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Enthalpy, heat of fusion and specific electrical resistivity of pure silver, pure copper and the binary Ag–28Cu alloy

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Abstract

Within the present work, recent investigation carried out with a fast pulse-heating technique on silver, copper and the Ag–28Cu binary alloy in the solid and the molten states are presented.

Properties like enthalpy or electrical resistivity of a pulse-heated sample can be obtained for a wide temperature range (solid state up into the liquid state) from the directly measured base quantities, namely: current through the sample, voltage drop across the specimen and pyrometric determined temperature. As a further result, enthalpy of fusion is computable from the enthalpy values at the melting transition or the solidus/liquidus transition. These thermophysical properties (mainly of the melting transition and the subsequent liquid phase) are commonly used as input data for numerical casting simulations.

The measurements presented within this work deal with group[1] 11 elements silver, copper and the binary eutectic 72–28 (wt.%) alloy of the two elements, respectively. One of the main goals of this work is to investigate to which extent the thermophysical properties of the two pure materials influence or determine the properties of its corresponding alloy. It is to proof if data for pure materials can be used to predict the thermophysical properties of simple alloys. For this specific copper–silver alloy, there is a certain mutual solid solubility with a quite large miscibility gap. Ag–28Cu is not a single phase alloy but an eutectic alloy with two phases.

Keywords: Ag72–28Cu; Copper; Silver; Enthalpy; Heat of fusion; Liquid metals; Resistivity

1. Introduction

Copper and silver are commonly used and well known group 11 metals. The discovery of both metals dates from prehistoric times and have been used in a broad range of applications ever since like jewelry, coinage, electrical and electronic devices among others. In some of these applications, silver is alloyed to improve its hardness and the primary alloying element is copper, which, in proportions of 7.5 wt.% forms the recognized standard for sterling silver [1].

The intrinsic qualities of copper and silver like excellent electrical and thermal conductivity, high reflectivity, good corrosion resistance (silver), malleability and ductility make them good material choices for a wide range of industrial applications, i.e., contact paths on electrical circuit boards, capacitor components, thin-film coatings for optically and thermally efficient glass, plating, conductive inks [1,2].

If both metals are alloyed, copper additions improve the hardness of silver appreciably and slightly decrease its conductivity. However, copper decreases the tarnish resistance of silver; hence, the oxidized film increases contact resistance. Switching devices that have silver–copper contacts should have a high closing force and large wiping action to break down the oxide films. Silver–copper alloys are used in place of fine silver where electrical, mechanical and atmospheric conditions are compatible. For the same application, silver–copper alloys usually cost less than fine silver. Addition of a small amount of nickel to a silver–copper alloy (as in Ag–24.5Cu–0.5Ni, for example) makes the oxide film

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[1] The coppers–silver subgroup of the periodic table of elements is either labeled 11 or I b.

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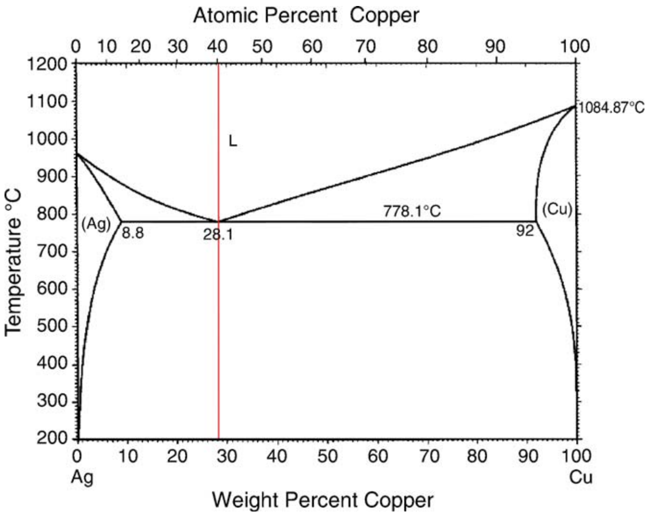

Fig. 1. Binary phase diagram of the Ag–Cu system taken from [3]. The vertical line indicates the composition of the alloy investigated within this work.

brittle, so that switching devices can use less closing force [1]. According to [3], the 28 wt.% Cu eutectic alloy finds some use as a brazing or soldering alloy. With heavy cold work, it is quite strong and is used for spring-type electrical contacts.

