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Comparison of experimental, calculated and observed values for electrical and thermal conductivity of aluminium alloys

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A model has been developed for calculating the electrical resistivity of commercial aluminium alloys from composition and heat treatments using the Matthiessen rule. The model is based on the approximation that the solubility of the alloying elements in heat treated alloys is equivalent to the equilibrium solubility at a higher temperature. These temperatures were determined from heat treatment data. The resistivity of a wide range of commercial alloys was calculated using the model, showing an agreement with most observed resistivity values of within 3 nΩm, except for alloys with special composition characteristics. According to the model, magnesium and manganese are important contributors to the resistivity for all main groups of alloys. In heat treated alloys the contribution of precipitates is 6–17% of the total resistivity. Thermal conductivity was calculated for alloys given in the literature using the Wiedeman–Franz law and the calculated resistivity. The calculated thermal conductivity agreed with the experimental values for the AlMg-alloys, but it was lower than the experimental values for pure aluminium and the AlCu-alloys in the annealed condition.

1. Introduction

For design engineers the importance of mechanical properties, weldability and workability of materials is well accepted. It has however taken a longer time to recognise the importance of the physical properties. Electrical or thermal conductors, such as power lines and components in car radiators are important areas of application for aluminium, since up to 20% of the total aluminium usage is as a conducting material. To supply the engineers with adequate and reliable property data, computerized databases are becoming more important in material engineering, because of the possibilities they have of fast access to a large amount of data on material properties. The availability of these data also enables materials scientists to use new methods to analyse the relationships between material properties. The resistivity of alloys is influenced by the microstructure of the alloys, so the resistivity can be an accurate indicator of the alloy condition and a valuable tool for quality control, for example in heat treatment. Measurement of the electrical resistivity requires only a simple procedure, applicable over a range of temperatures. It has been known for a long time that the resistivity increases nearly linearly with concentration of the alloying elements in solid solution. This dependency has been measured for binary alloys by many authors (Table I). This information can be used to determine the amount of elements in solid solution in binary alloys, or the amount in solid solution can be used to predict the resistivity. This may be complicated in commercial alloys where more than one element is precipitating from solution during heat treatment. After the heat treatment, the alloy is still in a metastable condition, which is generally unknown. In the present analysis, a semi-theoretical model is used to determine the solubility from phase diagrams.

Aluselect [1] is a data bank with about 50 properties for 100 commercial aluminium alloys, which was developed on the initiative of the European Aluminium Association (EAA). The individual aluminium producers have their own property databases in their internal files. Some variation is observed between company values, which may be due to differences in production technology, ranges of semi-products, etc. Instead of keeping all of these data in Aluselect, harmonized values were suggested for each alloy property and temper. These harmonized values were accepted as EAA's official harmonized values and put into Aluselect. The company data for resistivity are known to be based on experiments and are therefore referred to as *observed values*.

The purpose of this work is to evaluate the electrical resistivity of commercial aluminium alloys using the Matthiessen rule. The resistivity is calculated for the alloys in the database Aluselect and reference [2] and compared to the observed values in the sources. The thermal conductivity was calculated from the resistivity using the Wiedemann–Franz law and compared to experimental values for the alloys listed by Touloukian and Ho [2].

TABLE I Resistivity increment with alloying element content (wt %)

	Contribution of alloying elements to resistivity [nΩm per wt %]													
Name of original reference	Quoted in reference	Cr	Cu	Fe	Li	Mg	Mn	Ni	Si	Sn	Ti	V	Zn	Zr
Aluminium Taschenbuch 1974	[5]	41	3.3	32		5.1	36	1.8	6.8	2	31	43	1	20
Sacharow	[5]	36.5	4	4.1	43.6	5.1	26	3.8		2.8		45.6	1.5	15.8
Krupotkin	[5]			5.2										
Gauthier	[5]	47	3.1	1.4		6.3	38	0.9	4.7		37.5	39.4	1	
Vassel	[5]	32.7	3.4			7	36		7.7	2.1	22	28	1.7	2
Federighi	[5]	41					24							
Zoller	[5]		3.3	32					7.7					
Van Horn	[5]	40	3.44	25.6	33.1	5.4	29.4	8.1	10.2		28.8	35.8	0.9	17.4
Percier	[5]	42.1	1.8	2.8		5.6	25.5		Curve		31.2	39.9	1.3	
Zeerleder	[5]		2.3			5.1	32.4		Curve				1.2	
Kutner and Lang	[5]	42.2	3.06	8.5	36.8	5.6	30.7		5.16	3			1	45.4
Nielsen	[14]		3.3				32		6.8				1	
CRC-handbook	[15]	44.2	3.2		36.6	5	32	0.5	6.7		31.4	41.6	0.9	13.5
Fraenkel	[15]		3.5		37	5	24		0.8				1	
Bohner	[15]	40	4	2		5	30	2	20			40	1	
Gauthier	[15]	36	2.2	2.6		4	33	0.4	3.7		28	40	0.9	
Panseri	[10]		2			5					20			
Robinson	[10]		2.9										0.9	
Syz	[10]		4	2.5		6	32		7				1	
Zoller	[10]		3.2	3.3					0.9					
Willey	[10]	40	3.4	26	33	5	29	8	10		29	36	1	17
Harrington, R. H.	[10]	38	5	1		6	25	1			18			5
Vassel, K. R.	[10]			3.2					8					

