Surface tension and density of RENE N5® and RENE 90® Ni - based superalloys

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Abstract

The surface tension and density of Ni-based superalloys RENE N5® and RENE 90® have been measured by the pinned drop method at temperatures ranging from 1638 to 1780 K. In order to obtain accurate reliable data, the tests have been performed under a reducing atmosphere to minimize the oxygen contamination. In the temperature ranges investigated, both properties show a linear temperature dependence. With the aim of evaluating the reliability of the data, the present results have been analyzed by using different thermodynamic models. The new experimental data for RENE N5® and RENE 90® superalloys were also compared with the corresponding data obtained by different experimental techniques.

Keywords: RENE N5®; RENE 90®; Ni-based superalloys; pinned drop method; surface tension; density

Introduction

In recent years, there has been a growing interest in Ni-based superalloys came up because they exhibit a peculiar combination of properties such as high strength, toughness and resistance to degradation in oxidizing and corrosive environments. The presence of a Ni_3Al ordered intermetallic phase in their microstructure, designated as γ', is key to strengthening. The major applications of Ni-based superalloys are for turbine turbine materials, jet and rocket engines working at high temperatures and high stress levels, low-emission energy effective engines for cars and aerospace as well as functional materials with high efficiency in transport using electrical energy. Superalloys are also used in nuclear power and chemical processing plants, for production of the so-called supermetals, i.e. amorphous metal alloys such as thin sheets for

electronic components with high ultimate strength to weight ratio, as construction materials for furnace parts, for biocompatible medical implants such as hip replacements, and fine metallic powders used to catalyze chemical reactions [1, 2]. There are many different metal casting processes used in the manufacture of simple or complicated components. Since the casting process involves complex interactions between various parameters related to material composition, surrounding environments, operating conditions and steps in the process, the manufacture of defect free casting products is almost impossible. Indeed, to reduce or, if possible, to prevent formation of casting defects such as freckles, white spots and spurious grain growth, much attention has been paid to the modelling of solidification. The development of numerical optimization techniques, the availability of commercial software packages together with a new generation of powerful supercomputers and accurate property data obtained using advanced laboratory techniques, are needed for the design of materials through controlling composition and microstructure, in order to optimize their final properties [3, 4]. An efficient tool for the prediction of microstructural evolution during solidification is the phase-field method, recently applied to Ni-based alloys [5]. This approach can be extended readily to other grades of superalloys, such as CMSX-4®, RENE N5®, etc. But, the use of such mathematical and numerical tools for the modelling of solidification is often limited by the lack or paucity of reliable thermophysical property data, such as surface tension and density, thermal conductivity, diffusivity and the viscosity of relevant liquid metals and alloys, needed as input parameters for the computational models [6,7]. Among the thermophysical properties, density and surface tension are two critical parameters for modelling fluid flow during the solidification process, affecting both the dendrite morphology and the complex interactions between the solid and liquid phases of the mushy zone that may lead to the formation of defects [1]. Despite the

importance of Ni-based alloys, a scarcity or sometimes, the lack of thermophysical property is observed, owing to the experimental difficulties related to high temperature measurements. There are different factors that hamper this type of experiments, such as high melting temperatures, high chemical reactivity of many liquid alloys and the influence of gas impurities, in particular on the surface properties. Among all the contaminants, oxygen plays a crucial role because it strongly affects both, the surface tension and its temperature coefficient, even if it is present in only trace amounts [8, 9]. This fact has been experimentally confirmed with pure metals [10, 11] and their alloys [12] through the use of different measurement techniques. In addition, the high reactivity of molten industrial alloys, such as Ti- and Ni-based superalloys [13, 14], respectively, together with difficulties in finding chemically inert or highly resistant crucible or support materials in order to avoid the reactions at the interface, have to be taken into account when dealing with conventional surface tension experiments.

In the present work, the surface tension and the density of RENE N5® and RENE 90® Ni-based alloys have been measured by the pinned drop method and the new experimental results have been compared with the corresponding data obtained by other techniques under both 1-g and μ-g conditions in the framework of the Thermolab Project [15].

Experimental procedure

Sample preparation

The samples of RENE N5® and RENE 90® were taken from the same batches and used by the different research groups participating in the Thermolab project [15]. Nominal compositions of the two superalloys have not been provided by the manufacturers, but Energy Dispersive Spectroscopy (EDS) analysis was used to determine their compositions (Table 1). A slight

difference between the compositions of RENE N5® determined by EDS presented in this work and those given in other sources is found. The composition of RENE 90® was found to be identical to that determined by other members of the Thermolab project, and is given in Table 1. The samples were cut into small pieces with a mean mass of 2.5 g. Prior to the measurement, each sample was mechanically abraded and chemically cleaned with organic solvents in an ultrasonic bath. The samples were weighed before and after the experiments and losses were observed.

Experimental apparatus and procedure

All the measurements were performed in an *"ad hoc"* designed experimental apparatus utilizing applying a variant of the large drop method [16] called the pinned drop method [17]. A special circular crucible with sharp edges is used in order to block the triple line at an "apparent" contact angle leading to a value than reality, and to impose an axisymmetry on the drop. This method allows to use larger drop than in the classic sessile drop method, and thus, a higher accuracy in the determination of geometrical factors (e.g. diameters, surface area, height, etc.) can be achieved [8]. The experimental apparatus and the procedure adopted have been detailed in previous works [18, 19]. The temperature of the samples was measured using a calibrated Pt/Pt-10%Rh thermocouple placed close to the sample. During the surface tension measurements, the temperature of the sample was found to be stable within ± 2 K. Following cleaning, the sample was placed in a non-oriented monocrystalline alumina (sapphire) crucible (r = 5.5 mm) which was placed on the sliding alumina holder of the experimental apparatus. When the apparatus experimental conditions (temperature, oxygen partial pressure) had been reached, the sample was introduced into the center of the furnace with the aid of a magnetic manipulator. The surface

tension and density measurements of RENE N5® and RENE 90® Ni-based superalloys were carried out at temperatures ranging from their melting point to 1780 K under a reducing flowing atmosphere (Ar-5 at% H_2 mixture; mean flow rate $q = 0.8 \cdot 10^{-6}$ $m^3 \cdot s^{-1}$). The oxygen partial pressure, P_{O2}, was monitored by using two ZrO_2 oxygen sensors (μ-gauges POAS/SETNAG®) with the Pd/PdO as internal reference. The sensors measure the oxygen content in the feed and in the exhaust gas, giving a value around $P_{O2} = 10^{-18}$ Pa at 973 K. In order to further reduce the oxygen content, close to the alloy sample a Zr foil acting as an oxygen getter has been placed.

The temperature was decreased step by step from 1780 K to the corresponding melting points of 1641 and 1658 K for RENE 90® and RENE N5® [20], respectively. At each temperature, the sample was allowed to equilibrate for a time ranging from 10 to 20 min. The profile of the liquid drop was acquired using a CCD camera operating for a time between 10 and 15 min. The image acquisition frequency was up to 10 images per second. The surface tension was calculated by using a nonlinear regression method developed by Maze and Burnet [21]. The images were processed with a dedicated acquisition software in a LABView® environment which allowed the elaboration of surface tension and other drop parameters in real time [17, 18]. The density values were obtained from the ratio of the drop weight and the measured volume at each temperature step during the pinned drop experiments. The experimental values presented are results from different measurement runs. By consideration of the experimental uncertainties involved, the total error in the surface tension and density values is estimated to be about ± 3 %. After each experiment the samples were further analyzed using SEM-EDS in order to check the surface conditions of the solidified drop and any changes in the final composition.