The silver–copper alloy investigated within the recent work is the eutectic Ag–28Cu (wt.%) alloy. The liquidus curve of silver–copper was first published as early as 1875 and the existence of an eutectic, formerly assumed to be the compound Cu_2Ag_3 (28.1 wt.% Cu), was recognized a few years later in 1891 [4]. The phase diagram for the binary silver–copper system (taken from [3]) can be seen in Fig. 1. The eutectic temperature was conformably given as 778–779 °C (1051.15–1052.15 K), careful determinations yielded 779.8 °C on the 1948 International Temperature Scale. As well as the eutectic temperature, the eutectic composition was also reported to be 28–29 wt.%. Metallographic determination of the eutectic point proved to be impossible, as primary α_{Ag} or α_{Cu} or both appear in the microstructure of the same alloy, in the region 28–28.5 wt.% Cu, according to the rate of solidification [4]. Therefore, most references give an eutectic temperature of 779 °C and 28.1 wt.% Cu as the eutectic composition.

Experimentally, a dynamic, fast resistive pulse-heating technique has been used to investigate all three materials of this recent study. Over the last decades, vast knowledge on pulse-heating has been developed at the thermophysical laboratory at the Institute of Experimental Physics (Graz University of Technology), and successfully applied to the study of thermophysical properties in the solid state, the melting transition, and particularly, the liquid state of pure metals and alloys. The main reason for using this containerless technique is given by the fact that conventional heating techniques are often not suited for studying liquid metals due to their high chemical reactivity, and thus, contamination and exothermic reactions of the liquid samples with the crucibles and the ambient air/gas-atmosphere.

As mentioned above, pulse-heating devices are most commonly designed for the determination of thermophysical data at melting and the liquid state and a typical temperature range of $T > 1300$ K. Therefore, metals from group 11 (copper, silver, gold) of the periodic table are often omitted from standard studies due to their relatively low melting points (compared to refractory metals). These low melting temperatures are difficult to resolve with the optical pyrometers commonly used for temperature determination in pulse-heating systems and which are typically designed for temperatures up to 4000 K. As a result, thermophysical properties for group 11 metals (with the exception of copper) and its alloys are sparse throughout the literature.

2. Experimental

In principal, pulse-heating uses electrically conducting samples as a part of the discharge circuit and passing a large current pulse (up to 12 kA for 50 μs) over this specimen during the experiment. As a reaction to this intense current pulse, the sample will be heated due to its electrical resistivity at heating rates up to 10^8 K/s. As a result, the sample will be heated from room temperature up to the end of the stable liquid phase[2] in about 50 μs and will be destroyed during the experiment.

The time resolved quantities measured during such an experiment include the current injected in the sample, the voltage drop across its active length, the radial expansion of the sample, and the pyrometrical determined surface radiance at a given wavelength. Unfortunately, the expansion measurement has not been available at the time of this study, wherefore literature data of thermal expansion have been used instead. Since detailed information on the experimental setup has been extensively described and published earlier [5,6], further details and explanations will be omitted at this point.

For the measurements reported within this work, wire shaped specimens with an average diameter of Ø = 0.5 mm and a typical active length of about 40 mm have been used for all three materials. All sample wires have been purchased from commercial suppliers. Specific information about the three materials under investigation can be found in Table 1. Prior to the actual experiment, each specimen was treated with acetone to reduce surface contaminants like dust, grease, etc., which may affect the electrical contact and the optical temperature measurement. Further, to maintain a reproducible ambient atmosphere for all three specimen materials, nitrogen at a pressure of about 1 bar was used.

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[2] The end of the stable liquid phase is marked by the so-called ‘phase explosion’: as the sample temperature reaches the boiling point, the vapor pressure causes a rapid expansion which destroys the geometry of the liquid sample.

Table 1
Specific details on the different investigated materials

Material	Supplier	Purity	Temperature	Ø (mm)	d (kg m^{-3})	T_m (K)
Copper (Cu)	Advent Research Materials Ltd.	99.996%	As drawn	0.5	8960 [2]	1357.77 [8]
Silver (Ag)	Advent Research Materials Ltd.	99.99%	Annealed	0.5	10490 [1]	1234.93 [8]
Ag–28Cu	Goodfellow Cambridge Limited	–	As drawn	0.5	10018*	1052 [3,7]

Ø: Nominal diameter; T_m: melting temperature; d: density at 20 °C; *: the density of the Ag–28Cu alloy has been estimated from the densities of the two pure materials (taken from [7]), weighted by the actual composition (in wt.%). *Note:* the 72/28 (Ag to Cu) ratio is given in wt.%, since the alloy is the eutectic composition only one melting temperature (instead of a solidus and liquidus temperature) is given.

