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Note

Electrical Resistivity and Thermal Expansion of Liquid Titanium and Zirconium

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The electrical resistivity and thermal expansion have been measured to twofold expanded states for titanium and to 60% expanded states for zirconium using the isobaric expansion apparatus. Results are consistent with the literature where there is overlap.

KEY WORDS: electrical resistivity; high temperature; thermal expansion; titanium; zirconium.

1. INTRODUCTION

The thermophysical properties of titanium and zirconium are important because of their use in aerospace and nuclear power industries. At present, data for the liquid range is almost nonexistent in the literature. Preliminary measurements on these materials were made using the isobaric expansion apparatus [1].

2. EXPERIMENTAL RESULTS

2.1. Sample Details

The titanium samples used were in the form of 1 mm diameter wire obtained from Verbik Metals Corporation.[2] The chemical analysis supplied

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[2] Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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by the manufacturer was 99.9 Ti, 0.005 C, 0.022 Fe, 0.076 O_2, 0.001 H_2, and 0.009 Tl, in weight percent. The wire was pulled to straighten it before cutting to suitable lengths. The surface appearance was rather grainy and showed tarnish. Specimens were etched for 20 min in concentrated nitric acid to remove tarnish immediately before assembling for the experiments. The density of the material at room temperature was taken to be 4.46 $g \cdot cm^{-3}$.

The zirconium samples were obtained from Goodfellow Metals[2] as wire 1 mm in diameter. The purity was specified as 99.8% by the manufacturer. The wire was noticeably grainy, but no tarnish was evident; therefore, no etch was made. A length of wire was pulled straight before cutting the sample. The initial density was taken as 6.53 $g \cdot cm^{-3}$.

2.2. Titanium Results

The nature of the isobaric expansion experiment makes it much more convenient to determine measured quantities relative to specific enthalpy rather than temperature. In addition, the enthalpy is a much more reliably measured quantity than temperature. Results from the literature which use temperature as the independent variable have had the temperature converted to enthalpy using the 1973 Hultgren tables [2] for purposes of comparison. The measurements in this work were made at a pressure of 0.3 Gpa. Enthalpies are relative to the state at 298 K. No corrections for work done in pressurizing the cell were made. As a practical matter, the compressibilities of the metals at 298 K are so small that the correction would not show in the figures.

The resistivity measurements for titanium are shown in Fig. 1. The values are corrected for thermal expansion using the volume data obtained at the same time. The correction is made by multiplying the resistance ratio R/R_0 by the volume ratio V/V_0, where R_0 and V_0 are the initial values. The solid curve corresponds to a single experiment. The enthalpies for the phase transition from the α (hcp) to the β (bcc) phase and the melting transition shown correspond to the values of Hultgren et al.

Cezairliyan and Miiller [3–5] measured electrical resistivity through the solid phase transition and in the β phase. Their values were not corrected for thermal expansion. If the thermal expansion results from this work are used to make a correction to their β-phase results, the values would increase about 5%, giving excellent agreement with the data from this work. Arutyunov et al. [6] also measured resistivity and applied thermal expansion corrections. Their results are shown. Seydel and Fucke [7] made measurements similar to the isobaric measurements by using a water filled pressure cell. Their results are shown as the dashed curve in the figure.

Figure 2 shows the corresponding thermal expansion for the experiment. Burgers and Jacobs [8] made X-ray diffraction measurements of the

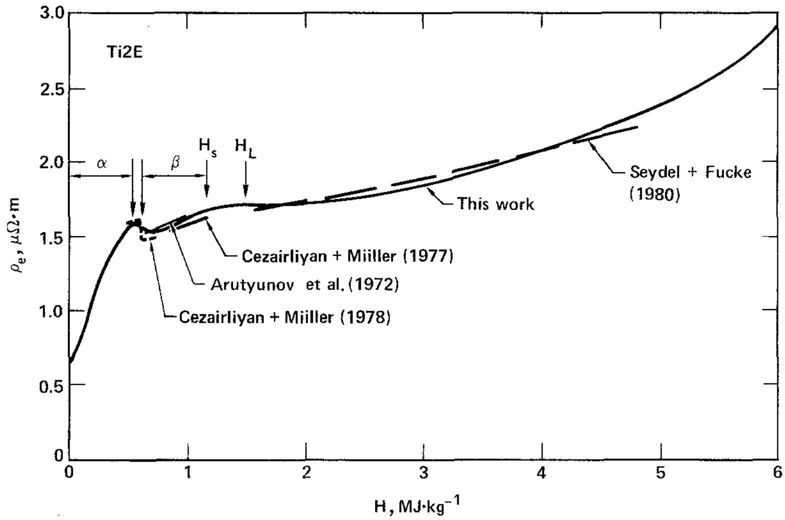

Fig. 1. Electrical resistivity of titanium. The solid curve marked "this work" corresponds to a single experiment.