Results and discussion

Some information on the thermophysical and mechanical properties of RENE N5® superalloy are already known [2,4,20,22-24], while in relation to RENE 90® there are only a few thermophysical property data available [20], and these have been obtained in the framework of the Thermolab Project [15]. However, discrepancies in the reported data, such as the composition of RENE N5®, listed in Table 1 [2,4,20,22-24], and as a consequence, different liquidus and solidus temperatures [2,20,22,24] as well as different values of other alloy properties can be observed [2, 4]. To our knowledge, there is only one paper related to the surface tension and density studies of liquid RENE N5® and RENE 90® [20]. In the present work the liquidus temperatures of RENE N5® and RENE 90® superalloys, T_m = (1658 ± 11) K and T_m = (1641 ± 10) K [20], respectively, are the results of the Thermolab Project [15], and these values are used as reference data in the equations describing the temperature dependence of their surface tension and density. It is worth noting that during the surface tension measurements performed on RENE N5® alloy, the sample appeared to be in the liquid phase even at a temperature of 20 K below its melting point; as has been observed in other industrial Ni-based alloys, such as CMSX-4®, CMSX10® and CM186LC® [25].

The thermodynamic analysis presented here has been undertaken in order to evaluate the validity and reliability of the data sets obtained. The new experimental data have been analyzed with respect to the binary and ternary subsystems by using different thermodynamic models and comparing to the corresponding data reported in [20]. A similar analysis has been reported for CMSX-4® superalloy [18], Al-Nb-Ti and Al-Ta-Ti alloys [13].

Surface tension

The surface tension of RENE N5® and RENE 90® (Table 1) has been measured from their melting point to 1780 K. For the superalloys investigated, the surface tension data obtained under the conditions described above, obey a linear relationship. The new surface tension values of the two superalloys are shown in Figs. 1 and 2, respectively. Each measured value shows a deviation of about ± 25 $mN \cdot m^{-1}$ around the mean value. The temperature dependence of the surface tension of RENE N5® and RENE 90® is described by Eqs. (1) and (2), respectively.

$$\gamma_{RENE\,N5} / mN \cdot m^{-1} = 1752 - 0.67 \cdot (\mathrm{T/K\text{-}1658}) \quad (1)$$

$$\gamma_{RENE\,90} / mN \cdot m^{-1} = 1851 - 0.52 \cdot (\mathrm{T/K\text{-}1641}) \quad (2)$$

For both Ni-based superalloys investigated the surface tension decreases with increasing temperature. Taking into account that the Al content of RENE N5® is almost double that of RENE 90® (Table 1) and the surface tension values are significantly lower, the surface tension polytherms of RENE N5® and RENE 90® are consistent with each other and are shown in Figs. 1 and 2, respectively, together with the corresponding literature data [20]. Until now, the surface tension data of liquid RENE N5® (Fig. 1) are only data set available in the literature and thus, a comparison is not possible.

<Fig. 1>

The surface tension temperature coefficients of the RENE N5® polytherm, i.e. $d\gamma / dT$ = -0.67 $mN \cdot m^{-1} \cdot K^{-1}$ is obtained by linear regression fitting (Eq. (1)) and the experimental points agree with the corresponding calculated values within the uncertainty of the measurement method.

The new surface tension values of the liquid RENE 90® alloy obtained in the present work are higher than those reported in the literature [20] and compared with data measured using the oscillating drop method in ground based electromagnetic levitation (EML-OD) and during the parabolic flights experiments (PF-OD), they exhibit a maximum difference of 7 and 11%, respectively. In particular, the slopes of the surface tension polytherms are significantly different, as shown in Fig. 2.

<Fig. 2>

The literature data on the surface tension of liquid RENE 90® alloy [20] agree with each other within an experimental error of about 4 %. The data obtained by PF-OD and by EML-OD exhibit a good agreement close to the liquidus temperature, while with an increase in temperature a greater difference between the two data sets can be observed because the temperature coefficients are significantly different. In fact, as shown in Fig. 2, the surface tension polytherms have negative slopes, i.e. $d\gamma / dT_{PF-OD}$ takes values of -0.425 and -0.447, while $d\gamma / dT_{EML-OD}$ is -0.216 $mN \cdot m^{-1} \cdot K^{-1}$, a difference of 100%.

As already mentioned above, the RENE N5® and RENE 90® alloy samples from the same batch have been used for surface tension measurement by different experimental methods and thus, in all cases, the alloy compositions and the levels of impurities should have no influence on the scatter in the results observed. Therefore, the discrepancies between the experimental results measured by the pinned drop method and the two data sets obtained by the PF-OD and EML-OD containerless methods probably arise from differing amounts of oxygen present in the working atmospheres as well as from the determination of experimental temperature. A modification of

the sample composition as a result of oxidation may have had an influence on the previous measurements. In addition, concerning the OD methods, the elaboration of the oscillating spectra of complex Ni-based superalloys may also be a critical point in the determination of the surface tension values. SEM-EDS analysis performed on RENE N5® and RENE 90® superalloys revealed the presence of highly reactive elements, such as Al, Re, Ta and Ti, which have great influence on the surface tension values owing to their intrinsic reactivity in a gaseous environment as well as with common crucible materials. The surface tension of metallic melts, such as Ni-based superalloys containing various reactive metals (Table 1) can be strongly affected by certain surface-active elements, mainly oxygen or/and sulphur. Even trace amounts of these surfactants can drastically reduce the surface tension of these alloys and affect the reliability of the experimental data [9]. Therefore, further analysis of the surface tension values obtained for RENE N5® and RENE 90® has been undertaken in order to evaluate the validity and reliability of the two data sets.

In the case of complex alloys it is possible to estimate a property value analyzing a key binary and/or ternary subsystem formed by the major components of a multicomponent system of interest and taking into account the effects of the minority components on that property. Ni, Al and Cr are the major alloying elements in both RENE N5® and RENE 90® alloys (Table 1) and hence the surface tension values of two Ni-based superalloys were compared to the model based predictions for Al-Ni and Al-Cr-Ni liquid alloys as well as to the data reported in [20]. Mathematical formalisms of thermodynamic models used in the present work to calculate the surface tension of liquid binary and ternary alloys have been described in detail in our previous papers [9,13]. The thermodynamic data and the optimized data set of the excess Gibbs free energy of mixing of liquid Al-Ni [26], Al-Cr, Cr-Ni and Al-Cr-Ni alloys [27], the melting

temperatures, densities and molar volumes of pure components [28] as well as the surface tension reference data of Al [29], Cr [30] and Ni [31] were taken as input data for the calculations of the surface tension isotherms and iso-surface tension lines. It is important to mention that reliable input data must be chosen in order to reduce any disparity between the predicted and experimental values.

The surface tension of Al-Ni liquid alloys has been investigated by the perfect solution model, by the Quasi-Chemical Approximation (QCA) for the regular solutions [32] and by the Compound Formation Model (CFM) [33], a simple structural model for the chemical complexes. The AlNi intermediate phase was postulated as energetically favored and thus preferential arrangements of Al and Ni constituent atoms favor the formation of AlNi complexes in the liquid phase. The presence of short range order ordering in the liquid phase increases the surface tension of Al-Ni alloys and its variations can be estimated by the difference between the surface tension isotherms calculated by the two models. The experimental surface tension data of RENE N5® and RENE 90® with 14.63 and 7.46 at% Al (Table 1) are compared to the corresponding values of the $Al_{14.63}Ni_{85.37}$ and $Al_{7.46}Ni_{92.54}$ compositions, respectively, having the same Al content and obtained using the same experimental apparatus. The effects of the minority alloying elements on the surface tension of Ni-based alloys are comparable, at least to a first approximation, to that of liquid nickel itself. Therefore, for the calculation, the Ni content was taken as the sum of the amount of Ni present plus the minority alloying elements. The surface tension isotherms of Al-Ni liquid alloys have been calculated using the three aforementioned models for 1773 K and together with literature data [19] are shown in Fig. 3. The surface tension data set for the RENE 90® superalloy [20] was also analyzed with the aim of evaluating the reliability of the new experimental values.