Different pyrometers had to be used for temperature determination, as the melting points of pure copper and silver are already on the lower end of the detectible temperature range of our NIR-pyrometer operating at a wavelength of 1570 nm. However, the eutectic Ag–28Cu alloy exhibits a melting temperature which is about another 200 K lower than the one of pure silver. Therefore, another pyrometer operating within a broad wavelength range (ca. 1600–2600 nm) had to be used to detect a surface radiance signal at the melting point. As a result, no interference filter could be used to narrow down the wavelength of the pyrometer whereof the validity of the detected temperature can only assumed to be acceptable within some few 10 K above and below the melting transition. To cope with this situation, the results for the Ag–28Cu alloy can only be given as resistivity versus enthalpy, as these both properties are purely electrically measured, and therefore, independent from the accuracy of the temperature signal.

3. Data reduction

Based on the directly measured, time resolved quantities current, I, voltage drop, U, radial expansion, r/r_0, and surface radiance, J (or radiance temperature, T_r, if a calibrated pyrometer is used) various thermophysical properties can be obtained. These properties include specific enthalpy, enthalpy of fusion, isobaric heat capacity, electrical resistivity (at initial geometry and in consideration of thermal expansion), thermal conductivity and thermal diffusivity. The two latter ones are obtained by applying the Wiedemann–Franz–Lorentz law. Within the recent work, only enthalpies and electrical resistivities are presented, which can be directly calculated from the measured electrical quantities. See [5] for further information and detailed descriptions of the evaluation.

4. Experimental measurements and results

For all three materials under investigation, a number of independent measurements have been performed and the result presented within the following section are mean values of these individual results. (The exact number of measurements used for averaging for each material is noted in the corresponding section.) The specific properties (i.e., melting temperature, density) as listed in Table 1 have been used for data evaluation.

4.1. Results for copper

The presented results for copper are obtained by means of an average of 11 individual experiments. The enthalpy versus temperature dependence of copper is shown in Fig. 2 whereof the following linear least-squares fits are obtained (H in kJ kg^{-1} and T in K):

$$H(T) = -207.8940 + 0.4809 \cdot T \quad 1100\,\text{K} < T < 1357\,\text{K} \tag{1}$$

$$H(T) = -45.4630 + 0.5315 \cdot T \quad 1357\,\text{K} < T < 2000\,\text{K}, \tag{2}$$

where enthalpy is referred to the enthalpy value at $T = 298$ K, $H(T) = H(T) - H_{298\text{K}}$. Therefore, the following values of enthalpy at melting of $H_s(T_m) = 444.7$ kJ kg^{-1}, $H_l(T_m) = 675.8$ kJ kg^{-1} and an enthalpy of fusion of $\Delta H(T_m) = 231.1$ kJ kg^{-1} are obtained. Furthermore, isobaric

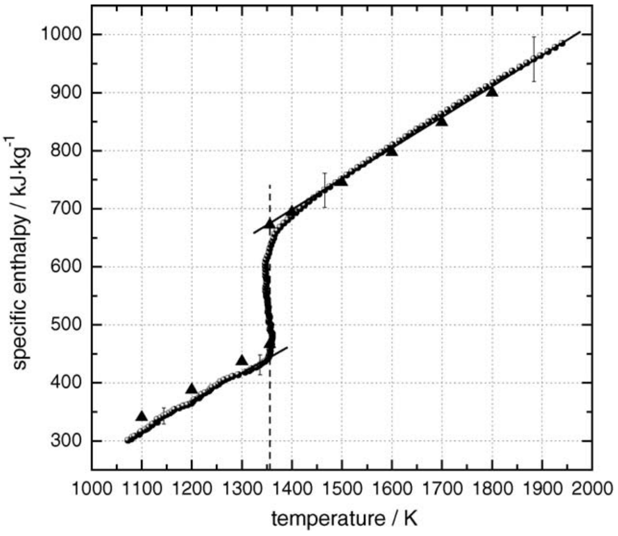

Fig. 2. Specific enthalpy of copper as a function of temperature. Solid circles: data of this work; solid lines: linear least-squares fits to the solid/liquid states; dashed line: melting temperature (1357 K); full up-triangles: reference data taken from [9].

