The Electrical Resistivity of Exploding Ni-Wires in Fast RCL-Circuits

U. Seydel, W. Fucke, and B. Möller

Institut für Experimentalphysik der Universität Kiel

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The electrical resistivity of Ni is derived from time-resolved measurements of current and voltage of exploding Ni-wires, which are part of a fast RCL-discharge circuit. The values of the resistivity at the Curie-point and at the melting point are in good agreement with stationary measurements. Deviations are discussed. Furthermore, the energy dependence of the resistivity of liquid Ni up to the boiling point (at normal conditions) is determined and compared with the temperature dependence assuming a constant specific heat.

Introduction

In connection with some problems concerning exploding wire experiments at high current densities – e. g. the dependence of the electrical resistivity of metals on current density or superheating effects at high energy input rates, which occur in fast RCL-discharges – it is of special interest to check the precision of voltage and current measurements in the nanosecond range and of data on specific energy, temperature, and resistivity derived therefrom.

A reasonable way for this is the comparison with data obtained from stationary measurements. The existence of distinct "bends" in the voltage oscillograms, which can be assigned to characteristic thermodynamical states – as for example the beginning and the completion of the melting transition and the Curie-point of ferromagnetic materials – would facilitate this procedure. For our experiments we used Ni-wires, which have a comparatively large ratio of the resistivities in the liquid and solid phase at the melting temperature and should therefore show a pronounced step in the voltage signal.

Data on the electrical resistivity of Ni at the Curie-point and at the melting point obtained by exploding wire technique have already been published twenty years ago [1–3]. These experiments have been carried out with different discharge circuits, i. e. cable discharges supplying a nearly constant current or comparatively slow RCL-circuits, and the reported data show a varying agreement with stationary measurements performed by Regel and Mokrovsky [4]. Also for liquid Ni experimental data on the electrical resistivity obtained from stationary measurements have been published by Regel and Mokrovsky and recently by Güntherodt et al. [5]. But these data extend only to temperatures of about 2000 K or 1900 K, respectively. As far as we know, no investigations on the electrical conductivity of liquid Ni have been performed by exploding wire technique.

Basing on the good agreement of our results for the resistivities at the Curie-point and the melting point with stationarily measured values and assuming the validity of thermodynamical data – especially for the specific heat – even for the extreme conditions of a fast RCL-discharge we obtain results for the temperature dependence of the electrical resistivity of liquid Ni up to the beginning of vaporization (3005 K). Our results agree very well with those published by Regel and Mokrovsky and by Güntherodt et al.

Reprint requests to Dr. U. Seydel, Institut für Experimentalphysik der Christian-Albrechts-Universität, Olshausenstraße 40–60, *D-2300 Kiel.*

Experimental Performance

The experimental set-up was similar to that described earlier [6]. The discharge circuit consisted of a capacitor-bank with a capacity of 5.1 μF, which could be charged up to $U_0 = 35$ kV. The short-circuit ringing period was 6 μsec and the circuit resistance and inductance came out to about $R = 18\ \mathrm{m}\Omega$ and $L = 180$ nH, respectively. The discharge current was measured by means of an induction-coil with RC-integration. The coil was placed in an Ω-shaped part of the current-transmission-line. The determination of the voltage across the exploding wire was performed with a coaxial ohmic voltage divider with a rise-time of about 8 nsec developed by Fucke [7]. The compensation of the inductive component of the voltage resulting mainly from the inductivity of the

coaxial discharge gap was carried out according to the method described in Reference [6].

The wires were exploded in water at atmospheric pressure to avoid peripheral gas discharges. The Ni-wires had diameters between $d = 0.01$ cm and 0.05 cm and lengths between $l = 4$ cm and 7 cm. The chemical purity was better than 99%.

Figure 1 shows the current and voltage oscillograms for the heating period up to the normal

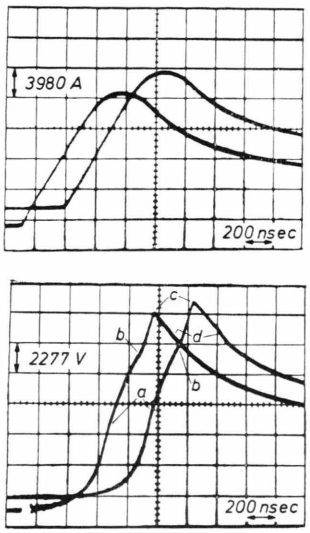

Fig. 1. Current and voltage oscillograms for two identical Ni-wire explosions ($d = 0.03$ cm, $l = 7$ cm, $U_0 = 10$ kV). a = Curie-point, b = beginning of melting, c = completion of melting, d = normal boiling point.

boiling point and beyond for two indentical Ni-wire explosions ($d = 0.03$ cm, $l = 7$ cm, $U_0 = 10$ kV). The upper and the lower traces respectively of each oscillogram belong to the same experiment. The bends in the voltage traces are caused by the phase transitions and are marked with a, b, c according to the Curie-point, the beginning of melting, and the completion of melting. The normal boiling point, as deduced from specific energy, is marked with d.