<Fig. 3>

The surface tension of the $Al_{14.63}Ni_{85.37}$ alloy calculated for 1773 K by the QCA and CFM varies between 1580 and 1742 $mN \cdot m^{-1}$, while for RENE N5®, at the same temperature, a measured value of $1675\, mN \cdot m^{-1}$ was obtained. As already discussed, the new surface tension value of RENE N5® is lower than that of the $Al_{14.63}Ni_{85.37}$ alloy calculated using the CFM (Fig. 3). The surface tension value for RENE N5® obtained by the pinned drop method and the model based prediction agree within the uncertainty of the measurement method adopted. In the case of the RENE 90® superalloy, the experimental surface tension value of 1782 $mN \cdot m^{-1}$ is compared to the corresponding values of 1680 and 1785 $mN \cdot m^{-1}$ calculated for the $Al_{7.46}Ni_{92.54}$ using the QCA and CFM, respectively. The pinned drop measured value is very close to that predicted by the CFM, while the data obtained by the EML-OD and by PF-OD containerless methods [15,20] are lower (Fig. 2) and agree well with the QCA predicted value, as shown in Fig. 3. In addition, it is worth emphasizing that the measurements of surface tension of two Ni-based superalloys as well as the series of Al-Ni binary alloys [19] have been carried out by using the same experimental apparatus. The experimental surface tension values obtained for the RENE N5® and RENE 90® alloys (see Fig. 3; inside a rectangular box) are close to those of the $Al_{11.4}Ni_{88.6}$ alloy (in at %) [19] having an Al content slightly different with respect to those of the two Ni-based superalloys.

Chromium, with contents of 8.20 and 10.09 at % is the third major component after Ni and Al in RENE N5® and RENE 90® (Table 1), respectively, and thus, the surface tension of Al-Cr-Ni ternary alloys having the same Al and Cr contents as the two Ni-based superalloys investigated

can be used for comparison (Fig. 4). As mentioned in the previous analysis, the contents of the minority alloying elements in RENE N5® and RENE 90® were replaced by that of Ni. Combining the excess Gibbs free energies of mixing of the three binary subsystems with that of the Al-Cr-Ni [27], the surface tension of liquid Al-Cr-Ni ternary alloys was calculated for T = 1773 K using the Butler model. Full details of the mathematical formalism are reported in [34]. The experimental values of the surface tension of RENE N5® and RENE 90®, obtained at T=1773 K are 1675 and 1782 $mN \cdot m^{-1}$, respectively, while the corresponding values calculated for ternary $Al_{14.63}Cr_{8.2}Ni_{77.17}$ and $Al_{7.46}Cr_{10.09}Ni_{82.45}$ (in at %) alloys amount to 1585 and 1700 $mN \cdot m^{-1}$, respectively, as shown in Fig. 4.

<Fig. 4>

The calculated surface tension values of the $Al_{14.63}Cr_{8.2}Ni_{77.17}$ and $Al_{7.46}Cr_{10.09}Ni_{82.45}$ alloys are lower (about 5 %) with respect to those of RENE N5® and RENE 90® obtained by the pinned drop method owing to the presence of minor components having the surface tension values higher than that of Ni. Model based predictions for different thermophysical properties of Ni-based superalloys have been reviewed by Mills et al. [7] and, in the case of surface tension, these authors reported probable a uncertainty of about ± 5 %. Therefore, the predicted ternary values support the new experimental surface tension data of RENE N5® and RENE 90® and can be interpreted as a lower bound for the measured values. Bearing in mind that the surface tension values of undercooled Cr, Co, W, Ta, Mo, Ti and Hf [10,11] are higher than those of Ni, while the presence of surfactants, such as oxygen that, even if it is present in trace amounts, contributes to a decrease in the surface tension of Ni-based superalloys, the corresponding values of binary

and ternary alloys can be useful to provide upper and lower bounds for the equilibrium surface tension of these complex alloy systems.

After the surface tension measurements, each alloy sample has been analyzed by SEM-EDS and only minor changes in composition were observed. The dendritic microstructures of RENE N5® (Fig. 5a) and RENE 90® (Fig. 5b) Ni-based superalloys were revealed and the micrographs are shown in Fig. 5a and 5b. Although the experimental conditions were the same, a different level of surface oxidation on the solidified alloy drops was found (Fig. 5a and 5b).

<Fig. 5a and 5b>

Indeed, the oxygen content detected by EDS at the top surface of RENE 90® was lower than 0.5 at %, while in the case of RENE N5®, it was more than 13 at %. Aluminum is one of the major alloying elements in RENE N5® and RENE 90® having the lowest surface tension and therefore Al atoms segregate to the surface of both superalloys. The Al content identified by SEM-EDX on the top layers of RENE N5® is comparable to that detected on RENE 90® superalloy and, therefore the higher initial Al content of the as received RENE N5® alloy (Table 1) cannot be the only cause for its strong surface oxidation (Fig. 5a). Probably, the RENE N5® alloy melt may be more susceptible to oxidation owing to the presence of highly reactive rhenium (Table 1), as it was observed in the case of other Ni-based alloys [35].

Density

The density of the two Ni-based superalloys has been determined at the same temperatures and by the same method used for the surface tension measurements. In order to ensure accurate

results, the experimental apparatus was calibrated using the melting point of pure gold. In the temperature ranges investigated, the densities of liquid RENE N5® and RENE 90® decrease linearly with increasing temperature and their temperature dependences can be described by

$$\rho_{RENE\,N5} / g \cdot cm^{-3} = 7.53 - 0.0016 \cdot (\mathrm{T/K\text{-}1658}) \quad (3)$$

$$\rho_{RENE\,90} / g \cdot cm^{-3} = 8.01 - 0.0018 \cdot (\mathrm{T/K\text{-}1641}) \quad (4)$$

Each measured value shows a deviation of about ± 0.12 $g \cdot cm^{-3}$ around the mean value. The density polytherms of RENE N5® and RENE 90® and the experimental values obtained are shown in Figs. 5 and 6, respectively. For the alloys investigated, the density was found to increase with decreasing Al content and the new results are congruous among them with respect to Al content (Table 1). The measured density values of the two Ni-based superalloys are consistently higher than those calculated by the ideal mixture approximation and the corresponding data sets differ between 4.5 and 6.2 %, respectively. Comparable values varying between 5 and 6 % were reported for CMSX-4®, CMSX-10® and CM186LC® Ni-based superalloys [25]. These findings can be substantiated by the mixing property data of liquid Al-Ni alloys [9,19,26]. Indeed, the thermodynamic data of the Al-Ni system [26] indicate a pronounced negative deviation from Raoult's law. From an energetic point of view, very strong exothermic effects in this system result in tighter bonding between Al and Ni atoms and consequently a decrease in the molar volume, leading to higher densities with respect to those of an ideal mixture [28]. Ni-based superalloys display similar density behaviour owing to strong bonding between Ni and Al [36] that also persists in solid solutions [2]. Mukai et al. [35] have used two experimental methods to measure the density of liquid Ni and of a series of Ni-based alloys,

from binary, ternary and quaternary to complex multicomponent systems of industrial interest, aiming to obtain reliable experimental data and subsequently to formulate a general prediction model for the densities of liquid Ni-based alloys [6]. The model is based on the molar volume of Ni and the partial molar volumes of Al, Cr, Co, W, Ta, Mo and Re, obtained from the experimentally determined densities [35], while the molar volumes of Ti, Hf and Nb were taken from the literature. In order to evaluate the reliability of new data sets, the Mukai model [6] has been used to calculate the densities of RENE N5® and RENE 90® and to compare with the corresponding experimental values. In the case of RENE N5®, the density data are lacking in the literature thus, it was only possible to compare the present results with the values estimated theoretically and described by

$$\rho_{RENE\,N5}^{CALC} / g \cdot cm^{-3} = 7.54 - 0.0010 \cdot (\mathrm{T/K\text{-}1658}) \qquad (5)$$

The measured density values are slightly lower than those predicted by the Mukai model [6], as shown in Fig. 6.