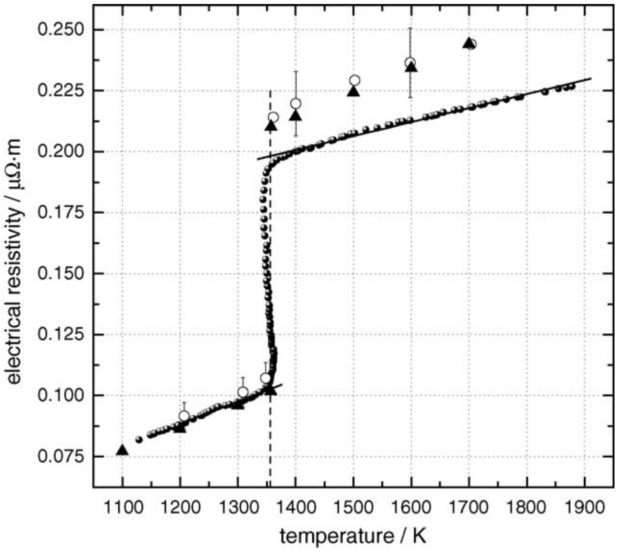

Fig. 3. Electrical resistivity (with initial geometry and with consideration of expansion) of copper as a function of temperature. Solid circles: data of this work with initial geometry; open circles: data of this work including volume expansion; solid lines: linear least-squares fits to the solid/liquid states (initial geometry); dashed line: melting temperature (1357 K); full up-triangles: reference data from [11].

heat capacities, c_p, for the solid state closest to melting[3] and the liquid states can be deduced from the slopes of the enthalpy versus temperature fits. The isobaric heat capacities for solid and liquid silver yield $c_{p,s} = 480.9\,\mathrm{J\,kg^{-1}\,K^{-1}}$ and $c_{p,l} = 531.5\,\mathrm{J\,kg^{-1}\,K^{-1}}$, respectively.

Results of electrical resistivity of copper as a function of temperature are presented in Fig. 3, whereof the linear least-squares fits for resistivity under initial geometry, ρ_{IG}, (no consideration of thermal expansion) are given by (ρ in µΩ m and T in K):

$$\rho_{IG}(T) = -0.0214 + 9.1542 \times 10^{-5} \cdot T \quad 1100\,\mathrm{K} < T < 1357\,\mathrm{K} \tag{3}$$

$$\rho_{IG}(T) = 0.1092 + 6.5009 \times 10^{-5} \cdot T \quad 1357\,\mathrm{K} < T < 1900\,\mathrm{K} \tag{4}$$

To calculate the resistivity values including thermal expansion (also shown in Fig. 3) reference data from [12] and [13] have been used.

4.2. Results for silver

The presented results for silver are obtained by means of an average of eight individual experiments. The enthalpy versus temperature dependence of silver is shown in Fig. 4 whereof the following linear least-squares fits are obtained (H in $\mathrm{kJ\,kg^{-1}}$ and T in K):

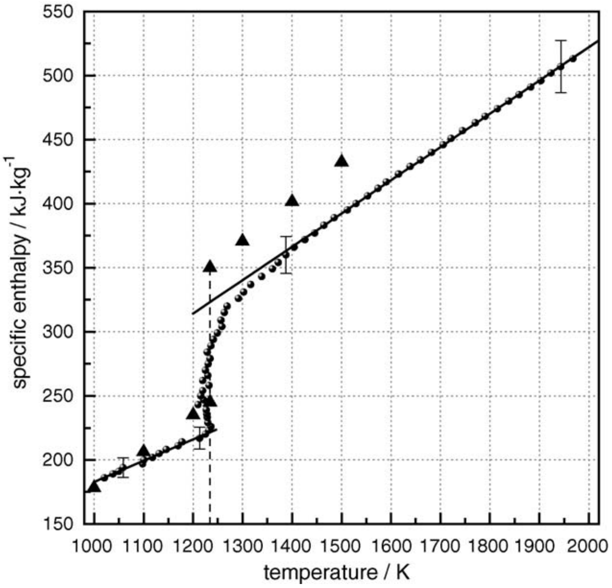

Fig. 4. Specific enthalpy of silver as a function of temperature. Solid circles: data of this work; solid lines: linear least-squares fits to the solid/liquid states; dashed line: melting temperature (1234 K); full up-triangles: reference data taken from [9].

