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An Assessment of Thermodynamic Data for the Liquid Phase in the Al-Rich Corner of the Al-Cu-Si System and Its Application to the Solidification of a 319 Alloy

X.M. Pan, C. Lin, J.E. Morral, and H.D. Brody

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A thermodynamic database for the liquid phase in the Al-rich corner of the Al-Cu-Si system has been developed by fitting all thermodynamic and phase diagram information that is currently available from the literature. A comparison between the calculated results and the experimental data is presented, and the calculated results reproduce all the liquidus and solidus boundaries to within experimental scatter. Also, the present assessment was used to predict the solidification behavior of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy. Subsequent experimental results validate these predictions.

1. Introduction

The unique properties of Al make its alloys some of the most commercially important materials in modern industry. For example, Al-Cu-Si alloys are of interest for application in automotive and aerospace technology due to their quality and lightweight. Their corrosion resistance is superior to that of Al-Cu alloys, and their strength is better than that of Al-Si alloys. Therefore, a basic understanding of the thermodynamics, phase relationships, and solidification behavior of this alloy system will be useful for future work on Al-Cu-Si alloys and process design.

Over the past several decades, much work has been done on this system, especially in the Al-rich corner. That work has laid a foundation for understanding the ternary system, but no thermodynamic assessment has been reported. The purpose of this work was to develop a thermodynamic description of the liquid phase in the Al-Cu-Si system to facilitate our further study of more complex Al-Cu-Si-X (X = Mg, Fe, Mn) multicomponent systems. Due to scarce experimental information away from the Al-rich corner, the present work will focus mainly on creating a database for the Al-rich corner.

In the following sections, a brief introduction to the experimental information available from the literature is presented first. Then the thermodynamic models are discussed, and the thermodynamic parameters are evaluated. Third, calculations from the present thermodynamic description are discussed and compared with the experimental information. Finally, the solidification behavior of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy that was studied experimentally will be compared with predictions made from the present assessed database.

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2. Evaluation of Previous Work

2.1 Binary Subsystems

Complete assessments of the binary subsystems Al-Cu and Al-Si are available from the COST Action 507 [1998Gro, 1998Sau]. Very recently, [2000Yan] reassessed the Cu-Si binary system. Their results are reproduced in Fig. 1 to 4. Their thermodynamic descriptions for these three binary systems are accepted in this work and are listed in Table 1.

2.2 Experimental Data of the Ternary System

Few thermodynamic data for the Al-Cu-Si ternary system are available in the literature. Recently, [2000Wit] mea-

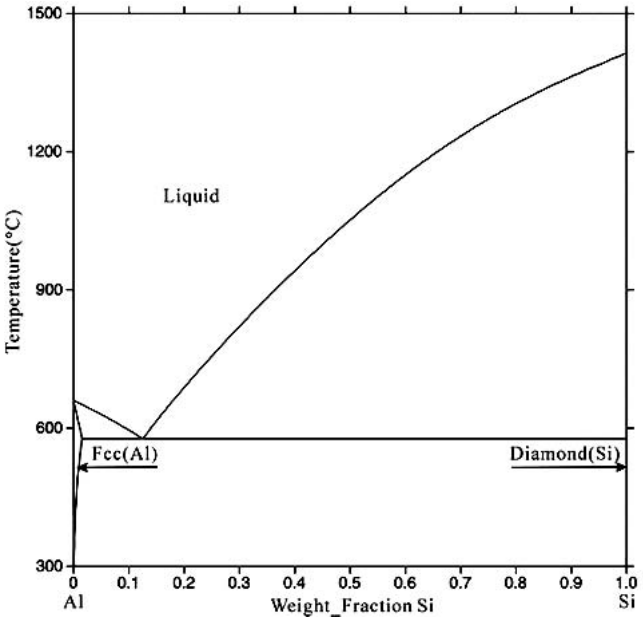

Fig. 1 The phase diagram of Al-Si system reproduced from [1998Gro]

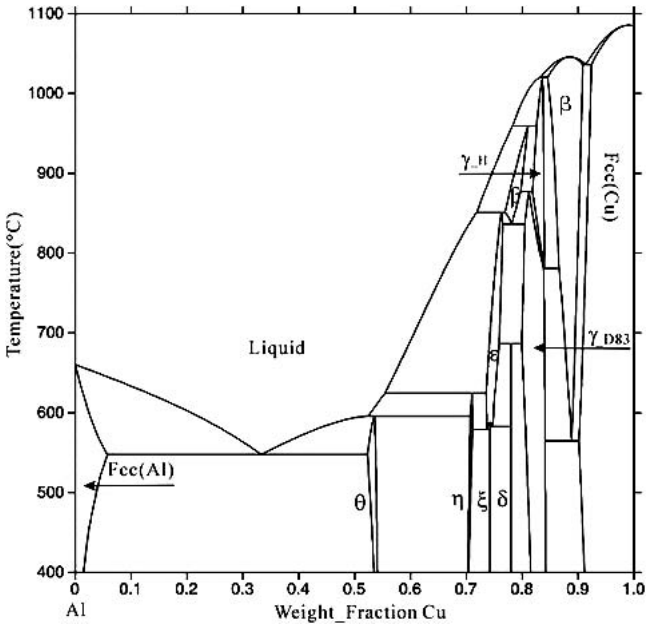

Fig. 2 The phase diagram of Al-Cu system reproduced from [1998Sau]

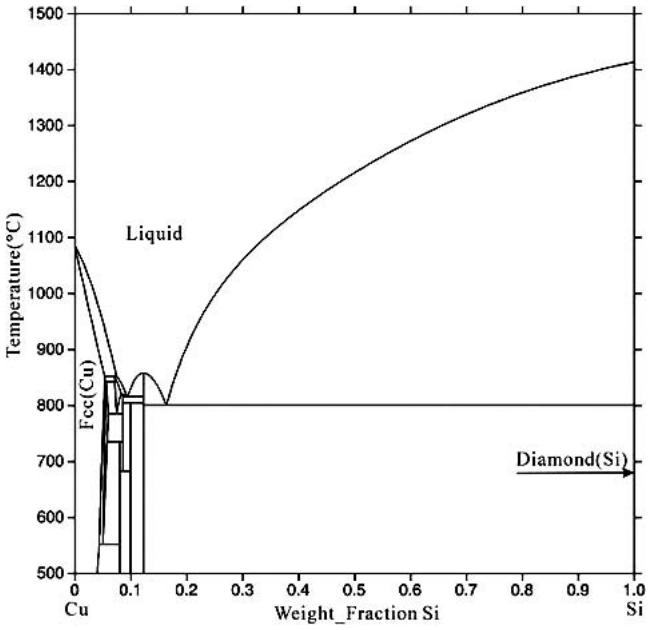

Fig. 3 The phase diagram of Cu-Si system reproduced from [2000Yan]

sured the mixing enthalpies of liquid Al-Cu-Si alloys at 1302 °C (1575 K) by high-temperature calorimetry, and [1997Bel] determined the heat of mixing of some liquid alloys at 1472 °C (1745 K) by high-temperature isoperibolic calorimetry. Moreover, the heat of melting of the eutectic in the Al-rich corner was determined by [1985Far] to be 13.5 kJ/mol. All of these thermodynamic data were used in this assessment.