2. Theoretical models

The thermal and electrical conductivity values at room temperature mainly depends on the type of alloying elements and their concentration in and out of solid solution. The resistivity also depends to a lesser extent on the occurance of precipitates, bulk deformations, microstructure and some other material characteristics [3]. However these contributions can usually be ignored for commercial alloys.

2.1. Electrical resistivity

According to the Bloch model, the resistivity (which is the inverse of the electrical conductivity) is a consequence of disturbances in the atomic periodicity in a crystal structure. These disturbances can be due to atomic vibrations from thermal agitation, other electrons, defects in the crystals such as vacancies, dislocations or grain boundaries, or substitution of impurity atoms in the pure metal lattice sites [4]. The most important of these effects is from the alloying elements in solid solution. The amount of solid solution lost during heat treatment is dependent on the precipitation rate and holding times. The precipitation rate strongly depends on the diffusion rate and the degree of supersaturation [3], which are both functions of the temperature. The diffusion rate increases and the supersaturation decreases with increasing temperature. The maximum precipitation rate is therefore at an intermediate temperature, between 200–450 °C.

If the alloy is dilute enough, a conduction electron can be considered to interact with only one impurity at any instant. The resistivity of a dilute alloy can then be expressed as the sum of two terms using the Matthiessen rule:

$$\rho(T, c_1, \ldots, c_\mathrm{n}) = \rho_p(T) + \rho_\mathrm{res}(c_1, \ldots, c_\mathrm{n}) \quad (1)$$

where $\rho_p(T)$ is the temperature dependent resistivity of the metal matrix (resistivity contribution from electron and phonon scattering), and $\rho_\mathrm{res}(c_1, \ldots, c_\mathrm{n})$ (residual resistivity) is the resistivity contribution from the alloying elements with a concentration c_i in solid solution. Matthiessen's rule was formulated from experimental data, but can be evaluated as a first approximation from the Boltzmann–Bloch approach [4].

Assuming the additivity of the contributions of different alloying elements to the resistivity, the residual resistivity in Equation 1 can be written as:

$$\rho_\mathrm{res} = \sum_i \rho_i c_i \quad (2)$$

where ρ_i is the characteristic resistivity (resistivity increase with each unit addition (wt %) of element i in the solid solution. For dilute alloys with all alloying elements in solid solution Equation 1 becomes:

$$\rho(T, c_1, \ldots, c_\mathrm{n}) = \rho(T) + \sum_i c_i \rho_i \quad (3)$$

Equation 3 can be generalized to take into account precipitated elements

$$\rho(T, c_1, \ldots, c_\mathrm{n}, s_1, \ldots, s_\mathrm{n}) = \rho(T) + \sum_i c'_i \rho'_i + \sum_k c''_k \rho''_k \quad (4)$$

where s_i is the solubility of element i in solution and c'_i, c''_k are the concentration (wt %) of element i in solution and element k out of solution, i, $k = 1, \ldots, n$. Here,

TABLE II Values of the constants in the Wiedemann–Franz law

Reference	Wiedemann–Franz (W–F) law	Value of L [WΩK^{-2}]	c in W–F law [W(mK)$^{-1}$]
Kempf, Smith, Taylor, as in Hatch, [3]	$\lambda = LT\sigma + c$	2.1×10^{-8}	12.6
Hatch [3]	$\lambda = LT\sigma + c^{a}$	$2.1 \times 10^{-8} + 0.021 \times 10^{-8}$ [Si]^{b}	12.6
Powell (as in reference [17])	$\lambda = LT\sigma + c$	2.22×10^{-8}	10.5
Metals Handbook, 8. Edn Vol. 1, (1961) [6]	$\lambda = LT\sigma + c$	2.12×10^{-8}	11.2
Altenpohl [17]	$\lambda/T = L\sigma + c^{a}$	2.05×10^{-8}	5×10^{-4}

[a] Units of thermal conductivity not given in reference, but assumed to be cal (S cm K)$^{-1}$

[b] [Si] is concentration of silicon (wt %) in the alloy.