<Fig. 6>

The differences between the two data sets vary from 0.3 to 1.35 % increasing with increasing temperature, from the alloy melting point to the end of the temperature interval of measurements. The discrepancies observed can be attributed to the different temperature coefficients of two density polytherms (Eqs.(3) and (5)). Preliminary analysis of density data of different Ni-based alloys indicates discrepancies between the predicted and measured values that lie within ± 2.5 %

[6,7]. The measured density values of liquid RENE 90® alloy are lower than those obtained by the EML-OD [15,20] and exhibit a maximum difference of 6 %. Larger differences, of up to 8 % were observed with respect to the corresponding predicted values [6], as it is shown in Fig. 7.

<Fig. 7>

Negative temperature coefficients of -0.00180 (Eq. (4)) and -0.00114 $g \cdot cm^{-3} \cdot K^{-1}$ [20], respectively, agree well with each other and are comparable to that obtained by Eq. (6). The density of RENE 90® predicted by the Mukai model [6] is given by

$$\rho_{RENE\,90}^{CALC} / g \cdot cm^{-3} = 8.49 - 0.0013 \cdot (\mathrm{T/K\text{-}1641}) \qquad (6)$$

As shown in Fig. (7), the density values calculated by Eq. (6) are higher than the present experimental data as well as with respect to literature data [20].

The experimental density data of RENE N5® and RENE 90® measured under the aforementioned experimental conditions can be considered as reliable and Eqs. (3) and (4) are given as the recommended equations for the two Ni-based superalloys investigated.

Conclusions

The surface tension and density of liquid RENE N5® and RENE 90® liquid Ni-based superalloys have been measured by the pinned drop method in the temperature range from their melting temperatures up to 1780 K. In order to evaluate the reliability of the new experimental values the obtained property data sets have been analyzed within various theoretical frameworks and compared with the available literature data. Model based predictions of the surface tension and

density of the two Ni-based superalloys exhibit a good agreement with the new experimental data. Taking into account the different measurement methods used, the surface tension and the density results obtained in the present work are consistent with the corresponding data sets measured by the other research groups participating in the Thermolab project.

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Figure Captions

Fig. 1 Temperature dependence of the surface tension of the liquid RENE N5® superalloy together with the experimental data (●)from the present work.

Fig. 2 Temperature dependence of the surface tension for the liquid RENE 90® superalloy together with the experimental data (▲) from the present work. Literature data (------) obtained by PF-OD (curves 1a and 1b) [20] and by EML-OD (-·-·-·-·)(curve 2) [20] are given for comparison

Fig. 3 The new surface tension experimental data of liquid RENE N5® (▲) and RENE 90® (●) obtained at 1773 K, together with literature data on RENE 90® (□) [20], (+) [20], (✶) [20]. For comparison, literature data on Al-Ni liquid alloys (■)[19] and the surface tension isotherms calculated by: the CFM (curve 1), the QCA for the regular solution (curve 2) and the perfect solution model (curve 3) are also shown

Fig. 4 Iso-surface tension lines for liquid Al-Cr-Ni alloys calculated by the Butler model for T = 1773 K. The symbols (▲,●) indicate the $Al_{14.63}Cr_{8.2}Ni_{77.17}$ and $Al_{7.46}Cr_{10.09}Ni_{82.45}$ alloys used for the evaluation of validity and reliability of new surface tension data of RENE N5® and RENE 90® Ni-based superalloys, respectively

Fig. 5 SEM micrographs and EDS analysis of the top surface of a) RENE N5® and b) RENE 90® solidified alloy drops after the pinned drop experiments performed under a reducing atmosphere of Ar-5 % H_2 (in at %) mixture

Fig. 6 Temperature dependence of the density for the liquid RENE N5® superalloy together with the experimental data (●) of the present work. The density values calculated by the Mukai model [6] (------)·are given for comparison

Fig. 7 Temperature dependence of the density for the liquid RENE90® superalloy together with the experimental data (▲) of the present work and the literature data (■) obtained by EML-OD [20]. The density values calculated by the Mukai model [6] (------)·are given for comparison

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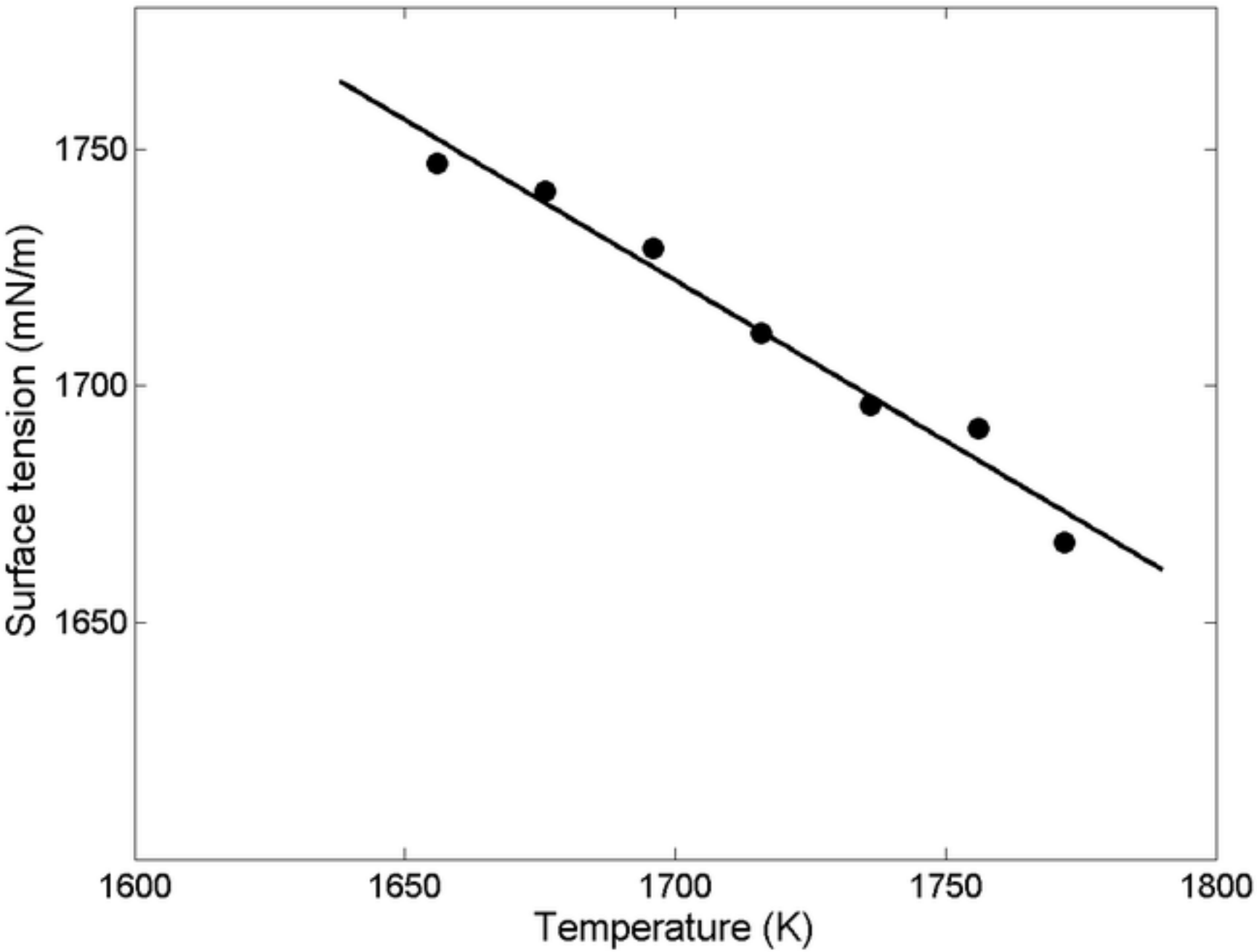