$$H(T) = 17.2367 + 0.1656 \cdot T \quad 1000\,\mathrm{K} < T < 1234\,\mathrm{K} \tag{5}$$

$$H(T) = 2.5807 + 0.2598 \cdot T \quad 1234\,\mathrm{K} < T < 2000\,\mathrm{K}, \tag{6}$$

where enthalpy is referred to the enthalpy value at $T = 298\,\mathrm{K}$, $H(T) = H(T) - H_{298\mathrm{K}}$. Therefore, the following values of enthalpy at melting of $H_s(T_m) = 221.6\,\mathrm{kJ\,kg^{-1}}$, $H_l(T_m) = 323.2\,\mathrm{kJ\,kg^{-1}}$ and an enthalpy of fusion of $\Delta H(T_m) = 101.6\,\mathrm{kJ\,kg^{-1}}$ are obtained. Furthermore, isobaric heat capacities, c_p, for the solid state closest to melting and the liquid states can be deduced from the slopes of the enthalpy versus temperature fits. The isobaric heat capacities for solid and liquid silver yield $c_{p,s} = 165.6\,\mathrm{J\,kg^{-1}\,K^{-1}}$ and $c_{p,l} = 259.8\,\mathrm{J\,kg^{-1}\,K^{-1}}$, respectively.

Results of electrical resistivity of copper as a function of temperature are presented in Fig. 5, whereof the linear least-squares fits for resistivity under initial geometry, $\rho_{IG,}$ (no consideration of thermal expansion) are given by (ρ in µΩ m and T in K):

$$\rho_{IG}(T) = -2.9415 \times 10^{-3} + 7.2481 \times 10^{-5} \cdot T \quad 1100\,\mathrm{K} < T < 1234\,\mathrm{K} \tag{7}$$

$$\rho_{IG}(T) = 0.0554 + 8.3336 \times 10^{-5} \cdot T \quad 1234\,\mathrm{K} < T < 1950\,\mathrm{K} \tag{8}$$

To calculate the resistivity values including thermal expansion (also shown in Fig. 5) reference data from [1] have been used.

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[3] Since the slope of a linear fit is a constant value, heat capacities are, therefore, obtained as constant numbers. This theoretically holds for the liquid state but not for the solid state as heat capacities usually change drastically before melting. Therefore, the values obtained from the enthalpy fit can only assumed to be valid within temperatures close to melting.

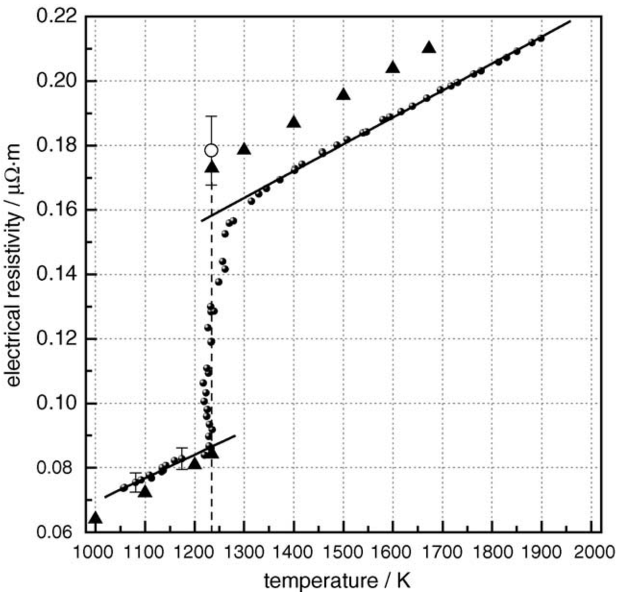

Fig. 5. Electrical resistivity (with initial geometry and with consideration of expansion) of silver as a function of temperature. Solid circles: data of this work with initial geometry; open circle: data of this work including volume expansion; solid lines: linear least-squares fits to the solid/liquid states (initial geometry); dashed line: melting temperature (1234 K); full up-triangles: reference data from [11].