In 1992, [1992Luk] reviewed all prior references to the

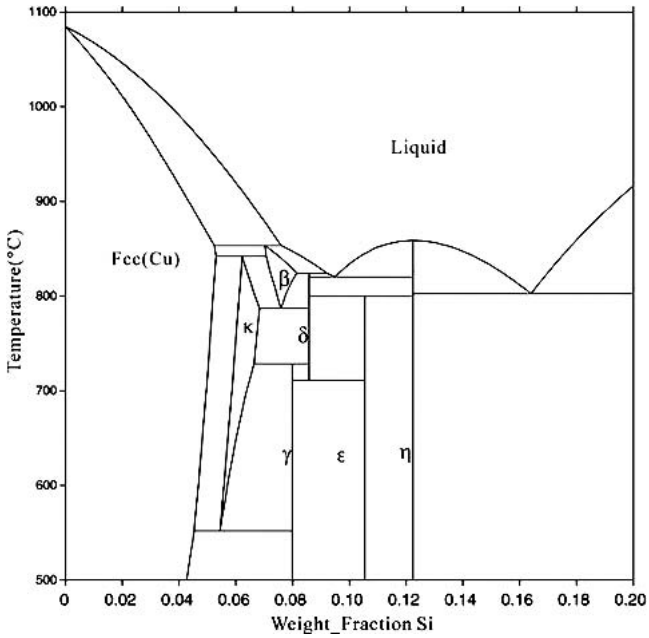

Fig. 4 An enlargement of the phase diagram from 0 to 20 wt.% Si in Fig. 3.

Al-Cu-Si ternary system. Most of the experimental phase equilibrium data of the system were focused on the Al-rich corner [1923Wet, 1928Gwy, 1934Mat, 1935His, 1940Wie, 1953Phi, 1975Kuz, 1990Kuz1, 1990Kuz2], which is the region of interest in the current study. The experimental results were in good agreement with each other. According to those results, a ternary eutectic reaction L ↔ (Al) + θ_{AlCu} + (Si) exists at 524 °C with a liquid composition of 13.4 at.% Cu and 6 at.% Si, and a solid face-centered cubic (fcc) (Al) composition of 2.1 at.% Cu and 1.1 at.% Si, respectively.

Part of the Cu-rich corner was investigated by [1948Wil]. His results suggest that Al can stabilize the hexagonal close-packed A3 (κ) phase and make it stable at room temperature in the ternary system. Both [1934Mat] and [1935His] investigated the whole system by thermal analysis and micrography. A series of isothermal and vertical sections were presented, and no ternary phase was reported in the system. All of the experimental information accepted in this work is shown in Fig. 5 to 14. Those assessed invariant reactions that were accepted in this work are summarized in Table 2.

3. Thermodynamic Models and Optimization

The substitutional solution model was used to describe the liquid, fcc(Al), and bcc_A2 phases. This model yields the following expression for the Gibbs energy:

$$G_m = x_{Al}{}^0G_{Al} + x_{Cu}{}^0G_{Cu} + x_{Si}{}^0G_{Si} + RT(x_{Al}\ln x_{Al} + x_{Cu}\ln x_{Cu} + x_{Si}\ln x_{Si}) + {}^{ex}G_m \quad \text{(Eq 1)}$$

in which the parameter ^0G_i represents the Gibbs energy of the pure component i (I = Al, Cu, or Si) taken from the

Scientific Group Thermodata Europe (SGTE) standard substance database [1991Din]. The excess energy term ${}^{ex}G_m$ can be expressed in Redlich-Kister polynomials:

$$
\begin{aligned}
{}^{ex}G = {} & x_{Al}x_{Cu}\sum_{j=0}^{n}{}^{j}L_{Al,Cu}(x_{Al}-x_{Cu})^{j} \\
& + x_{Al}x_{si}\sum_{j=0}^{n}{}^{j}L_{Al,Si}(x_{Al}-x_{Si})^{j} \\
& + x_{Cu}x_{si}\sum_{j=0}^{n}{}^{j}L_{Cu,Si}(x_{Cu}-x_{Si})^{j} \\
& + x_{Al}x_{Cu}x_{Si}(x_{Al}L_{Al}+x_{Cu}L_{Cu}+x_{Si}L_{Si}) \qquad \text{(Eq 2)}
\end{aligned}
$$

in which ${}^{j}L_{AlCu}$, ${}^{j}L_{Alsi}$ and ${}^{j}L_{CuSi}$ are binary interactive parameters taken from the constituent binary systems, and the L_i(i = Al, Cu, or Si) = $a_i + b_iT$ are ternary interactive parameters that are obtained from optimization. Models for all other phases were taken from their constituent binary systems.

Optimization was carried out using the Parrot module in Thermo-Calc, which was developed by [1991Din]. First, a set of rough values for the ternary interactive parameters of the liquid were obtained by fitting the thermodynamic data of the liquid. Then phase diagram information was taken into consideration to obtain a better thermodynamic description. The final optimization was performed by considering all information available from the literature at the same time.