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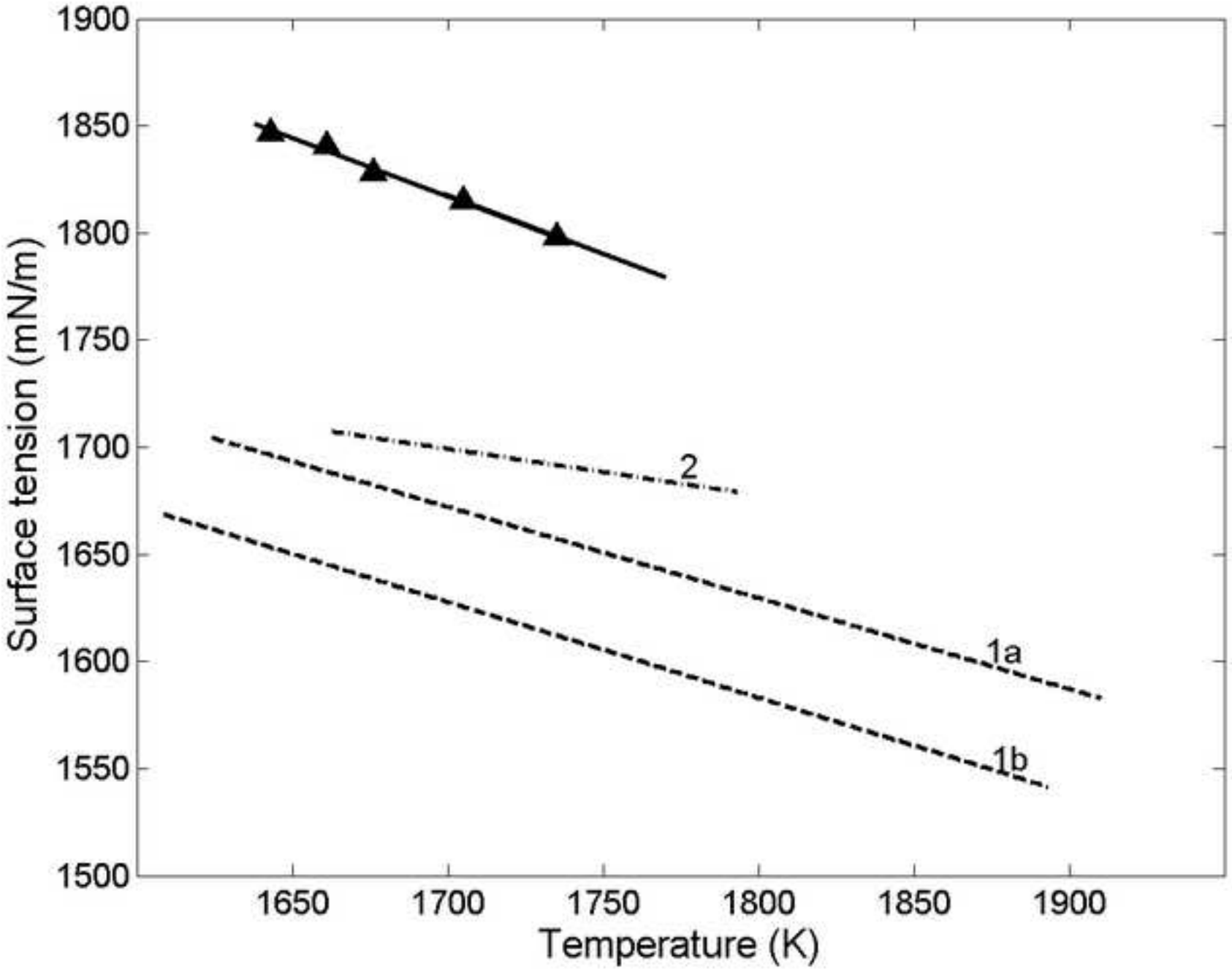

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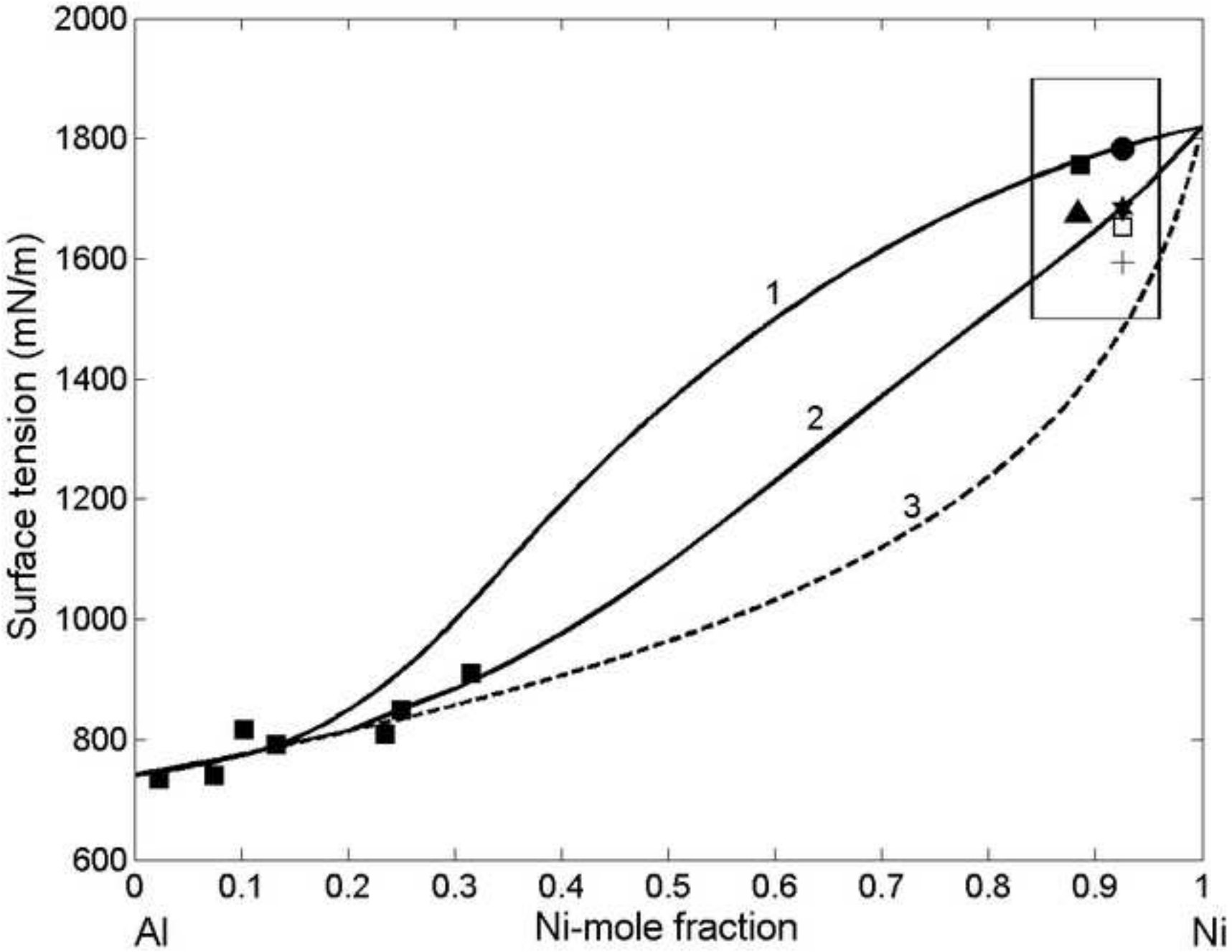