$c_i = c'_i + c''_i$ is the total concentration of element i, and $c'_i = c_i$ if $c_i < s_i$, $c'_i = s_i$ and $c''_i = c_i - s_i$ if $c_i > s_i$ for $i = 1, \ldots, n$. The constants ρ'_i, ρ''_i are the characteristic resistivities (resistivity increase with each wt % addition) of element i in and out of solid solution respectively. These constants can vary considerably between sources as can be seen in Table I. The alloying elements for which the constants vary most (Fe, Zr, Ti, V) are generally found in low concentrations and low solubility, and therefore have a marginal influence on the total resistivity. The resistivity contribution of the precipitates is not as well documented as for the elements in solid solution. Kutner and Lang [5] have reported the characteristic resistivity (ρ'_i) for several elements determined for different heat treatments in binary aluminium alloys. The constants were found to vary at most up to 20% (for silicon) between the cold worked, annealed and solution treated conditions. For the alloying elements copper, chromium, manganese and magnesium, the constants vary by less than 10% [5].

2.2. Thermal conductivity

The principal carriers of heat in metals are electrons and lattice waves, which allow the overall thermal conductivity to be written as:

$$\lambda = \lambda_e + \lambda_g \tag{5}$$

where λ_e is the electronic conductivity and λ_g the lattice conductivity. The thermal conductivity (λ) and the electrical resistivity are related according to Wiedemann–Franz law

$$\lambda = \frac{LT}{\rho} + \lambda_g \tag{6}$$

where L is the Lorentz constant, T the temperature, and ρ the electrical resistivity [6]. This equation is valid for highly conducting metals, where λ_e is the dominant component over most temperatures. At higher temperatures the scattering of electrons by lattice waves becomes more significant.

The theoretical value for the Lorentz constant in Equation 6 is $L = 2.44 \times 10^{-11}$ WΩK^{-2}. In the literature the experimentally determined constants in Equation 6 can vary. A few of these values from the literature are given in Table II.

3. The data sources

The data used in the present analysis is extracted from Touloukian and Ho [2] and the database Aluselect. Touloukian and Ho [2] contains a collection of data on physical properties of aluminium, measured by different researchers during the years from 1900 to 1970. According to Touloukian and Ho [2], the data was critically evaluated and screened for erroneous data. All the electrical resistivity and thermal conductivity data for the aluminium alloys was collected from this reference and entered into a database. Aluselect contains values based on experimental data from different aluminium producers.

4. The model evaluation

4.1. Assumptions in the model

In the calculations the following assumptions and simplifications have been made:

(1) The metastable equilibrium of an alloy is assumed to be equivalent to equilibrium at a higher temperature, the temperature of equivalent equilibrium.

(2) The alloys are grouped with respect to the heat treatment, and the condition of the alloys within each group is considered similar with respect to the degree of precipitation, i.e., the difference in solubility depends only on compositional effects.

(3) The resistivity is calculated using Equation 4, with the linear constants from Hatch [3] (Table I) for all alloy groups and tempers on non-dilute alloys (i.e., containing alloy elements above 0.5 wt %).

(4) The values for the composition and the resistivity were taken as the half maximum, or the mean of the minimum and maximum values given in Touloukian and Ho [2]or Aluselect.

The coefficients in Equation 4 can vary somewhat between different sources as can be seen in Table I. The coefficients for Equation 4 as in Hatch [3] are close to the mean of the values in Table I, so these values were used in the calculations.

4.2. Grouping of the alloys according to heat treatment

The heat treatment of the heat treatable alloys includes solution treatment followed by ageing. Generally the heat treatments can be divided into three categories according to the ageing temperature, alloys which have been annealed (O), alloys which have been naturally aged (T1, T2, T3, T4), and alloys which have been artificially aged (T5, T6, T8, T9). Some alloys from the AlZn- series are in a so called overaged condition (T7). The heat treatment temperature for alloys within these groups are within a relatively narrow temperature interval, where lower temperatures are usually followed by longer holding times. In the resistivity model the degree of precipitation is assumed equal within each of these groups.