4.3. Results for Ag–28Cu

The presented results for the eutectic silver–copper alloy are obtained by means of an average of seven individual experiments. The resistivity versus specific enthalpy dependence of silver–copper is shown in Fig. 6 whereof the following linear least-squares fits are obtained (ρ in $\mu\Omega$ m and H in kJ kg^{-1}):

$$\rho(H) = 0.02125 + 2.3177 \times 10^{-4} H$$
$$0\,\mathrm{kJ\,kg^{-1}} < H < 229.6\,\mathrm{kJ\,kg^{-1}} \qquad (9)$$

$$\rho(H) = 0.09229 + 1.9926 \times 10^{-4} H$$
$$396.0\,\mathrm{kJ\,kg^{-1}} < H < 800\,\mathrm{kJ\,kg^{-1}} \qquad (10)$$

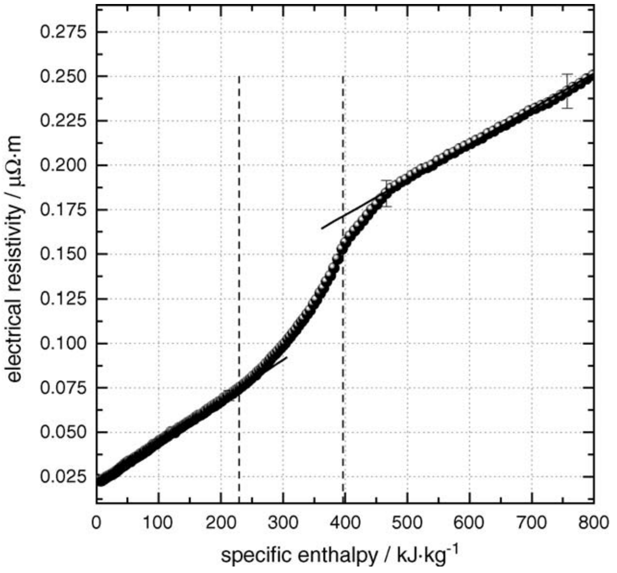

Fig. 6. Electrical resistivity (with initial geometry) of the eutectic Ag–28Cu alloy versus specific enthalpy. Solid circles: data of this study; solid lines: linear least-squares fits to the solid/liquid states; vertically dashed lines: enthalpy values at begin/end of melting (229.6 and 396.0 kJ kg^{-1}, respectively).

As indicated by two dashed lines in Fig. 6 but not explicitly given in a separate enthalpy versus temperature plot, the following values of enthalpy at melting of $H_s(T_m) = 229.6$ kJ kg^{-1}, $H_l(T_m) = 396.0$ kJ kg^{-1} are obtained. Hence, a value of $\Delta H(T_m) = 166.4$ kJ kg^{-1} is obtained from the recent measurements for enthalpy of fusion the copper–silver alloy.

From the resistivity fits presented above, the following figures of electrical resistivity (with initial geometry) at melting can be found: $\rho(H_s) = 0.07438$ $\mu\Omega$ m, $\rho(H_l) = 0.1720$ $\mu\Omega$ m and $\Delta\rho_{\mathrm{melt}} = 0.0976$ $\mu\Omega$ m.

5. Discussion

5.1. Copper

Measurements on copper have been straight forward and the results reported in Figs. 2 and 3 seem to be in good agreement with reported literature data. As can be seen in the enthalpy versus temperature graph for copper, the recent values for the solid state are little higher than those reported by Hultgren et al. [9] or Dinsdale [10], whereas, the liquid state value show an almost perfect match. Nevertheless, the resulting heat of fusion value of $\Delta H = 231.1$ kJ kg^{-1} is about 12% larger than the values reported in literature, i.e., $\Delta H = 205.6$ kJ kg^{-1} [9], $\Delta H = 205$ kJ kg^{-1} [7], or $\Delta H = 208.7$ kJ kg^{-1} in Dinsdale [10]. Up to now, no explicit explanation has been found for this phenomena.

A similar behaviour can be observed for electrical resistivity of copper. Values for electrical resistivity with initial geometry as well as in consideration of thermal expansion are reported in Fig. 3 versus temperature. In the case of electrical resistivity, the solid and the liquid state values are a small amount larger than the ones reported and recommended by Matula [11] but the overall agreement is good. Compared to the values from [11], the resistivity including thermal expansion exhibits a slightly different trend in the liquid state. This fact is most probably related to different values for thermal expansion, as such expansion (or density) values are sparse for liquid metals.