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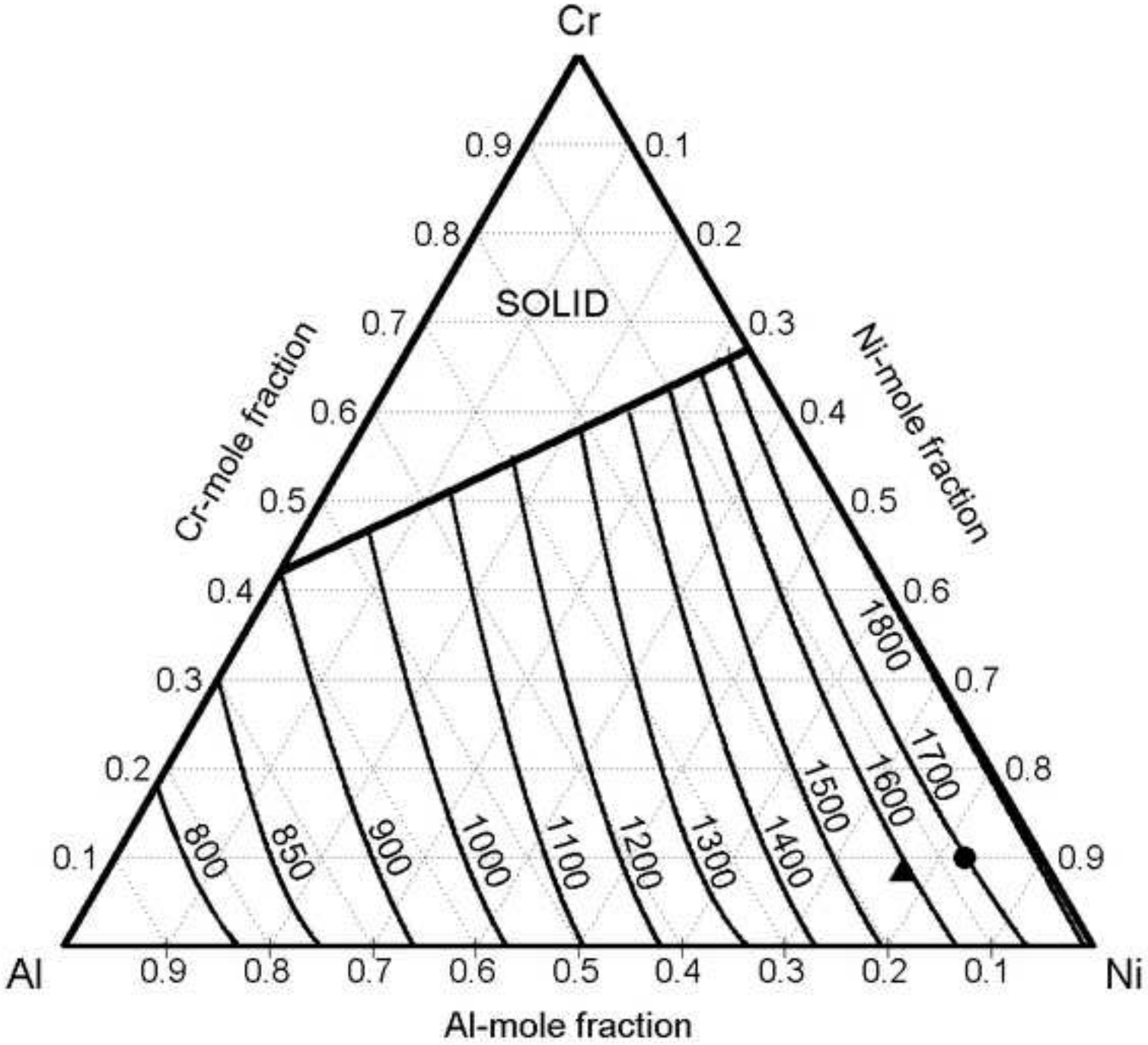

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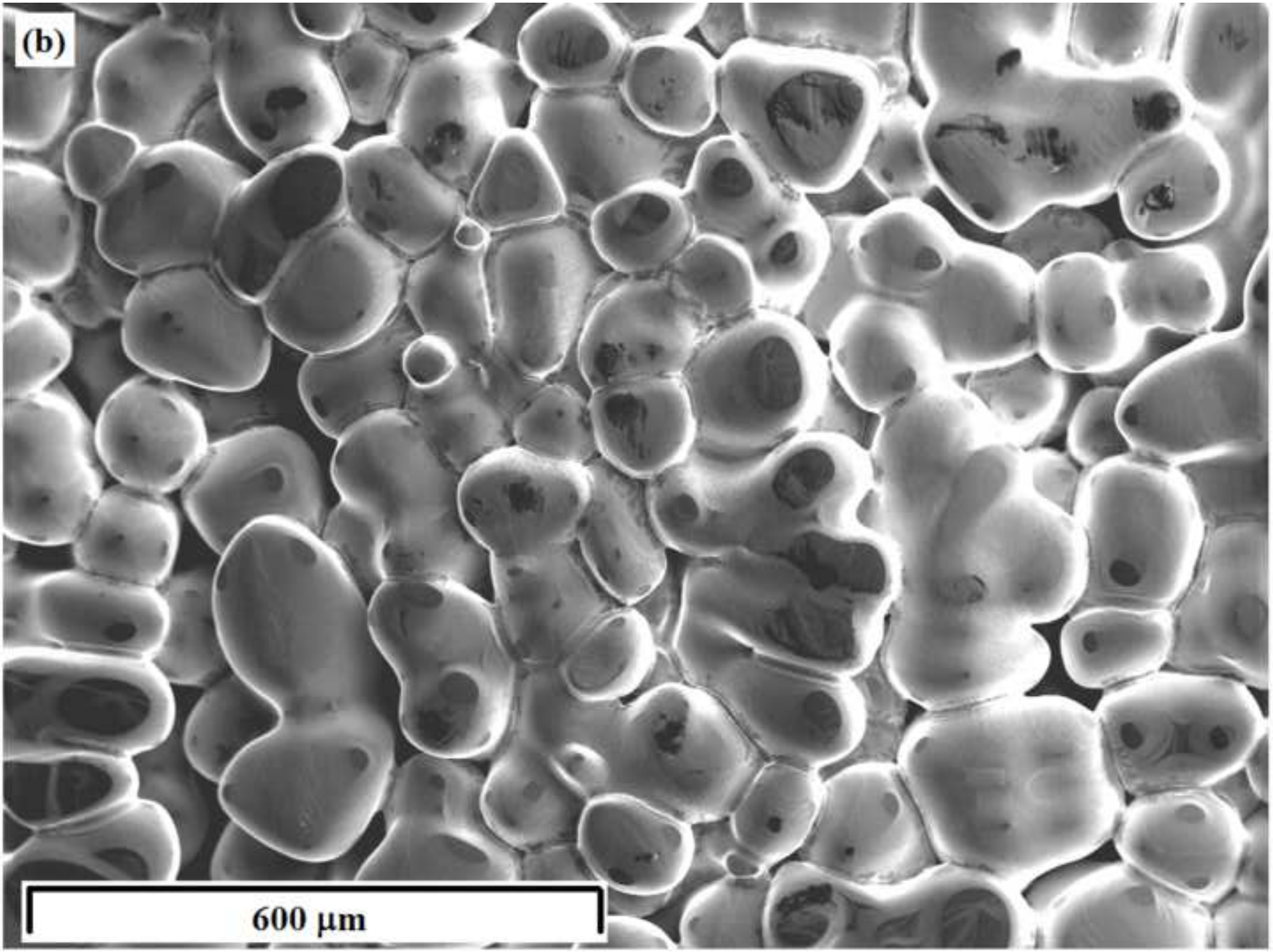