The annealed alloys and alloys in H1X, H2X and H3X tempers of the non-heat treatable alloys were placed in one group, due to the small influence of cold work on the resistivity.

4.3. The temperature of equivalent equilibrium

After the ageing process the alloy may still be supersaturated, with a part of the alloying elements in solid solution given by a solubility limit, which is higher than the equilibrium solubility at room temperature. In the resistivity model, it is assumed that the metastable condition of each alloy can be represented by an equilibrium at an elevated temperature, the *temperature of equivalent equilibrium*. According to this approach, the solubility in the supersaturated alloy equals the equilibrium solubility at the temperature of equivalent equilibrium. Since the equilibrium solubility strictly decreases with temperature, the temperature of equivalent equilibrium must be found between the room temperature and the temperature for solution treatment. Temperatures of equivalent equilibrium were determined from the heat treatment temperatures and holding times for the annealed and also the naturally and artificially aged alloys. By this, the influence of the ageing temperatures and holding times on the degree of precipitation is taken into account in the model. The difference in solubility in alloys within a group mainly depends on composition. The solubility is determined from equilibrium phase diagrams at the temperature of equivalent equilibrium for the alloys in a group, and thereby taking into account the influence of the composition on the degree of precipitation.

The temperatures of equivalent equilibrium for the annealed and also the naturally and artificially aged alloys were chosen as described below:

During *annealing* the alloy is slowly cooled to intermediate temperatures. Slow cooling allows precipitation so that the amount of the alloying elements in solid solution is close to equilibrium at any instant. Therefore the temperature of equivalent equilibrium for the annealed alloys is set as the temperature where the cooling is accelerated. Typical annealing temperatures for alloys in the 2000-, 6000- and 7000-series are 280–350 °C or 380–450 °C. In the latter case, the annealing includes slow cooling (a few $^\circ\mathrm{C\,h^{-1}}$) to about 260 °C in the case of the 2000- and 6000-series, and to 200 °C in the case of the 7000-series [6]. Therefore the 300 °C temperature, is used as the temperature of equivalent equilibrium for the annealed alloys of the 2000- and 6000- series and 200 °C for the 7000-series.

The alloys in the *artificially aged* temper group have not attained as high a degree of precipitation as the annealed temper, because of the lower precipitation temperature and shorter holding times (typical ageing temperature 130–200 °C). The degree of precipitation in the alloys in the *naturally aged* temper is for the same reasons lower than in alloys in the artificially aged temper. We choose the temperature of equivalent equilibrium for the naturally aged alloys to be between the solution treatment temperature (about 520 °C) and the temperatures of equivalent equilibrium previously determined for the annealed alloys, 300 or 400 °C. The temperature of equivalent equilibrium for the artificially aged temper, is chosen between the temperatures of equivalent equilibrium for the naturally aged and the annealed temper or 350 °C. The alloys in the T7 temper group (only appearing for alloys in the 7000-series) are artificially overaged (stabilized). These alloys have therefore attained a higher degree of precipitation than those in the T6 temper. The solubility for these alloys was read from phase diagrams at a lower temperature than for the T6 temper, i.e., 300 °C.

The temperature of equivalent equilibrium for AlMg- and AlMn- alloys in the annealed condition is taken as described above at the annealing temperature, i.e., at 350 °C for the AlMg- alloys and 420 °C for the AlMn- alloys. The effect of strain hardening on the resistivity is small in pure aluminium alloys [5], but the effect on the resistivity for the higher alloyed alloys is not as well known. Miyake and Fine [7] have reported that this effect is very small in a copper-nickel alloy. The effect of the partial annealing on the resistivity of the AlMg- alloys is not included in the model. Because of the limited availability of phase diagrams, the solubility was determined for several elements at temperatures close to these temperatures, generally within ± 50 °C.

4.4. Thermal conductivity

The room temperature thermal conductivity for the alloys in Touloukian and Ho [2] were calculated using Equations 4 and 6 and compared to the experimental thermal conductivity listed in the same source. The experimental room temperature thermal conductivity of the alloys in Touloukian and Ho [2] was found by linear interpolation of the experimental thermal conductivity values between − 100 – + 100 °C for about 170 alloys and tempers.

5. Results

5.1. Comparison of the calculated and the observed resistivity

The calculated resistivity and the resistivity from Aluselect and Touloukian and Ho [2] are shown as a function of the concentration of the main alloying element in Figs. 1–9 for some tempers of the AlCu-, AlMg- and AlZn- series and as a function of excess silicon (i.e., $\mathrm{Si_{excess}} = [\mathrm{Si}] - [\mathrm{Mg}]/1.73$) for the alloys from the AlMgSi-series.