Table 1 Thermodynamic parameters assessed in the present work and accepted from the selected literature for the binary systems (J/mol of formula units)

Phase	Model	Parameters	Reference
Liquid	(Al, Cu, Si)	${}^{0}L^{Liquid}_{Al,Si} = -11{,}340.1 - 1.23394 \times T$	[1998Gro]
		${}^{1}L^{Liquid}_{Al,Si} = -3530.93 + 1.35993 \times T$	
		${}^{2}L^{Liquid}_{Al,Si} = +2265.39$	
		${}^{0}L^{Liquid}_{Al,Cu} = -66{,}622 + 8.1 \times T$	[1998Sau]
		${}^{1}L^{Liquid}_{Al,Cu} = +46{,}800 - 90.8 \times T + 10 \times T \times \ln(T)$	
		${}^{2}L^{Liquid}_{Al,Cu} = -2812$	
		${}^{0}L^{Liquid}_{Cu,Si} = -38{,}763.5 + 12 \times T$	[2000Yan]
		${}^{1}L^{Liquid}_{Cu,Si} = -52{,}431.2 + 27.4571 \times T$	
		${}^{2}L^{Liquid}_{Cu,Si} = -29{,}426.5 + 14.775 \times T$	
		${}^{0}L^{Liquid}_{Al,Cu,Si} = +78{,}020.2765 - 69.9963082 \times T$	[This work]
		${}^{1}L^{Liquid}_{Al,Cu,Si} = +141{,}474.671 - 73.3794012 \times T$	
		${}^{2}L^{Liquid}_{Al,Cu,Si} = -29{,}828.7935 + 11.6733603 \times T$	
Fcc	(Al, Cu, Si)	${}^{0}L^{Fcc}_{Al,Si} = -3143.78 + 0.39297 \times T$	[1998Gro]
		${}^{0}L^{Fcc}_{Al,Cu} = -53{,}520 + 2 \times T$	[1998Sau]
		${}^{1}L^{Fcc}_{Al,Cu} = -38{,}590 - 2 \times T$	
		${}^{2}L^{Fcc}_{Al,Cu} = +1170$	
		${}^{0}L^{Fcc}_{Cu,Si} = -42{,}203.5 + 13.89137 \times T$	[2000Yan]
		${}^{1}L^{Fcc}_{Cu,Si} = -1102.2 - 18.177912 \times T$	
Hcp(κ)	(Al, Cu, Si)	${}^{0}L^{Hcp}_{Al,Si} = -3143.78 + 0.39297 \times T$	[1998Gro]
		${}^{0}L^{Hcp}_{Al,Cu} = +38{,}107$	[1998Sau]
		${}^{0}L^{Hcp}_{Cu,Si} = -26{,}798.8 - 0.731518 \times T$	[2000Yan]
		${}^{1}L^{Hcp}_{Cu,Si} = -28{,}064.75 - 0.028889 \times T$	
Bcc	(Al, Cu, Si)	${}^{0}L^{Bcc}_{Al,Cu} = -73{,}554 + 4 \times T$	[1998Sau]
		${}^{1}L^{Bcc}_{Al,Cu} = +51{,}500 - 11.84 \times T$	
		${}^{0}L^{Bcc}_{Cu,Si} = -26{,}447.3 + 10.21623 \times T$	[2000Yan]
		${}^{1}L^{Bcc}_{Cu,Si} = -47{,}275.11 - 8.517323 \times T$	
Diamond	(Al, Si)	${}^{0}L^{Diamond}_{Al,Si} = +113{,}246.16 - 47.55509 \times T$	[1998Gro]

(continued)

Table 1 Thermodynamic parameters assessed in the present work and accepted from the selected literature for the binary systems (J/mol of formula units) (continued)

Phase	Model	Parameters	Reference
AlCu_θ	$(Al)_2(Al, Cu)_1$	${}^0G^{AlCu\_\theta}_{Al:Al} = +3 \times {}^0G^{Bcc\_A2}_{Al}$ ${}^0G^{AlCu\_\theta}_{Al:Cu} = -47{,}406 + 6.75 \times T + 2 \times {}^0G^{Fcc\_A1}_{Al} + {}^0G^{Fcc\_A1}_{Cu}$ ${}^0L^{AlCu\_\theta}_{Al:Al,Cu} = +2211$	[1998Sau]
AlCu_η	$(Al, Cu)_1(Cu)_1$	${}^0G^{AlCu\_\eta}_{Al:Cu} = -40{,}560 + 3.14 \times T + {}^0G^{Fcc\_A1}_{Al} + {}^0G^{Fcc\_A1}_{Cu}$ ${}^0G^{AlCu\_\eta}_{Cu:Cu} = +2 \times {}^0G^{Bcc\_A2}_{Cu}$ ${}^0L^{AlCu\_\eta}_{Al,Cu:Cu} = -25{,}740 - 20 \times T$	[1998Sau]
AlCu_ζ	$(Al)_9(Cu)_{11}$	${}^0G^{AlCu\_\zeta}_{Al:Cu} = -420{,}000 + 18 \times T + 9 \times {}^0G^{Fcc\_A1}_{Al} + 11 \times {}^0G^{Fcc\_A1}_{Cu}$	[1998Sau]
AlCu_δ	$(Al)_2(Cu)_3$	${}^0G^{AlCu\_\delta}_{Al:Cu} = -106{,}700 + 3 \times T + 2 \times {}^0G^{Fcc\_A1}_{Al} 3 \times {}^0G^{Fcc\_A1}_{Cu}$	[1998Sau]
AlCu_ϵ	$(Al, Cu)_1(Cu)_1$	${}^0G^{AlCu\_\epsilon}_{Al:Cu} = -36{,}976 + 1.2 \times T + {}^0G^{Fcc\_A1}_{Al} + {}^0G^{Fcc\_A1}_{Cu}$ ${}^0G^{AlCu\_\epsilon}_{Cu:Cu} = 2 \times {}^0G^{Bcc\_A2}_{Cu}$ ${}^0G^{AlCu\_\epsilon}_{Al,Cu:Cu} = +7600 - 24 \times T$ ${}^1G^{AlCu\_\epsilon}_{Al,Cu:Cu} = -72{,}000$	[1998Sau]
γ_D83	$(Al)_4(Al, Cu)_1(Cu)_8$	${}^0G^{\gamma\_D83}_{Al:Al:Cu} = -300{,}716 + 390 \times T - 52 \times T \times \mathrm{Ln}(T) + 5 \times {}^0G^{Fcc\_A1}_{Al} + 8 \times {}^0G^{Fcc\_A1}_{Cu}$ ${}^0G^{\gamma\_D83}_{Al:Cu:Cu} = -280{,}501 + 37{,}906 \times T - 52 \times T \times \mathrm{Ln}(T) + 4 \times {}^0G^{Fcc\_A1}_{Al} + 9 \times {}^0G^{Fcc\_A1}_{Cu}$	[1998Sau]
γ_H	$(Al)_4(Al, Cu)_1(Cu)_8$	${}^0G^{\gamma\_H}_{Al:Al:Cu} = -219{,}258 - 45.5 \times T + 5 \times {}^0G^{Fcc\_A1}_{Al} + 8 \times {}^0G^{Fcc\_A1}_{Cu}$ ${}^0G^{\gamma\_H}_{Al:Cu:Cu} = -200{,}460 - 58.5 \times T + 4 \times {}^0G^{Fcc\_A1}_{Al} + 9 \times {}^0G^{Fcc\_A1}_{Cu}$	[1998Sau]
$Cu_{56}Si_{11}$_γ	$(Cu)_{56}(Si)_{11}$	${}^0G^{Cu56Si11\_\gamma}_{Cu:Si} = 70{,}114.649 - 393.60377 \times T + 56 \times {}^0G^{Fcc\_A1}_{Cu} + 11 \times {}^0G^{Diamond\_A4}_{Si}$	[2000Yan]
$Cu_{33}Si_7$_δ	$(Cu)_{33}(Si)_7$	${}^0G^{Cu33Si7\_\delta}_{Cu:Si} = 78{,}895.28 - 278.65573 \times T + 33 \times {}^0G^{Fcc\_A1}_{Cu} + 7 \times {}^0G^{Diamond\_A4}_{Si}$	[2000Yan]
$Cu_{15}Si_4$_ϵ	$(Cu)_{15}(Si)_4$	${}^0G^{Cu15Si4\_\epsilon}_{Cu:Si} = 23{,}578.314 - 127.66321 \times T + 15 \times {}^0G^{Fcc\_A1}_{Cu} + 4 \times {}^0G^{Diamond\_A4}_{Si}$	[2000Yan]
$Cu_{19}Si_6$_η	$(Cu)_{19}(Si)_6$	${}^0G^{Cu19Si6\_\eta}_{Cu:Si} = 34{,}191.555 - 179.94057 \times T + 19 \times {}^0G^{Fcc\_A1}_{Cu} + 6 \times {}^0G^{Diamond\_A4}_{Si}$	[2000Yan]