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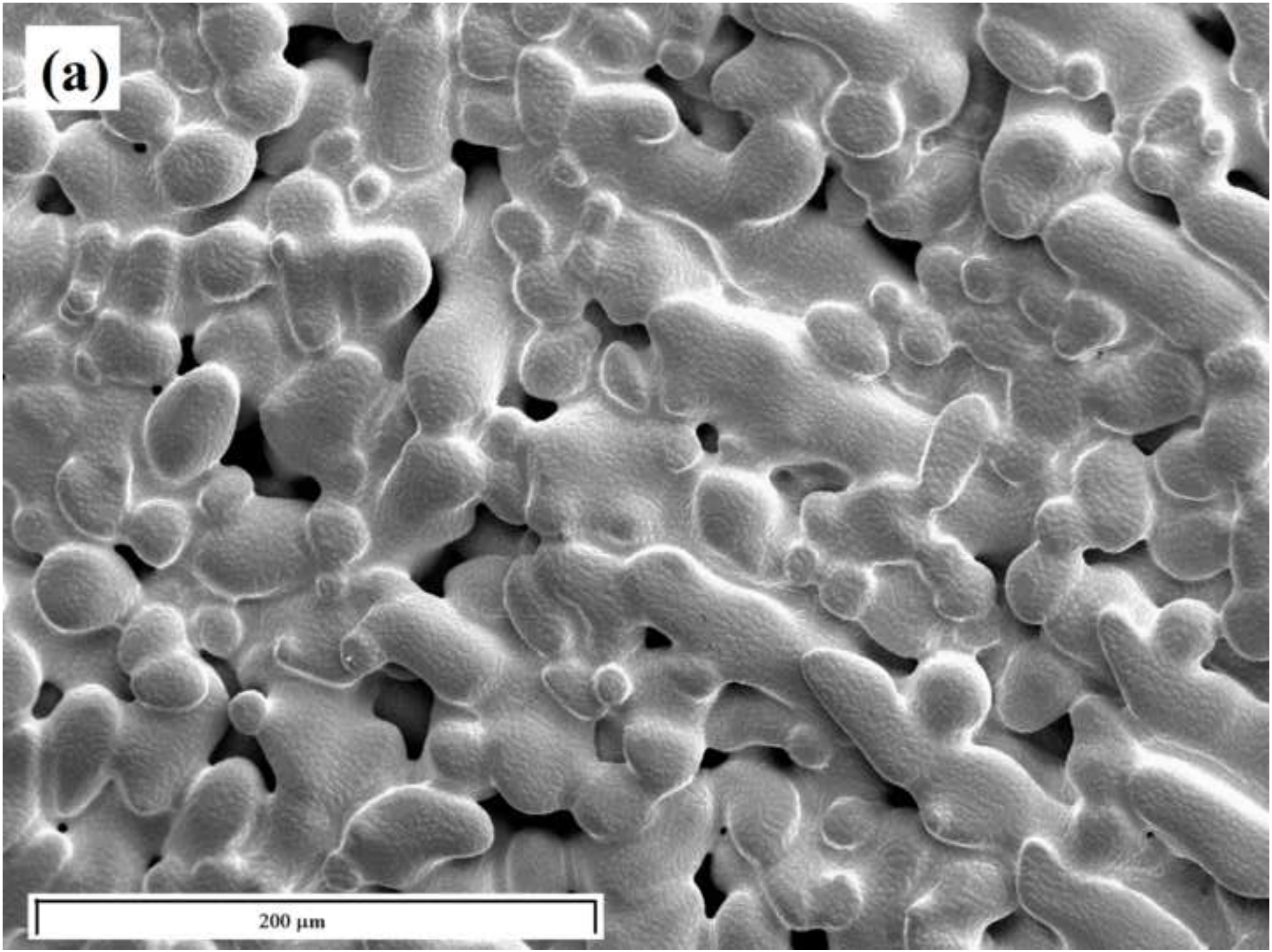

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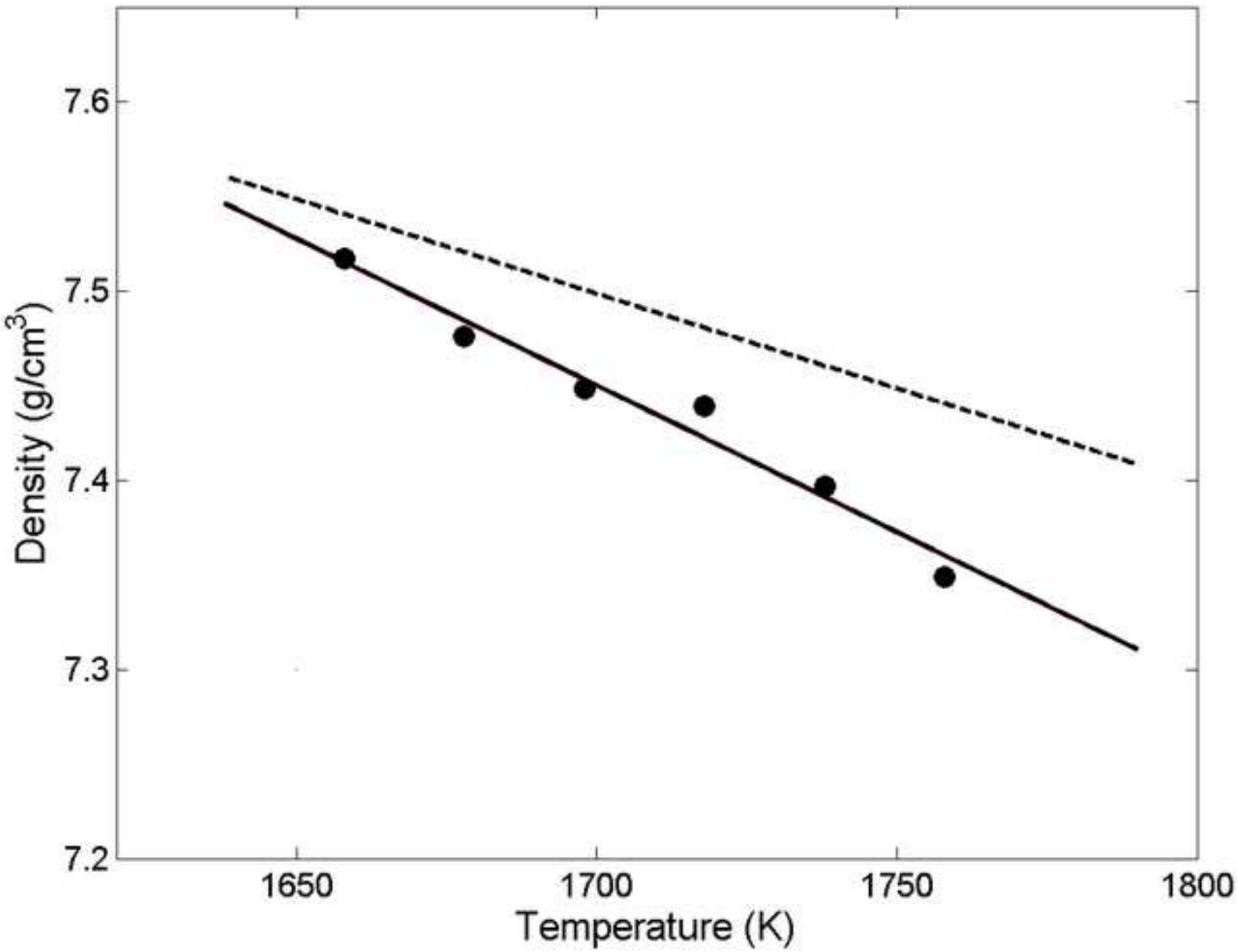