5.2. Silver

The graphical presentation of the recent results for pure silver are shown in Figs. 4 and 5. In contrary to copper, elec-

Table 2
Summarized results of the recent measurements

Material	$H_s(T_m)$ (kJ kg^{-1})	$H_l(T_m)$ (kJ kg^{-1})	ΔH (kJ kg^{-1})	$\rho_s(T_m)$ (μΩ m)	$\rho_l(T_m)$ (μΩ m)	$\Delta\rho$ (μΩ m)
Copper (Cu)	444.69	675.78	231.1	0.1028	0.1974	0.0946
Silver (Ag)	231.49	323.17	101.59	0.0865	0.1582	0.0717
Ag–28Cu	229.6	396.0	166.4	0.0744	0.1720	0.0976

$H_s(T_m)$: enthalpy of the solid at begin of melting; $H_l(T_m)$: enthalpy of the liquid at end of melting; ΔH: heat of fusion; $\rho_s(T_m)$: electrical resistivity of the solid at begin of melting; $\rho_l(T_m)$: electrical resistivity of the liquid at end of melting; $\Delta\rho$: change in resistivity at melting.

trical resistivity shows a better agreement with literature data than enthalpy. The enthalpy values obtained within this study and given in Fig. 4 as a function of temperature are lower than the values reported in [9], whereas, the resulting enthalpy of fusion of $\Delta H = 101.6\,\mathrm{kJ\,kg^{-1}}$ is in good agreement with other published literature values of $\Delta H = 104.8\,\mathrm{kJ\,kg^{-1}}$ [9], $\Delta H = 103\,\mathrm{kJ\,kg^{-1}}$ [7], $\Delta H = 104.7\,\mathrm{kJ\,kg^{-1}}$ [10] and $\Delta H = 101.3\,\mathrm{kJ\,kg^{-1}}$ [11].

As mentioned above, the measurement results for electrical resistivity as presented in Fig. 5 show a decent match with the recommended values (in consideration of thermal expansion) published by Matula [11] for the solid and the liquid states. For the liquid state only one value including expansion is given, as thermal expansion values for liquid silver are sparse throughout literature, and if available, show some scattering. Therefore, we decided to use the only reliable density (or expansion) value directly after the melting transition. Therefore, a vast study of thermal expansion for liquid metals including silver is planned, as soon as our thermal expansion measurement system is reinstalled.

5.3. Ag–28Cu

As already mentioned in the paragraph describing the experimental setup, the low melting point of the eutectic Ag–28Cu alloy forced us to use a wide-range NIR-pyrometer without interference filter to properly detect the melting transition. Such a pyrometer constricts accurate temperature determination, wherefore the results for the Ag–28Cu alloy report exclusively electrically measured properties. A graphical display of these electrical resistivity versus enthalpy is presented in Fig. 6. The data obtained for Ag–28Cu include some interesting effects, which are discussed in the following paragraphs.

One of the dominant effects can be seen directly after the melting transition, as resistivity does not directly show the often reported linear behaviour throughout the liquid state but takes about another $80\,\mathrm{kJ\,kg^{-1}}$ at a different slope to develop the anticipated linear trend. As almost all investigated materials (pure metals and alloys) exhibited this linear behaviour for the liquid state, we decided to extrapolate the fit down to the melting enthalpy instead of presenting two different fits. Up to now, we do not have an explicit explanation for this behaviour, but looking at the results for pure silver (Figs. 4 and 5) one can see that a similar phenomena can be observed which is not as distinctive as with Ag–28Cu. Therefore, it can be assumed that this phenomena is caused by silver, although we do not have a complete explanation for it.

Another interesting discussion is originated by the fact that a resistivity value of $\rho_s(T_m) = 0.0744$ is obtained by our measurements at the end of the solid state. As can be found throughout the scientific literature, silver is ranked as the best thermal and electrical conductor of all metals (see, i.e., [2]). The comparable resistivity for pure silver at the end of the liquid state was found to be $\rho_s(T_m) = 0.0865$. Assuming the correctness of the obtained values, Ag–28Cu shows a lower electrical resistivity at the end of the solid state compared to pure silver although alloying metals is mostly expected to increase resistivity[4] than decrease it. The overall increase of resistivity at melting is indeed larger than the increase of pure silver as can be seen from Table 2. Up to now, no final explanation can be given with respect to this unexpected behaviour.