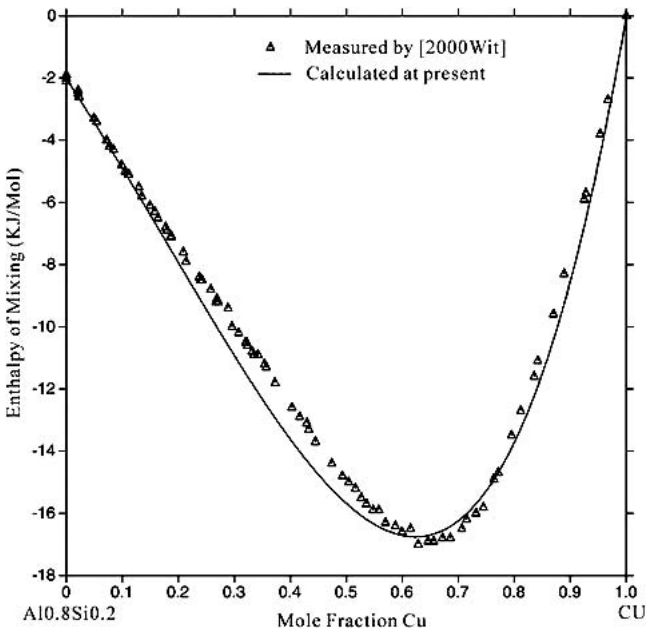

Fig. 5 Calculated enthalpy of mixing of liquid at 1302 °C (1575 K) along with the section Cu-80at.%Al-20at.%Si compared with the experimental data

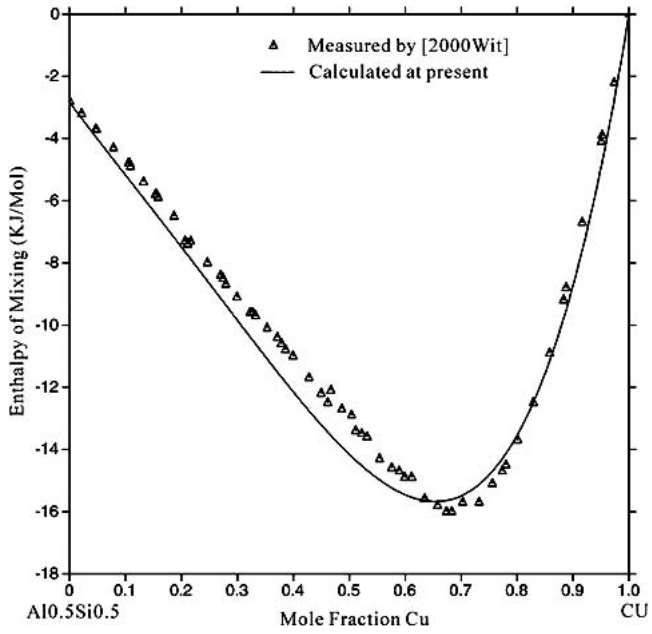

Fig. 6 Calculated enthalpy of mixing of liquid at 1302 °C (1575 K) along with the section Cu-50at.%Al-50at.%Si compared with the experimental data

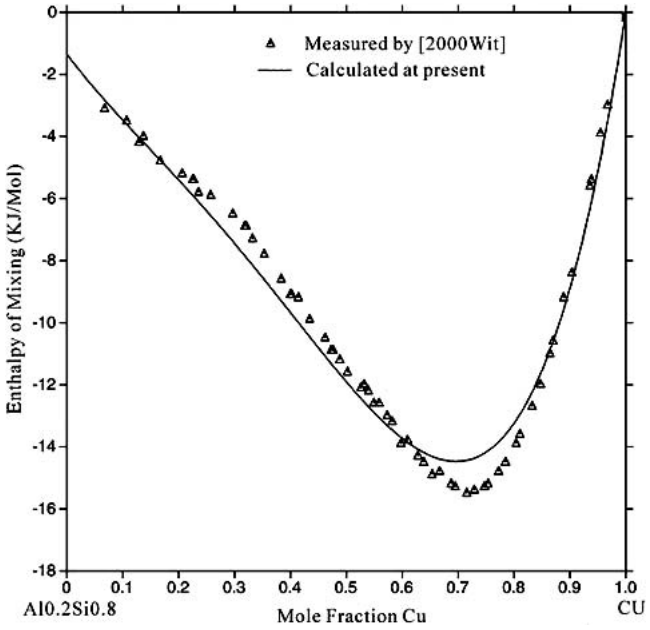

Fig. 7 Calculated enthalpy of mixing of liquid at 1302 °C (1575 K) along with the section Cu-20at.%Al-80at.%Si compared with the experimental data