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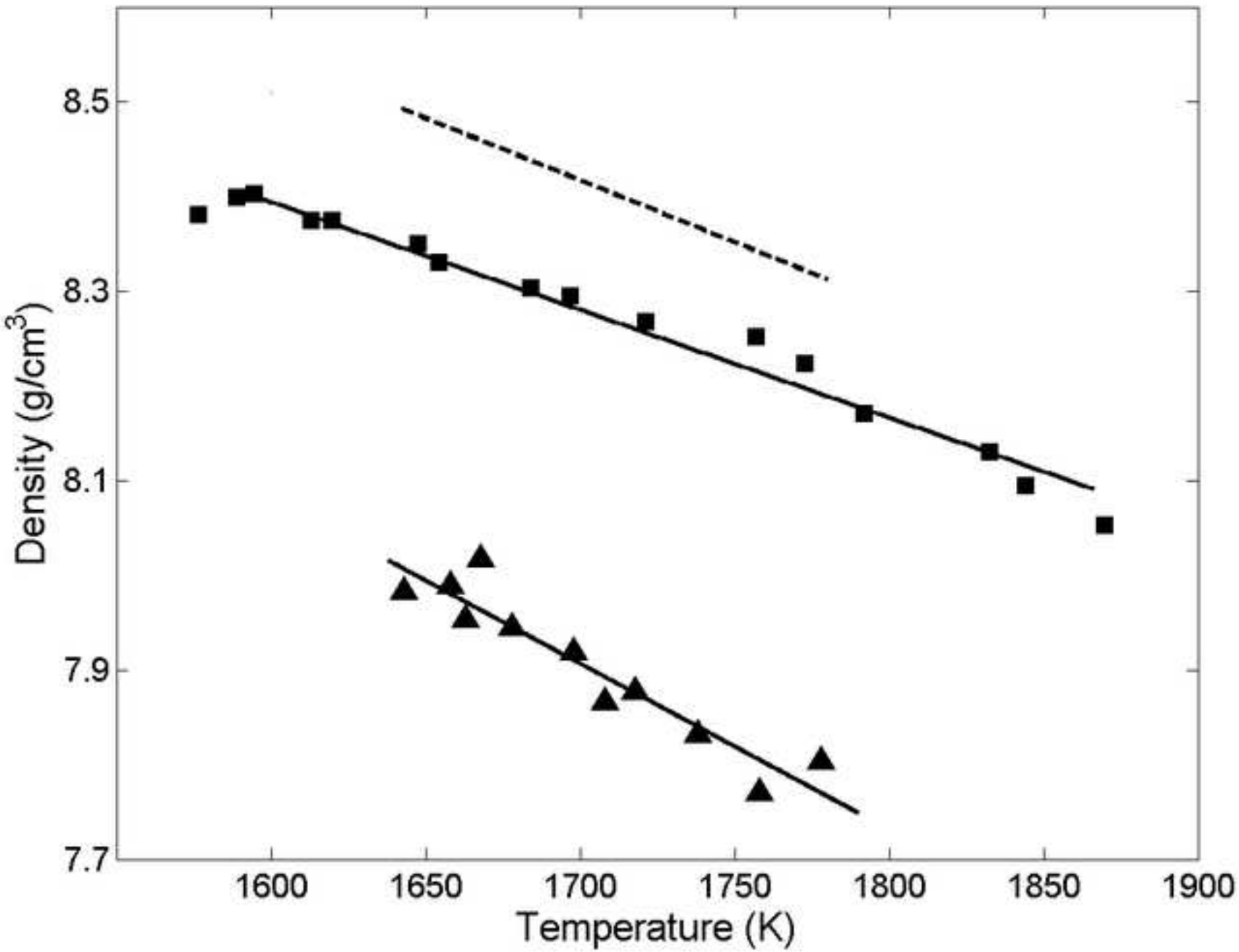

Table1
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Table 1. Composition of RENE N5® and RENE 90® Ni-based superalloys[a] (in wt %). The data obtained by EDS analysis are indicated by "*"

Alloy / Refs.	Ni	Cr	Co	Al	W	Ta	Mo	Ti	Re	Si	C	Nb	Hf	Y	B	Liquidus temp. / K
*RENE N5® present work	63.27	7.2	7.4	6.63	5.9	6.4	1.7	ND	1.5	ND	ND	ND	ND	ND	ND	1658 ± 11
(at %)	(64.1)	(8.2)	(7.5)	(14.63)	(1.9)	(2.1)	(1.1)		(0.47)							
*RENE N5® [20]	62.3	7.3	7.9	5.1	4.9	8.1	1.2	ND	3.2	ND	ND	ND	ND	ND	ND	1658 ± 11
RENE N5® [2]	63.09	7.0	7.5	6.2	5.0	6.5	1.5	ND	3.0	ND	0.05	ND	0.15	0.01	ND	1593-1723
RENE N5® [4]	61.80	7.0	8.0	6.2	5.0	7.0	2.0	ND	3.0	ND	ND	ND	ND	ND	ND	-
RENE N5® [22]	63.49	7.01	7.25	6.23	5.05	6.61	1.39	ND	2.71	ND	ND	ND	0.26	ND	ND	1676; 1668; 1648
RENE N5® [23]	60.71	7.48	7.72	6.18	6.38	7.13	1.4	ND	2.85	ND	ND	ND	0.15	ND	ND	-
RENE N5® [24]	60.596	7.0	8.0	6.2	5.0	7.0	2.0	1.0	3.0	ND	0.05	ND	0.15	ND	0.004	1660
*RENE 90® [20], present work	67.4	8.6	5.2	3.3	7.6	4.9	1.6	1.4	ND	ND	ND	ND	ND	ND	ND	1641 ± 10
(at %)	(70.08)	(10.09)	(5.39)	(7.46)	(2.52)	(1.65)	(1.02)	(1.79)								

[a] the compositions of RENE N5® and RENE 90® superalloys investigated in the present work are also indicated in at %;
ND - non detected.