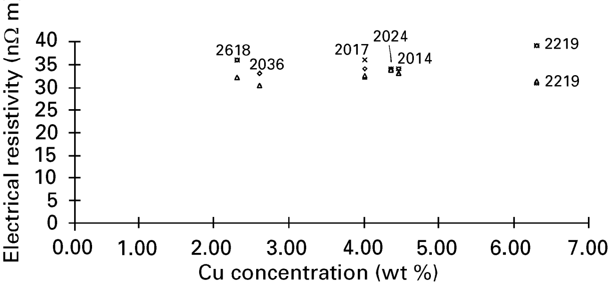

Figure 1 The calculated and observed resistivities for the AlCu-series, temper O(×) from Touloukian and Ho, (◇) Aluselect and (△) present analysis.

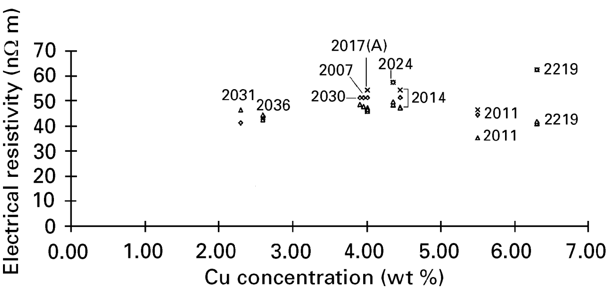

Figure 2 The calculated and observed resistivity for the AlCu-series, temper T4 (×) from Touloukian and Ho [2], (◇) Aluselect and (△) present analysis. Points for similar tempers may coincide (e.g., T3, T4, etc.).

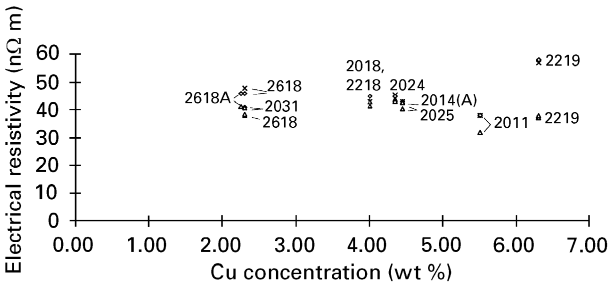

Figure 3 Calculated and observed resistivity for the AlCu- series, temper T6 (×) from Touloukian and Ho [2], (◇) Aluselect and (△) present analysis. Points for similar tempers may coincide (e.g., T5, T6, etc.).

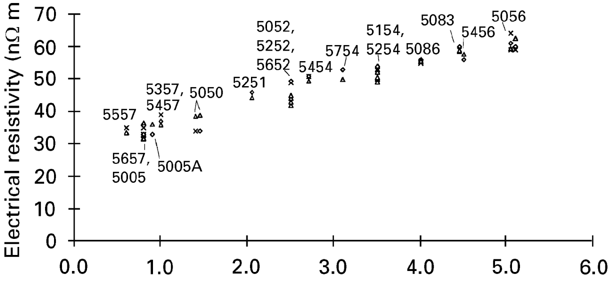

Figure 4 Calculated and observed resistivity for the AlCu- series, all tempers (×) from Touloukian and Ho [2], (◇) Aluselect and (△) present analysis. Similar tempers may coincide (e.g., H2, H4 …).

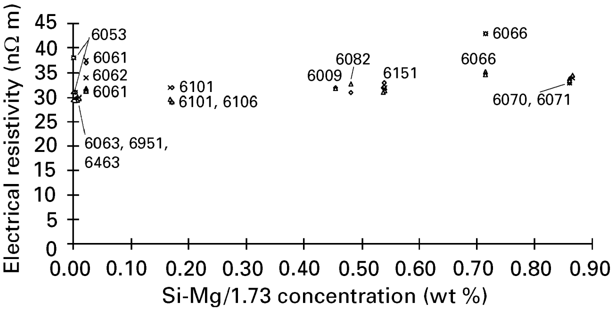

Figure 5 Calculated and observed resistivity for the AlMgSi- series, temper O (×) from Touloukian and Ho [2], (◇) Aluselect and (△) present analysis.