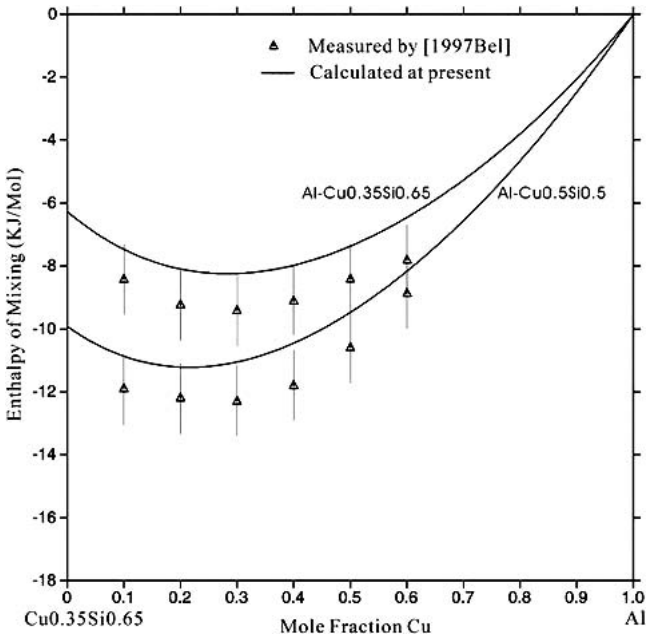

Fig. 8 Calculated enthalpy of mixing of liquid at 1472 °C (1745 K) along with the section Al-35at.%Cu-65at.%Si and Al-50at.%Cu-0.5wt.%Si compared with the experimental data, respectively

4. Results and Discussion

The ternary interactive parameters for the liquid phase that were assessed in this work are summarized in Table 1, together with the accepted binary parameters of the Al-Cu, Al-Si, and Cu-Si systems. Figures 5 to 7 compare calculated mixing enthalpies of the liquid Al-Cu-Si with experimental values measured by [2000Wit] at 1302 °C (1575 K), along with the three sections *Cu-80at.%Al-20at.%Si, Cu-50at.%Al-50at.%Si, and Cu-20at.%Al-80at.%Si, respectively. Considering the experimental uncertainty in measuring thermodynamic properties, the present results are

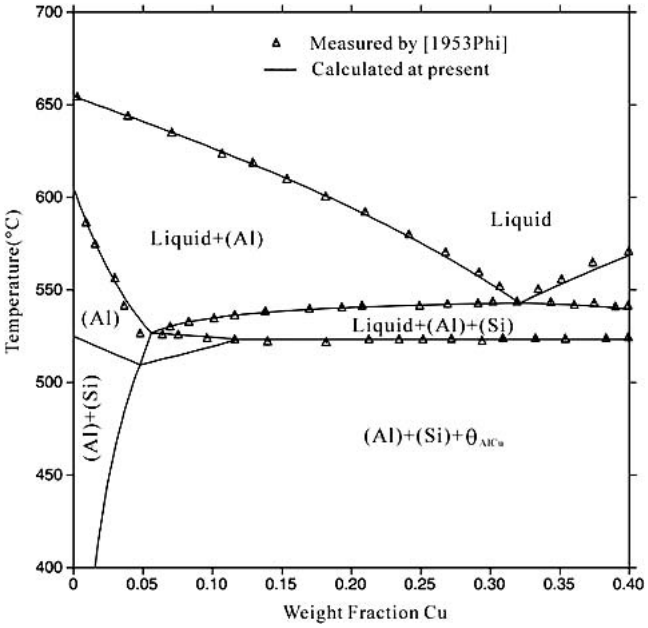

Fig. 9 Calculated isopleth of the Al-Cu-Si system at 1 wt.% Si compared with experimental data from [1953Phi]

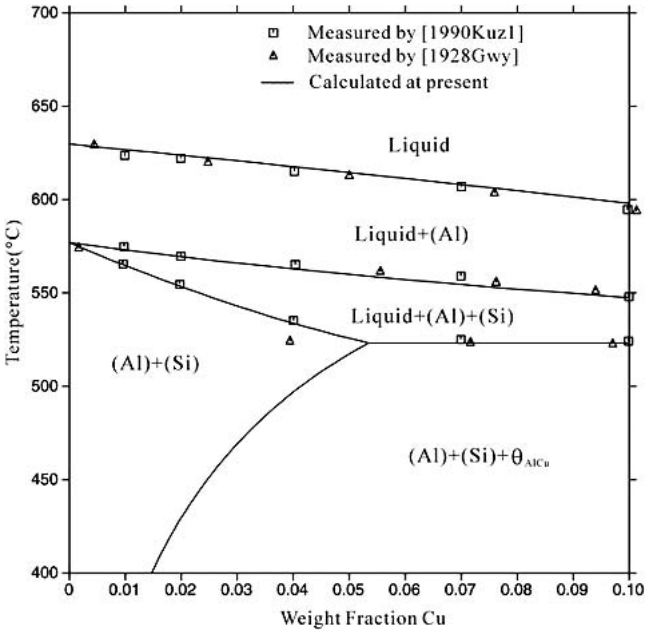

Fig. 10 Calculated isopleth of the Al-Cu-Si system at 5 wt.% Si compared with experimental data from [1990Kuz1] and [1928Gwy]

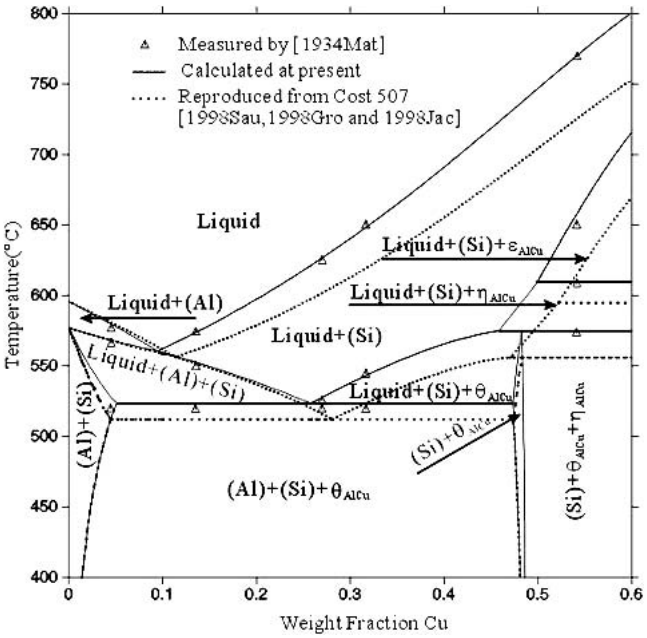

Fig. 11 Calculated isopleth of the Al-Cu-Si system at 10 wt.% Si compared with experimental data from [1934Mat]