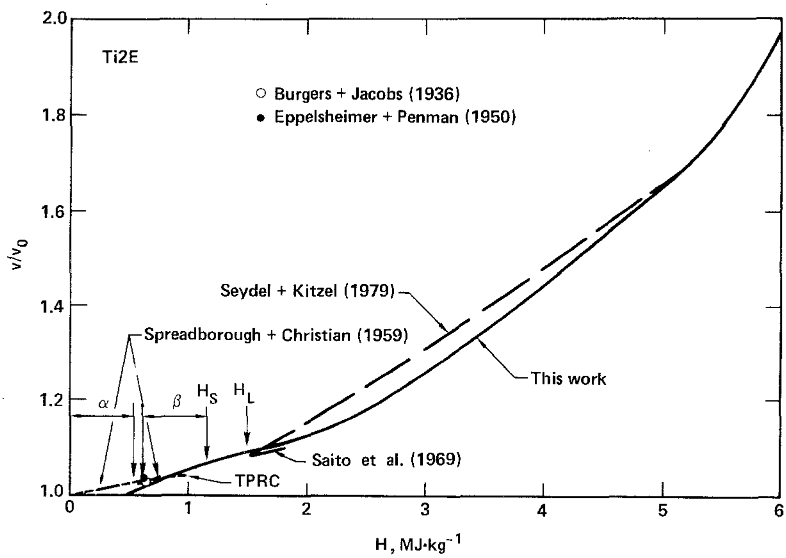

Fig. 2. Thermal expansion of titanium. The dotted curve marked "TPRC" corresponds to the recommended data of Touloukian et al.

lattice constant of the bcc phase of both titanium and zirconium at 1173 K and gave lattice constants for the hcp phase at room temperature. The corresponding specific volume ratio was calculated as 1.025 and is shown. Eppelsheimer and Penman [9] also made X-ray diffraction measurements at 1173 K. The calculated specific volume ratio from their result is 1.031.

Spreadborough and Christian [10] made X-ray diffraction studies of thermal expansion for both phases. The specific volume ratios calculated from their results are also shown. The recommended curve for linear thermal expansion of polycrystalline material of Touloukian et al. [11] was used to calculate the specific volume ratio assuming cubical expansion (the c/a ratio of the hcp phase changes very little). The result is shown as the dotted curve. Saito et al. [12] measured density in the liquid range by a levitation technique. Temperatures were determined with an optical pyrometer. The volume was deduced by photographing the levitated droplet and fitting a model to the observed shape. Their corresponding specific volume is shown. Seydel and Kitzel [13] reported thermal expansion results well into the liquid range. Their results are in good agreement with this work.

It is of interest for theoretical modeling to consider resistivity as a function of specific volume. Figure 3 shows the corresponding results from this work. The results of Seydel and Kitzel may be combined with those of

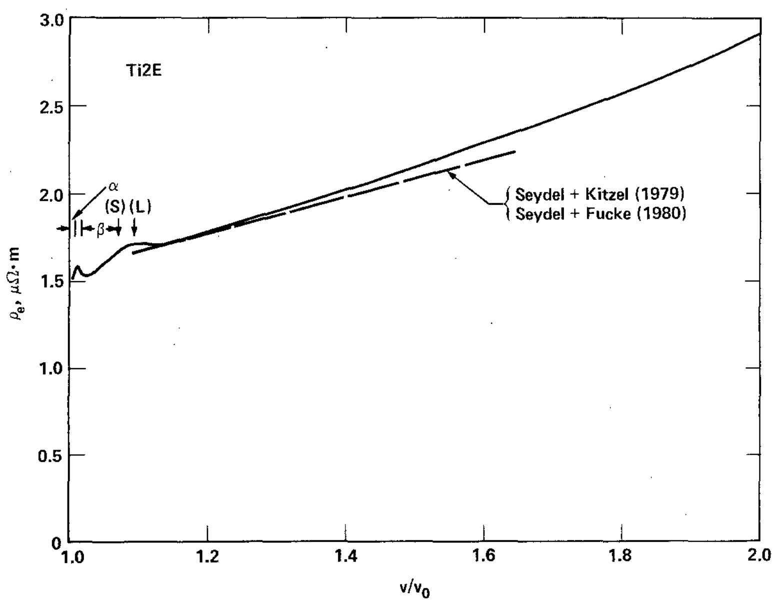

Fig. 3. Electrical resistivity vs volume for titanium. The results of Seydel and Fucke and of Seydel and Kitzel were combined to produce the dashed curve.