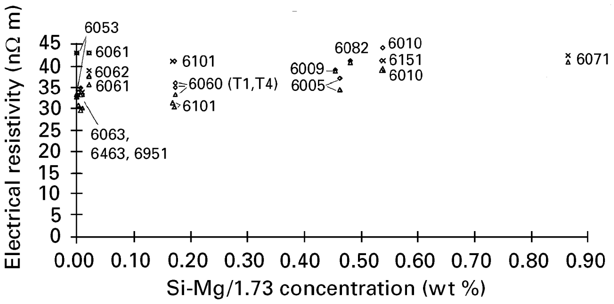

Figure 6 Calculated and observed resistivity for the AlMgSi- series, temper T4 from (×) Touloukian and Ho [2], (◇) Aluselect and (△) present analysis.

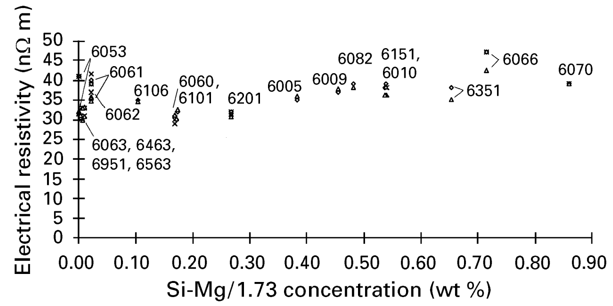

Figure 7 Calculated and observed resistivity for the AlMgSi- series, temper T6 from (×) Touloukian and Ho [2], (◇) Aluselect and (△) present analysis.

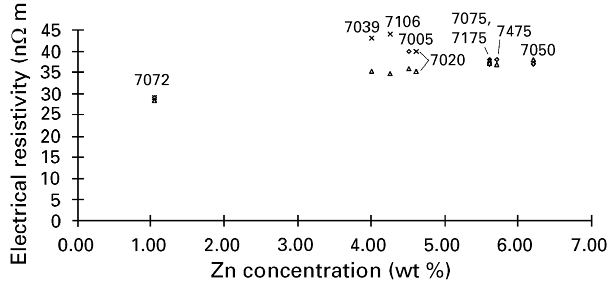

Figure 8 Calculated and observed resistivity for the AlZn- series, temper O from (×) Touloukian and Ho [2], (◇) Aluselect and (△) present analysis.

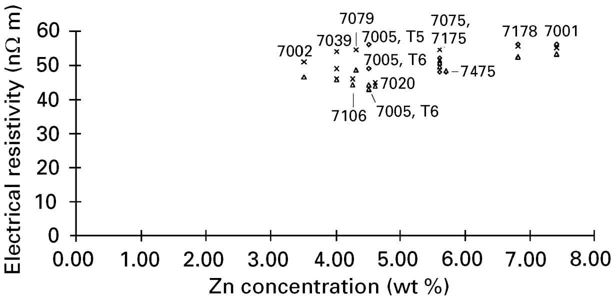

Figure 9 The calculated observed resistivity for the AlZn- series, temper T5 and T6 from (×) Touloukian and Ho [2], (◇) Aluselect and (△) present analysis.

As can be seen in Table III, the calculated resistivity agreed with the observed resistivity within 3 nΩm for all tempers of 41 alloys, for all tempers but one (usually the naturally aged temper) for 10 alloys, and the difference was larger than 3 nΩm for all tempers of 23 alloys. For the AlCu- series the largest deviation between the calculated and observed resistivity is for the alloys AA2011, AA2219 and AA2618 (Figs. 1–3). For the AlMg-alloys the largest deviation is for the alloys AA5050 and AA5252 for all tempers (Fig. 4). The calculated resistivity of AA5050 and AA5252 are above and below the observed values respectively (Fig. 4). The largest deviation for the AlMgSi- alloys is for the alloys AA6053, AA6061 and AA6066 in all tempers (Figs. 5–7). Furthermore a large deviation is also observed for the T4 temper of AA6101 and AA6262. The largest deviation for the AlZn- alloys is for the alloys AA7005, AA7020, AA7039 and AAX7106 for all tempers (Figs. 8–9).

5.2. Characteristics of the resistivity model

According to the model, the influence of the alloying elements on the resistivity is greatest for the solid solution hardened alloys, i.e., alloys from the 3000 and 5000 series (Table IV). The contribution of manganese and magnesium seems to be important for all alloy groups. According to the model, the precipitated elements contribute to the total resistivity with up to 17% (Table IV).