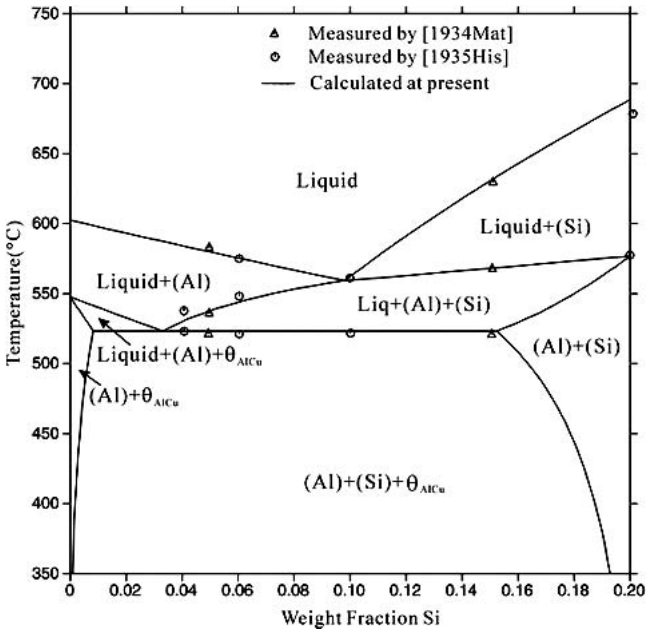

Fig. 13 Calculated isopleth of the Al-Cu-Si system at 80 wt.% Al compared with experimental data from [1935His] and [1934Mat]

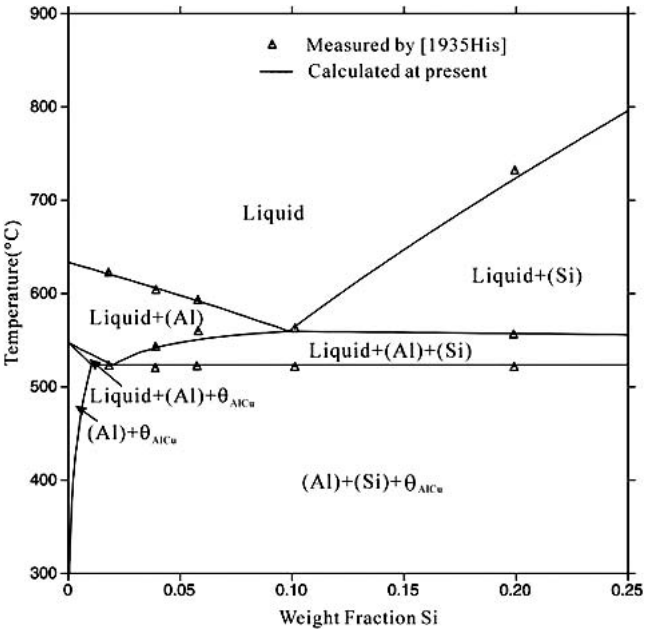

Fig. 12 Calculated isopleth of the Al-Cu-Si system at 10 wt.% Cu compared with experimental data from [1935His]

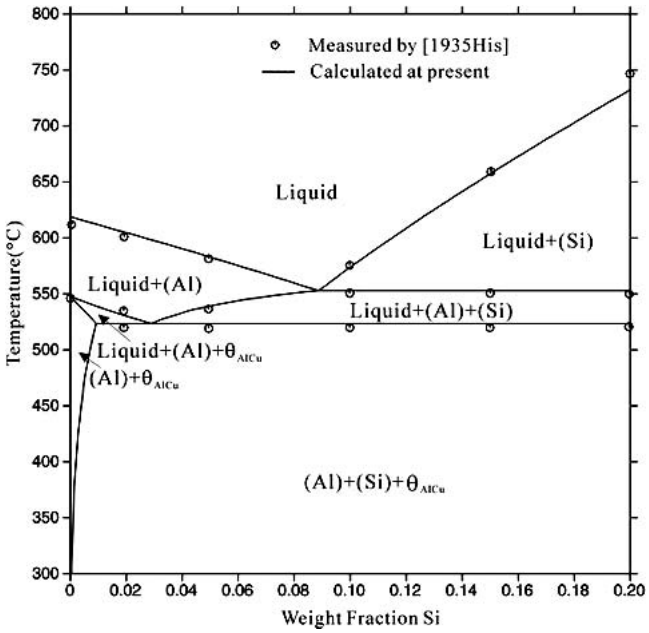

Fig. 14 Calculated isopleth of the Al-Cu-Si system at Si-85wt.%Al-15wt.% Cu compared with experimental data from [1934Mat]

acceptable. The calculated mixing enthalpies of the liquid Al-Cu-Si at 1472 °C (1745 K), along with the two sections Al-35at.%Cu-65at.%Si and Al-50at.%Cu-50at.%Si, appear to deviate from the data of [1997Bel] but are still within the claimed experimental uncertainty, as shown in Fig. 8. Efforts to improve the fit yielded worse agreement with the phase diagram.

Figures 9 to 11 show the agreement between the calculated vertical sections and the experimental data obtained in the Al-rich corner of the system with an Si content of 1, 5, and 10 wt.%, respectively. It should be mentioned that the Cost 507 database for the Al-Cu-Si ternary system obtained from the three corresponding binary subsystems [1998Gro, 1998Jac, 1998Sau] can reproduce the experimental results to some extent. But it is noticeable in Fig. 11 that the current

database improves the fit of the calculated phase boundaries compared to the experimental phase boundaries by 5 to 50 °C.

