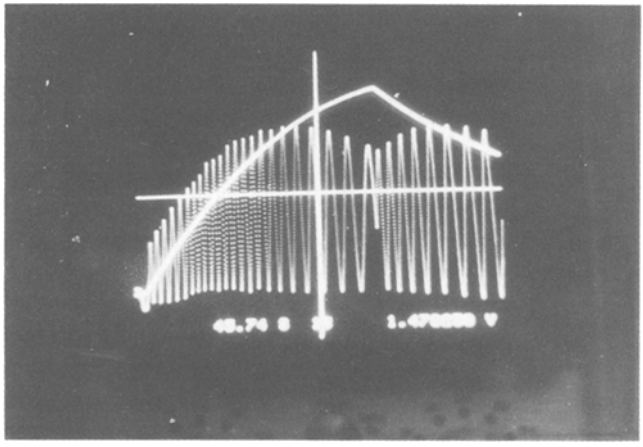

Fig. 6. Photograph of the two traces of a dual-beam digital oscilloscope recorded during a typical experiment. The sine wave-like trace shows the fringe shift produced by the expansion of specimen as it was heated. The other trace is the temperature variation of the specimen during heating.

function of temperature to the fringe number/temperature data pairs by the method of least squares and then using the smooth function for N in Eq. (7).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 6 is a photograph of the two traces of a dual-beam digital oscilloscope (Nicolet 4094A) taken during a typical experiment. The sine wave-like trace shows the fringe shift produced by the expansion of the heated specimen. The other trace is the temperature variation of the heated specimen.

Figure 7 shows the present results for the mean linear expansion coefficient of 1Cr18Ni9Ti stainless steel; the points represent values of $\bar{\alpha}$ as determined from the fringe number N at each recorded temperature, and the solid curve represents $\bar{\alpha}$ as determined from the smoothed values of N.

A comparison of the present results for 1Cr18Ni9Ti stainless steel with the linear thermal expansion coefficient data found in Ref. 7 is given in Table I. The maximum deviation between them is about 2.3% at the highest temperature, 900°C.

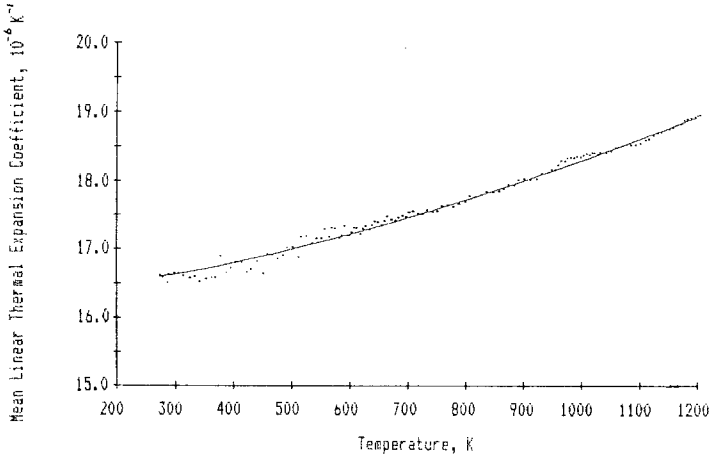

Fig. 7. Mean thermal expansion coefficient of 1Cr18Ni9Ti stainless steel measured in the present work. Individual points are the data prior to smoothing and the solid curve is the result after smoothing.

Table I. A Comparison of the Present Results for the Mean Linear Thermal Expansion Coefficient of 1Cr18Ni9Ti Stainless Steel with Data Reporterd in Ref. 7

Temperature (°(C)	$\bar{\alpha}$ $(10^{-6}\,K^{-1})^a$	$\bar{\alpha}$ $(10^{-6}\,K^{-1})^b$	Deviation (%)
100	16.75	16.6	0.90
200	16.93	17.0	0.41
300	17.15	17.2	0.88
400	17.39	17.5	0.63
500	17.65	17.9	1.40
600	17.92	18.2	1.54
700	18.21	18.6	2.10
800	18.52	—	—
900	18.84	19.3	2.34

[a] Present results based on a reference temperature of 20°C.

[b] Values from Ref. 7, based on a reference temperature of 20°C. Chemical composition (%): C, <0.12; Si, <0.80; Mn, <2.00; Cr, 17.0–19.0; Ni, 8.00–11.00; Ti, $(C-0.02)\times 5=0.8$; S, <0.030; P, <0.035.

4. CONCLUSION

A dynamic technique for measuring the thermal expansion coefficient of electrically conducting materials over the range from room temperature to 1200 K has been described. In the proposed laser scanning microdisplacement detection method, the specimens do not require special preparation and the measurement accuracy and sensitivity are reasonably high. Therefore, this technique is well suited for industrial applications.

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