Evaluation of the Experimental Data

From the current and voltage oscillograms the current density $i(t)$, resistivity $\varrho(t)$, specific energy $e(t)$, and the action integral $G(t) = \int_{t_0}^{t} i^2(t')\,\mathrm{d}t'$ [6, 8] were computed. The action integral and the specific energy allowed the calculation of the temperature of the wire using handbook values for the thermodynamic data [9–13] and assuming that all the electric energy is solely converted into thermal energy of the wire – i. e. energy losses due to heat conduction or radiation and end effects at the electrodes are negligible. Furthermore we assumed that the transient skin effect can be neglected, so that the heating of the wire material occurs uniformly over its cross-section, and that longitudinal inhomogeneities (MHD-instabilities, $m = 0$) are not existent. The reliability of these assumptions will be discussed later.

Figure 2 shows the diagram of the action G versus the temperature T for Ni calculated up to the end of the melting transition.

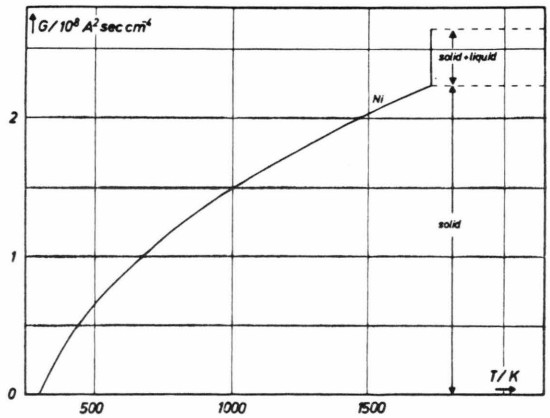

Fig. 2. $G(T)$-diagram for nickel.

Figures 3 a, b show the dependence of the resistivity on action and on specific energy for one experiment, always up to the completion of melting.

In Figure 4, for the same experiment $\mathrm{d}\varrho/\mathrm{d}G$ (in arbitrary units) is drawn versus G for the direct vicinity of the Curie-point. From this and from Fig. 2 the Curie-point is found to be at 617 K. The slight deviation from the handbook value of 631 K [12] will also be discussed later.

Figure 5 shows as an average of several explosions the resistivity of Ni versus specific energy from the beginning of melting up to the normal boiling point for two different current densities. The values for the current density corresponding to the end of the melting transition are given as parameter.

In Figure 6 a conversion of the $\varrho(e)$-dependence in Fig. 5 into a $\varrho(T)$-dependence under the assumption of a constant specific heat in the liquid phase ($c_p = 9.20$ cal grad^{-1} mol^{-1}) has been carried out for the lower current density.

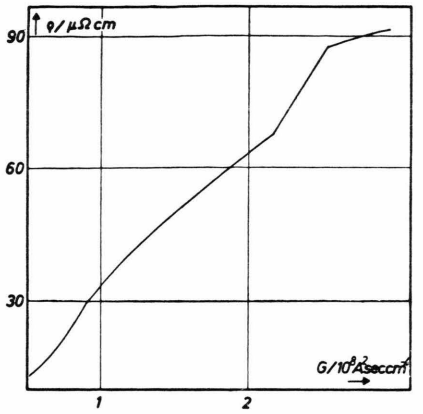

Fig. 3 a. $\varrho(G)$-diagram up to the completion of melting ($d = 0.05$ cm, $l = 7$ cm, $U_0 = 20$ kV).

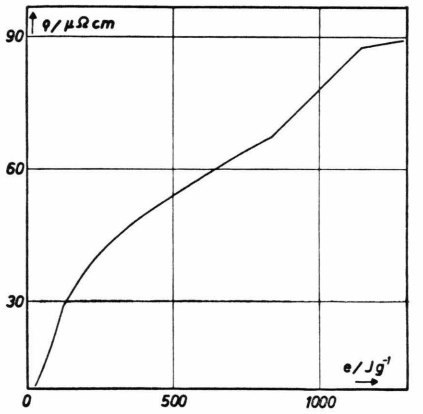

Fig. 3 b. $\varrho(e)$-diagram up to the completion of melting (experimental parameters see Figure 3 a).