Figures 12 and 13 show similar agreement in isopleths with a constant Cu content of 10 wt.% and a constant Al content of 80 wt.%, respectively. Another calculated isopleth for the Si-85wt.%Al-15wt.%Cu section is compared with the experimental data of [1934Mat] and [1935His] in Fig. 14. It again shows that the present thermodynamic description agrees with the experimental results.

Figure 15 gives the liquidus projection in the Al-rich corner, while the calculated and experimental values for invariant reactions in the Al-rich corner are presented in Table 2. During the assessment, much importance was attached to invariant data. As we can see, the current database improved the fit of the calculated quantities to the experimental results, especially for the invariant reaction temperature. The calculated results for invariant reactions from the current database agree within several degrees and atomic percent of the experimental data.

5. Prediction of the Solidification Behavior and Experimental Verification

To verify the accuracy of the present thermodynamic database for the Al-Cu-Si ternary system, samples with the composition Al-7wt.%Si-3.5wt.%Cu (similar to Al alloy 319) were made from 99.9 wt.% pure Al, 99.9 wt.% electrolytic Cu, and a Al-26.6wt.%Si master alloy. The master alloy was prepared by induction melting with 99.6 wt.% Si nuggets. Solidification of the alloy was followed by thermal analysis and a subsequent metallographic examination. Thermal analysis was conducted on small ingots contained in stainless steel crucibles that were furnace-cooled. The temperature of the alloy was recorded by a data-acquisition system that was attached to a computer.

Figure 16 gives predictions of the solid fraction vs the temperature by assuming an equilibrium state and by using the Scheil model, which assumes infinite diffusion in the

Table 2 Three invariant liquidus reactions in the Al-rich corner of the Al-Cu-Si system

		Experimental data			
Reactions	**Type**	**T, °C**	**Cu, at.%**	**Si, at.%**	**References**
$L \leftrightarrow \theta_{AlCu} + (Al) + (Si)$	E1	524	13.4	6.0	[1992Luk]; this work reproduced from Cost507 [1998Sau, 1998Gro, 1998Jac]
		523.5	13.6	6.0	
		512.22	14.9	7.28	
$L + \eta_{AlCu} \leftrightarrow \theta_{AlCu} + (Si)$	U1	573	25.1	6.7	[1992Luk]; this work reproduced from Cost507 [1998Sau, 1998Gro, 1998Jac]
		574.7	29.0	5.2	
		556.13	29.3	7.68	
$L + \epsilon_{AlCu} \leftrightarrow \eta_{AlCu} + (Si)$	U2	608	31.7	8.2	[1992Luk]; this work reproduced from Cost507 [1998Sau, 1998Gro, 1998Jac]
		609	32.6	6.1	
		594.83	33.7	8.76	

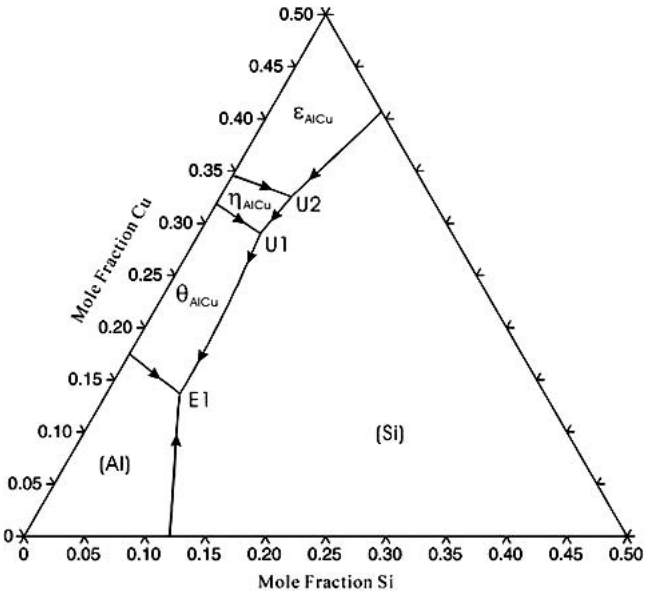

Fig. 15 Calculated liquid projection in the Al-rich corner of the Al-Cu-Si system

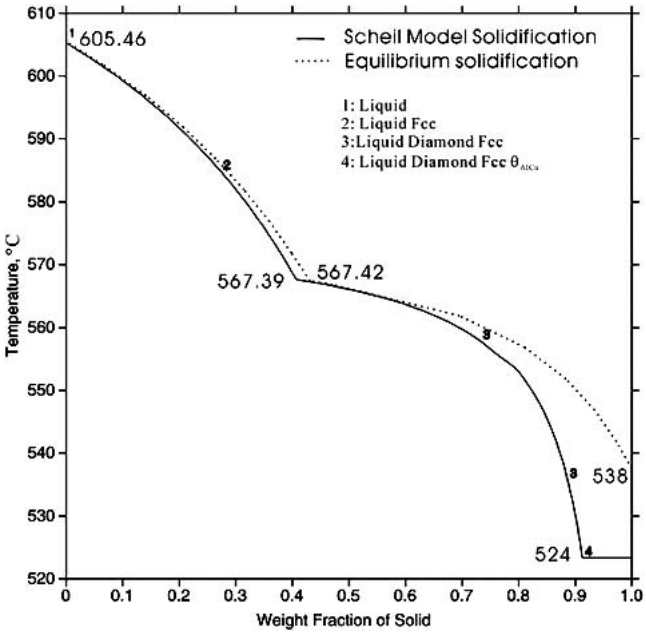

Fig. 16 Solidification path of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy

liquid and no diffusion in the solid. Figure 17 presents the composition path of the liquid according to the Scheil model. As can be seen from Fig. 16 and 17, there are only three phases existing in the as-cast microstructure. The fcc(Al) primary dendrites form below 605 °C, dramatically reducing the Al content in the liquid, while the Cu content remains almost constant (Fig. 17). Below 567 °C, the solidification proceeds by the formation of the binary eutectic containing fcc(Al) plus diamond(Si), which leads to a steady increase in the Cu content of the remaining interdendritic liquid. Under equilibrium conditions, the alloy solidifies completely at 538 °C. However, for the Scheil model, which includes segregation, the alloy undergoes the liquid → (Al) + (Si) + θ_{AlCu} ternary eutectic reaction at 524 °C.