Seydel and Fucke to determine resistivity as a function of volume for the liquid. The corresponding curve is shown in the figure and is in agreement with this work.

2.3. Zirconium Results

The electrical resistivity for a single experiment is shown in Fig. 4. Resistivities were corrected for thermal expansion as described above. As with titanium, the enthalpies shown for the phase transitions were taken from Hultgren et al. The values for the melting transition are only estimates in the tables. The enthalpy at the liquidus determined by Bonnell [14] is shown for comparison. Peletskii et al. [15] measured resistivity for both α (hcp) and β (bcc) phases using a compensation method to determine resistance. Temperatures were measured using thermocouples in the low

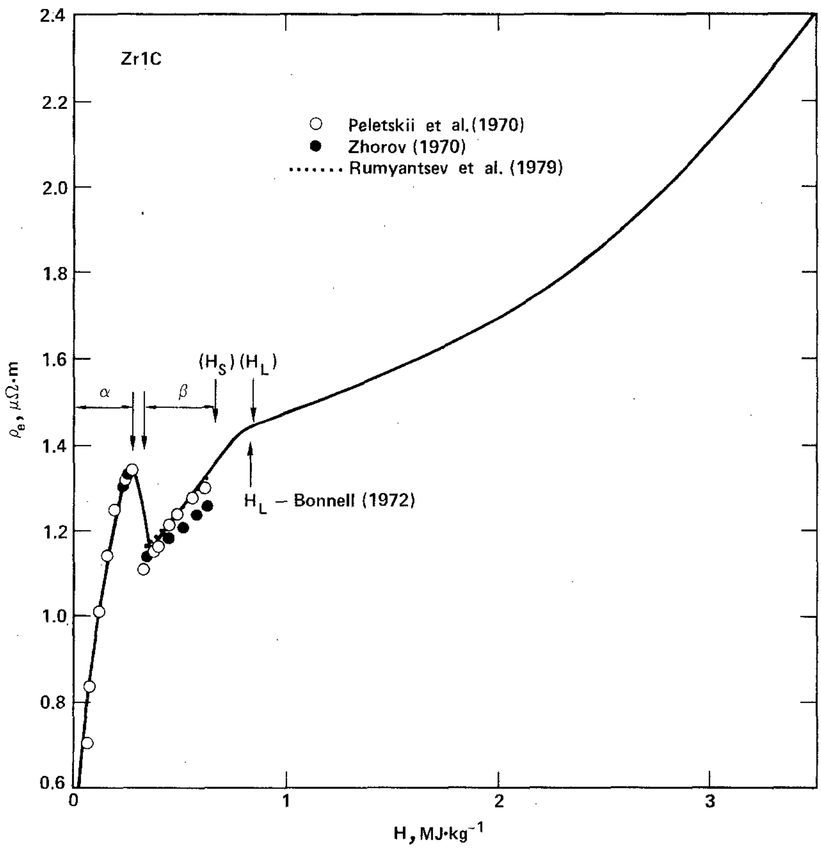

Fig. 4. Electrical resistivity of zirconium. The solid curve corresponds to a single experiment.

range and a pyrometer in the high range. Their results were corrected for thermal expansion and are in excellent agreement with this work. Zhorov [16] also measured resistivity. His results for the β-phase are significantly lower than those of Peletskii et al. It is not clear whether thermal expansion corrections were made. Rumyantsev et al. [17] measured resistivity in the β phase and corrected their results for thermal expansion. The results are in excellent agreement with this work.