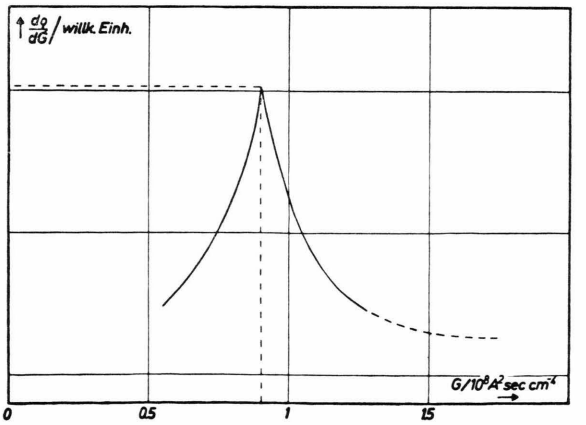

Fig. 4. $d\varrho/dG(G)$-diagram for the direct vicinity of the Curie-point (experimental parameters see Figure 3 a).

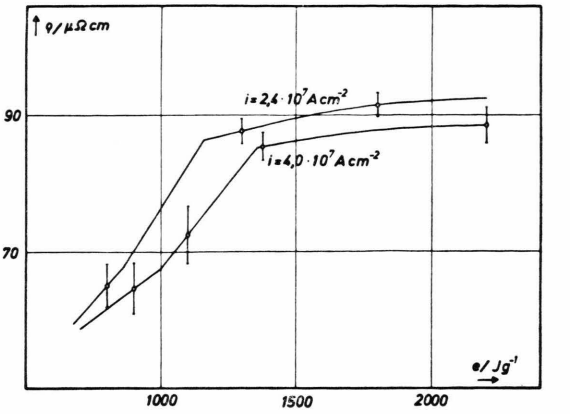

Fig. 5. $\varrho(e)$-diagram as an average of several explosions from the beginning of melting up to the normal boiling point for two different current densities.

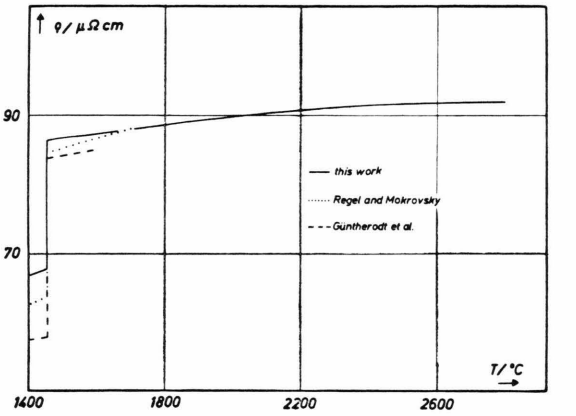

Fig. 6. $\varrho(T)$-diagram converted from the $\varrho(e)$-diagram (Fig. 5) for the lower current density under the assumption of a constant specific heat in the liquid phase ($c_p = 9.20$ cal Grad^{-1} mol^{-1}) compared with Güntherodt et al. [5] — and Regel and Mokrovsky [4] — measurements.

Discussion

The primal interest in these experiments was to find a material and experimental parameters, for which the characteristic bends in the voltage trace at the start and at the end of melting, and, if possible, at still more phase transitions and the assigned values of resistivity, specific energy, and action could be exactly determined. This way we should be able to estimate the influence of the transient skin effect and of high current density or high energy input rates on the total energy input and on resistivity. The latter effect has been investigated by several authors e. g. [14, 15], who used Au- or Cu-wires.

In these cases the determination of the beginning of melting based either on changes in slope in the resistance-energy-diagrams or on the stationary value for resistivity. Because for Au and Cu these changes in slope are smooth, the first method brings along some uncertainty for quantitative measurements. But also the presumption of the validity of stationary values requires checking, in the course of which possible current density effects may be explained.

In our experiments the current densities at the melting transition lay at $2.4 \cdot 10^7$ and at $4.0 \cdot 10^7$ $\mathrm{Acm^{-2}}$. In this range an increased energy input up to the beginning of melting with increasing current density is indicated (Figure 5). The discrepancy between the measured energy density and the stationary value is still more evident at the end of melting and, in any case, the resulting heat of fusion Λ comes out too high. Even though this effect has not been fully understood yet, we believe that a significant part of the excess energy may be dissipated in shock waves which are produced by the expansion of the wire material. This assumption is confirmed by the fact that Λ seems to increase with increasing energy input rate (current density) and with increasing wire length. Furthermore, on streak photographs from underwater explosions of Cu-wires these shock waves can be observed [6]. Too high values of Λ for impulse heating experiments have also been reported by Vermij [16], who explains this by a non-isothermal heating process – the liquid outer part of the wire should be partially vaporized before the core is totally melted. At this time neither of these two mechanisms can be absolutely excluded. They may even work simultaneously. Further experiments should give more evidence about the melting process in pulse discharges.