5.3. Thermal conductivity

The calculated thermal conductivity and the corresponding experimental thermal conductivity from Touloukian and Ho [2] are shown for the AlMg-alloys in Fig. 10 as a function of the main alloying element. The calculated thermal conductivity seems to be in agreement with the experimental thermal conductivity for the AlCu- alloys in temper T6 (only five alloys), and AlMg- alloys but a bit lower for the annealed AlCu- alloys (about 30 $W^{-1}mK$). The values for the alloys AA5050 and AA5252 (Fig. 10) (from Aluselect) have, as expected, a similar difference between the calculated and observed thermal conductivities.

TABLE III List of alloys with deviation between the calculated and observed resistivity below and above 3 nΩm

Below 3nΩm	Below 3nΩm except for T4 temper	Above 3nΩm
2018, 2025(T6), 2030(T4), 2036, 2117, 2124, 2218(T6)	2014(A), 2024, 2031	2011, 2017, 2219, 2610(A)
3004, 3103 (except O), 3105 (except O)		3003
5056, 5083, 5086, 5154(A), 5182, 5251, 5454, 5456, 5457, 5557, 5657		5005(A), 5050, 5052, 5252, 5652, 5754
6005, 6060, 6062, 6063, 6070, 6071, 6082, 6151, 6201(T8), 6351, 6951	6010, 6101, 6463(T1)	6053, 6061, 6066, 6262
7001, 7010, 7049, 7050, 7072, 7075, 7079(T6) 7175, 7475		7002(O), 7005, 7010(T7), 7020(T6), 7039, 7178, 7106

TABLE IV Average contribution of alloying elements to the electrical resistivity according to the resistivity model, as a percent of the mean resistivity in each group

	Mean resistivity [nΩm]	Cu [%]	Fe [%]	Si [%]	Mg [%]	Ni [%]	Mn [%]	Ti [%]	Zn [%]	Cr [%]	Total precipitated [%]	Al-matrix [%]
AlCu-O	34	9	1	1	4	0	5	0	0	1	17	78
AlCu-T4	46	14	0	5	7	0	11	2	0	3	6	57
AlCu-T6	41	11	1	4	7	1	7	1	0	3	9	65
AlMn-all	39	1	1	2	2	0	23	1	0	2	11	68
AlMg-all	47	0	0	1	32	0	6	1	0	4	2	56
AlMgSi-O	31	2	1	1	6	0	4	0	0	2	12	84
AlMgSi-T4	35	2	0	3	7	0	6	2	0	5	6	75
AlMgSi-T6	34	2	0	2	6	0	6	1	0	4	7	78
AlZn–O	34	2	0	0	11	0	2	0	5	1	14	77
AlZn-T5,T6	49	5	0	0	18	0	6	1	10	5	9	54
AlZn-T7	41	5	0	0	10	0	3	1	13	2	12	64

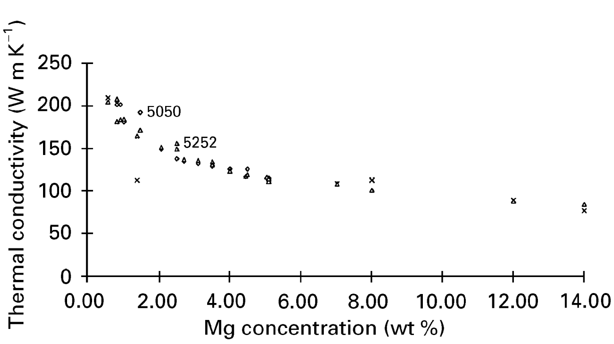

Figure 10 Experimental and calculated thermal conductivity of the 5000- series, all tempers from (◇) Aluselect and (×) Touloukian and Ho [2], and present analysis results (△). AA5050 and AA5252 in Aluselect calculated from electrical resistivity (see Fig. 4).

6. Discussion

Most of the alloys with a significant difference between the calculated and observed electrical resistivities show special characteristics in their composition. The possible causes for this deviation may be found in the precipitation processes.

6.1. AlCu-alloys

The AlCu-alloys (AA2011 and AA2219) contain a high copper content and small amounts of other elements, so their precipitation behaviour may be similar to that of high copper content binary alloy. In a binary AlCu-alloys with 6 wt % copper, it has been observed that the copper mainly precipitated on grain boundaries [8]. In this case, the conductivity of the precipitates may determine the overall conductivity. Also the copper content of the alloys is much higher than for other alloys of this series, and close to or above the maximum solubility limit of copper (5.65 wt %). In the model, the same solubility of copper is assumed for all of the alloys in a group (i.e., 2.5 wt % for the T4 group). This means that for the T4 temper, 3 wt % copper has precipitated during natural ageing for the high copper alloys, while only 1 wt % has precipitated in alloys containing 4 wt % copper. The large deviation for the high copper alloys may therefore be caused by the generalizations made in the model.