Table 3 compares the predicted phase transformation temperature with the experimental data. It can be seen that the Scheil model predictions in Table 3 are within ~1 °C of the measured values. Figures 18 to 20 show the microstructures of the alloy quenched at different temperatures. They consist of liquid and fcc(Al) at 573 °C (Fig. 18), liquid + fcc(Al) + diamond(Si) at 525 °C (Fig. 19), and fcc(Al) + diamond(Si) + θ_{AlCu} at room temperature (Fig. 20). All agree with the Scheil predictions.

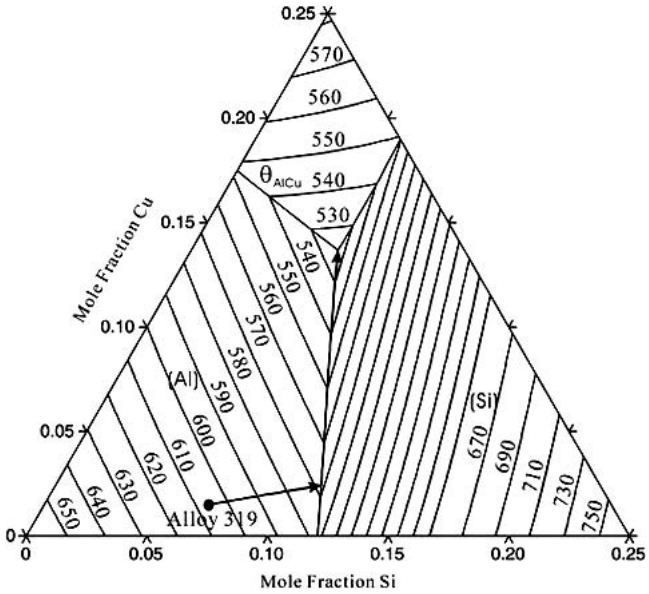

Fig. 17 Schematic that shows the liquid composition path of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy during solidification

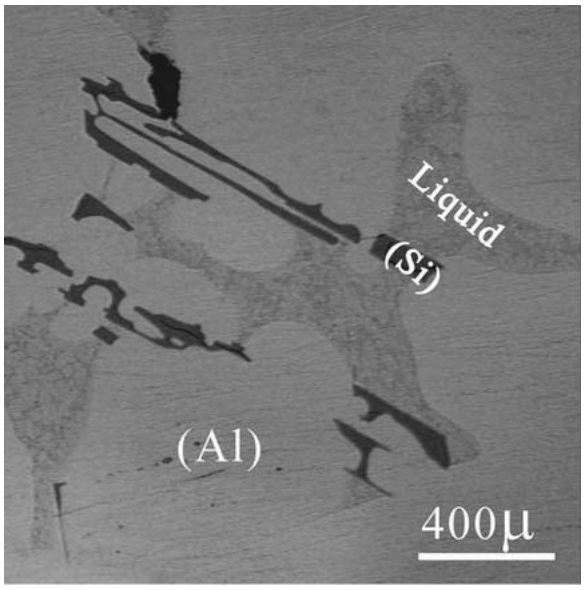

Fig. 19 Microstructure of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy quenched at 525 °C

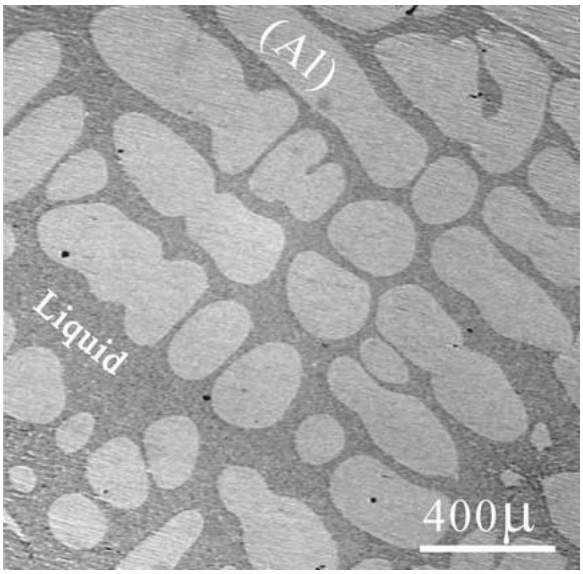

Fig. 18 Microstructure of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy quenched at 573 °C

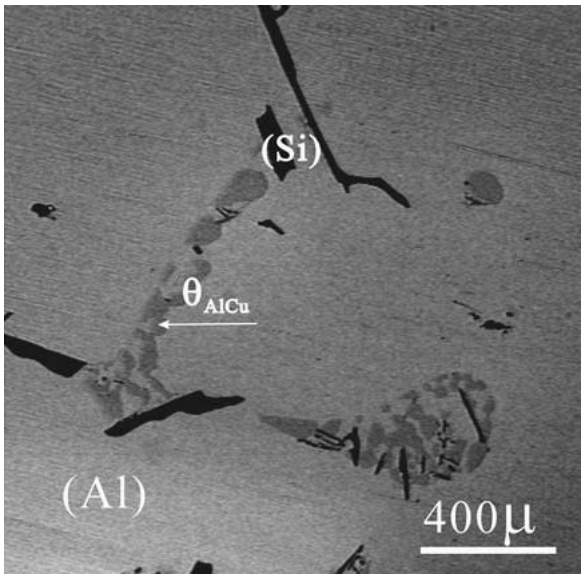

Fig. 20 Microstructure of an Al-3.5wt.%Cu-7wt.%Si, 319-type alloy quenched at 513 °C

Table 3 Critical temperatures for a Al-3.5Cu-7Si 319-Type alloy during solidification

Model	Liquid → (Al)	Liquid → (Al) + (Si)	(Al) + (Si)	Inveriant reaction: liquid → (Al) + (Si) + θ_{AlCu}	(Al) + (Si) + θ_{AlCu}
Equilibrium calculation from current database	605.46 °C	567.42 °C	537.56-486.27 °C	…	486.27 °C and below
Experimental result [2003Lin]	607 °C	568.7 °C	…	521 °C	…
Scheil model calculation from current database	605.46 °C	567.39 °C	…	523.89 °C	…

6. Conclusions

A thermodynamic database for the liquid phase in the Al-rich corner of the Al-Cu-Si ternary system was developed in this work using the CALPHAD method. The predictions of the database were compared with thermochemical quantities and experimental data. These are in excellent agreement in most cases. The present description can be used to predict the solidification behavior of Al-3.5wt.%Cu-7wt.%Si, 319-type alloys, and thus can be used as the basic information for designing and optimizing Al-Cu-Si alloys.

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