In our experiments with Ni-wires for both current densities the deviations in Λ from handbook values are much less than the 30% mentioned by Vermij for Ag-wires. Because the deviation is smallest for the lower current density the transformation of the $\varrho(e)$-into a $\varrho(T)$-dependence (Fig. 6) is based on these values assuming an isothermal melting process at 1452 °C. We achieve very good agreement with values obtained from stationary measurements by Güntherodt et al. (dashed line) and by Regel and Mokrovsky (dotted line) up to about 1700 °C. The resistivities at the beginning (67.8 $\mu\Omega$cm) and at the end (86.3 $\mu\Omega$cm) of melting are – within the margins of estimated error – in good agreement with stationary values. Deviations may be explained by impurities of the wire material.

The resistance temperature coefficient α comes out to $6.5 \cdot 10^{-5}\,\mathrm{Grad^{-1}}$ in the temperature range $1452\,^\circ\mathrm{C} \leqq T \leqq 2300\,^\circ\mathrm{C}$ and thus about a factor of 2 lower than the value given by Regel and Mokrovsky for $1450\,^\circ\mathrm{C} \leqq T \leqq 1700\,^\circ\mathrm{C}$.

The temperature dependence of resistivity shows a high-temperature behavior that tends to bend away from linear T-dependence toward the temperature axis. This behavior becomes particularly evident at temperatures above 2300 °C.

In all our experiments the Curie-point was found to lie systematically at considerably too low temperatures derived from measured energies, whereas the agreement between temperature from action and handbook values is good. Discrepancies between calculated and experimental energies at the Curie-point have also been reported by Meeker [3]. We believe that this fact may be explained by possibly incorrect voltage measurements, which do not affect action. The voltage measurements may also be influenced by the transient skin effect. According to the formula for the skin relaxation time given by Haines [17]

$$\tau = \mu\,\sigma\,a^2/15$$

($\mu = \mu_0\,\mu_r$ permeability in Vs/Am, σ conductivity in $\Omega^{-1}\,\mathrm{m^{-1}}$, a initial wire radius in m) assuming a constant μ and σ (both at room temperature), τ should be only 67 nsec for a Ni-wire with $d = 2.5 \cdot 10^{-4}$ m. For this estimate μ is set equal to μ_0, because already at current densities of $2 \cdot 10^5\,\mathrm{Acm^{-2}}$ the magnetic saturation flux density of Ni is reached. These current densities are already exceeded about 10 to 20 nsec after the beginning of the discharge and therefore far below the Curie-point.

But in the very early phase the transient skin effect may cause a considerably higher voltage across the wire than would be expected from a homogeneous current distribution, which in turn results in too low energy values.

In similar experiments with Cu-wires in the very early phase of the explosion we have observed – in spite of an increasing current – an initial decrease in voltage until the increase due to ohmic heating predominates. This effect, yet not as significant, occurs in Ni-wire explosions, too. Also other experimentators, who achieved comparatively high

time resolution and who used the same compensation method [18], have observed this downward slope. No satisfying explanation for this has been found yet but we think that it may be caused at least partially by the transient skin effect because there is a run in specific energy with wire diameter. In any case, this voltage decrease may also give rise to an incorrect compensation and thus to incorrect energy measurements, especially in the early phase. This would explain the fairly good agreement between experimental and calculated energies at the melting transition, whereas this agreement is poor at the Curie-point.

Longitudinal inhomogeneities caused by MHD-instabilities do not occur in the heating period up to the melting transition, so they have not to be taken into account for the energy balance, at least in this interval. However, the influence of MHD-instabilities cannot be absolutely excluded in the liquid phase. But with conventional optical diagnostics (Kerr-cell- and streak-photographs) we did not get any hint for their existence under our experimental conditions. This was to be expected because of the relatively fast discharge, which should produce at most very narrow-spaced striations.

Other longitudinal inhomogeneities as for instance end effects at the electrodes could be suppressed by exploding the wires in water at atmospheric pressure.

Energy losses due to heat conduction are negligible for times of the order of microseconds or less. Losses due to radiation can also be neglected, because for typical experimental parameters ($U_0 = 10\,\mathrm{kV}$, $l = 7\,\mathrm{cm}$, $d = 0.03\,\mathrm{cm}$) the radiant power at the normal boiling temperature amounts only to about 300 W according to Stefan-Boltzmann's law, while the electrical power is about $1 \cdot 10^8\,\mathrm{W}$.

Quantitative statements on the total experimental error can hardly be made. The statistical error may be taken from Figure 5. The systematical error resulting mainly from the voltage measurement and the time correlation of the current and the voltage signals can only be estimated and should be about 15% up to the Curie-point and about 5% in the liquid phase as well as for the resistivity as for specific energy.

Taking into account the above limitations and presumptions, the pulse heating method supplies a useful tool for determining the electrical resistivity of liquid metals at high temperatures. An improvement of this method will be achieved by the additional determination of the surface temperature of the wire, which can be assumed to be constant over the total cross section at least in the liquid phase.

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