Another interesting fact is given by the enthalpy values at melting of Ag–28Cu, as the value of $H_s(T_m)$ is close to the value of pure silver (only ca. 3% larger). This seems to be realistic, as silver is the dominant (in wt.%) component of the alloy, and therefore, outweighs the smaller contribution of copper. A similar statement can also be found for $H_l(T_m)$ of Ag–28Cu, but this time the value is about 22% larger with respect to pure silver. As an overall result, an enthalpy of fusion of $\Delta H = 166.4\,\mathrm{kJ\,kg^{-1}}$ is found, a number which seems reasonable as it lies in the range between pure silver and pure copper. If one tries to estimate the heat of fusion for the alloy the following contributions have to be taken into account: the enthalpy of melting of the pure components (weighed by their concentration) plus the enthalpy of mixing ΔH_{Mix} of the liquid alloy. ΔH(Ag–28Cu) is determined with the following equation:

$$\Delta H(\text{Ag–28Cu}) = \Delta H(\text{Ag}) \times 0.72 + \Delta H(\text{Cu}) \times 0.28 + \Delta H_{\mathrm{Mix}}(\text{Ag–28Cu}) \qquad (11)$$

By estimating the value for (H_{Mix}(Ag–28Cu) from [14] ($\Delta H_{\mathrm{Mix}} = 46.56\,\mathrm{kJ\,kg^{-1}}$) a total value of $\Delta H_{\mathrm{Mix}} = 184.4\,\mathrm{kJ\,kg^{-1}}$ is obtained for the heat of fusion of the eutectic Ag–28Cu alloy. This result is about 11% higher than the directly measured value, and therefore, fortifies the often reported assumption that thermophysical properties of alloys

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[4] The term 'increase in resistivity' is related to the main component of the alloying materials, i.e., pure silver in our case.

only can roughly by estimated by knowing the corresponding properties of its constituting components.

6. Uncertainties

An in-depth analysis of the uncertainty according to Guide to the Expression of Uncertainty in Measurement (GUM) [15] for all feasible thermophysical properties is currently under development for the pulse-heating system used at TUG. These results will be incorporated and published as soon as the analysis is completely finished. Meanwhile, the up to now used estimation of uncertainties has to be applied to the recent measurements which already incorporates expanded relative uncertainties with a coverage factor of $k = 2$, as demanded by the GUM concept.

Two lists of final evaluated sets of uncertainties are given, first for the directly measured quantities such as: current, I, 2%; voltage drop, U, 2%; temperature, T, 4%, mass m, 2%, and second for the variables obtained accordingly: enthalpy, H, 4%; enthalpy of fusion ΔH, 8%, specific heat capacity c_p, 8%, specific electrical resistivity at initial geometry, $\rho_{\mathrm{el(IG)}}$, 4%; ρ_{el}, 6%. The actual uncertainty has been included as uncertainty bars to the individual figures.

7. Conclusions and outlook

Thermophysical properties enthalpy, heat of fusion and electrical resistivity (at initial geometry and in consideration of thermal expansion) at melting and in the liquid state are reported within this work for pure copper and silver as well as for the eutectic Ag–28Cu alloy. Whereas, such data can be found in literature for the two pure metals, the data presented for Ag–Cu alloy are to our knowledge a novelty. One of the most interesting details observed is that Ag–Cu exhibits a lower electrical resistivity at the onset of melting compared to pure silver although the contrary effect would be expected as silver is the best electrical conductor among all metals.

All efforts to estimate thermophysical properties, such as enthalpy of fusion, of the alloy based on the data of its constituting pure metals failed for the recent alloy although the obtained data seem to be reasonable.

Nevertheless, the measurements performed on Ag–28Cu are subject to two restrictions: (i) the deficiency of thermal expansion data for (which holds accordingly for pure silver) and (ii) the lack of precise pyrometric temperature determination. Both issues are subject to further investigations, whereas, the focus is on the reinstallation of the expansion measurement system for the liquid state as a lack of such data for some pure metals and some alloys is still noticeable.

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