An increase in the resistivity is observed during the first stage of ageing where dispersoids are formed through zone formation. When high copper content alloys are cooled from solution temperature, the supersaturation is higher than for alloys with a low copper content, which may result in denser zones. An increased number of zones in a unit volume results in a higher resistivity, but it also means increased interfacial strain in the matrix, which counteracts precipitation which in turn increases the resistivity.

In alloys with a [Mg] : [Cu] ratio above 0.4, the main precipitate is $CuMgAl_2$ [9, 10]. The main precipitate formed during ageing of the alloy AA2618 ([Mg] : [Cu] ratio equal to 0.8) is therefore probably $CuMgAl_2$ and not $AlCu_2$ as in other AlCu- alloys. It has been observed that $CuMgAl_2$ may mainly precipitate on the grain boundaries in the alloy AA2618 [12].

From industrial practice, it can be seen that the alloys AA2219 and AA2618 need a higher solution treatment temperature and higher ageing temperatures and/or longer holding times compared to other AlCu- alloys [11, 12] to reach their optimal mechanical properties.

6.2. AlMgSi-alloys

The calculated resistivity agrees with the experimental value for most of the alloys from this series as can be seen in Table III. The deviation of the calculated resistivity from the observed value is larger for all tempers of the alloys AA6053, AA6061, AA6101 and AA6066 and the free cutting alloy AA6262, compared to similar alloys. Three of these alloys, AA6053, AA6061 and AA6262 belong to a group of alloys with $Mg + Si > 1.5$ wt %, balanced in magnesium and silicon to form Mg_2Si and are alloyed with chromium (0.15–0.35%). Alloys with $Mg + Si > 1.5$ wt % generally need a higher temperature for the solution treatment, so they are solution treated separately [3]. Only one alloy AA6062 in the paper of Touloukian and Ho [2] and Aluselect belongs to this group and where the calculated and observed resistivity agree, but the difference is that it is not alloyed with chromium.

Two alloys with excess silicon and alloyed with chromium are found in the database, namely AA6151 (with a low chromium content) and the rather highly alloyed AA6066. The calculated and observed resistivities agree for the alloy AA6151 but not for AA6066 (Figs. 5–7). For the alloy AA6066 the elements are given within large intervals.

It can be concluded that the resistivity of the balanced alloys from the AlMgSi- series, alloyed with chromium is higher than the calculated resistivity.

A large difference was observed for the T4 temper of the Alloy AA6101. It is alloyed with boron as a grain refiner and thus improves conductivity by precipitating vanadium, titanium and chromium, so the observed resistivity is expected to be lower than the calculated resistivity. Nevertheless, the observed resistivity from Aluselect and Touloukian and Ho [2] is higher than the calculated resistivity for the naturally aged temper of this alloy (Fig. 6). The observed resistivity for this temper is much higher than in the annealed and T6x conditions. This difference generally is much smaller for similar alloys.

6.3. AlZn- alloys

There is a significant deviation between the calculated and observed resistivities for the alloys AA7005, AA7020 and AA7039 for all tempers. These alloys have similarities in their compositions, i.e., all contain less than 0.1 wt % copper, magnesium 1.4–2.8 wt % and manganese 0.25–0.45 wt %. The calculated resistivity agrees with the observed resistivity for the one alloy that does not contain any copper, i.e., AA7072. This alloy is considered as a non-hardenable alloy containing low contents of alloying elements (1 wt % Zn, 0.05 wt % Mg), and is special compared to similar alloys. The difference between the calculated and observed resistivities for the alloys AAX7002 and AA7079 in T6 from Touloukian and Ho [2] does not seem to be related to differences in composition. The copper containing alloys from this series generally are solution treated at higher temperatures than the copper free ones, and are more sensitive to cooling rates [13].

7. Conclusions

The resistivity was calculated for commercial aluminium alloys in terms of their composition and heat treatments. The calculated and observed values deviated by less than 3 nΩm except for three groups of alloys with special composition characteristics:

- magnesium free and/or high copper alloys of the AlCu- series
- chromium alloyed alloys of the AlMgSi- series
- copper free alloys of the AlZn- series.

Generally these alloys are heat treated and/or solutionized at higher temperatures than similar alloys. Magnesium and manganese are large contributors to the resistivity for all main commercial alloy groups. Precipitated elements, if present, contribute to the resistivity by 6–17% of the total resistivity.

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