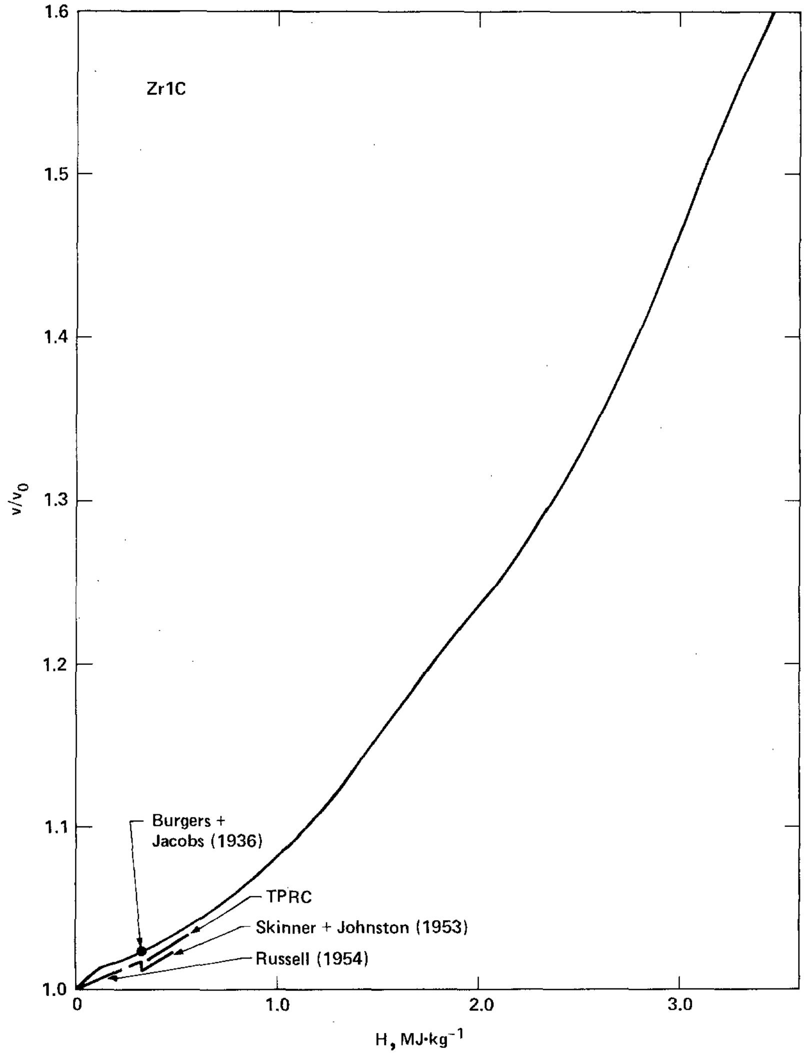

Fig. 5. Thermal expansion of zirconium. The solid curve represents the data corresponding to the experiment shown in Fig. 4. The curve marked "TPRC" corresponds to the recommended data of Touloukian et al.

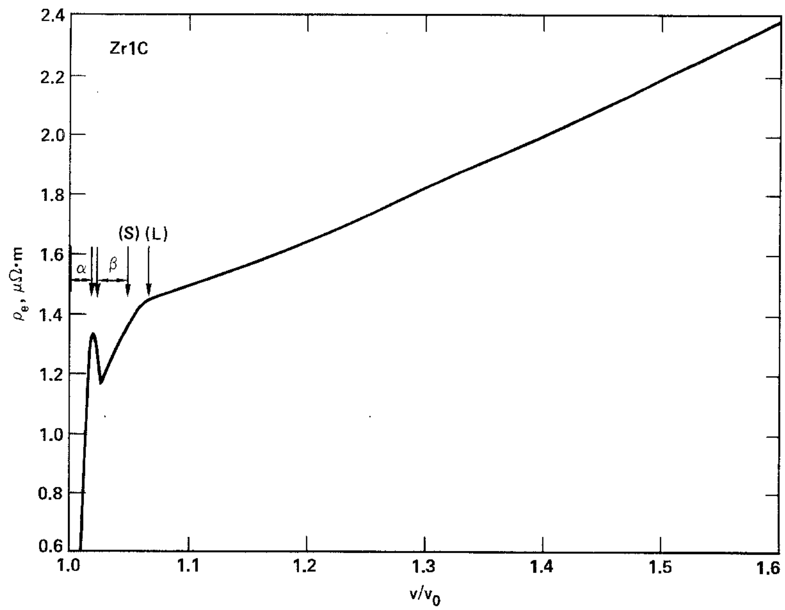

Fig. 6. Electrical resistivity vs volume for zirconium. The enthalpies in Figs. 4 and 5 were eliminated to produce the curve.

The corresponding volumes that were used to correct the resistivities for this work are shown in Fig. 5. The author was not able to find any liquid range data in the literature. The calculated volume from the X-ray measurement of Burgers and Jacobs [8] at 1173 K is shown. Russell [18] made X-ray measurements of lattice parameters in the α (hcp) phase. The corresponding calculated volumes are shown. Skinner and Johnston [19] also made X-ray measurements for both α and β phases, and made direct measurement of linear thermal expansion for the β (bcc) phase. The corresponding calculated volumes are shown.

As with titanium, the recommended curves for linear thermal expansion of polycrystalline material given by Touloukian et al. were used to calculate specific volume. Only the results for the β phase are shown, in order to reduce clutter in the figure. The corresponding resistivity as a function of volume is shown in Fig. 6. The resistivity in the liquid range appears almost proportional to the specific volume.

3. CONCLUSIONS

Preliminary measurements of the electrical resistivity and thermal expansion of liquid titanium and zirconium have been made. The measurements for liquid zirconium are the only results known to the author. For liquid titanium the results are in good agreement with the only other known data.

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