JJMIE

Volume 8 Number 6, December 2014
ISSN 1995-6665
Pages 359 - 367

Jordan Journal of Mechanical and Industrial Engineering

On Phase Equilibria of Sn-Sr and Mn-Sn-Sr Systems

Mohammad Aljarrah[a *], Atef Alkhazali[a], Suleiman Obeidat[a], Ahmad Almagableh[b], and Mahmoud Rababah[b]

[a]*The Hashemite University, Industrial Engineering Department, Zarqa 13115, Jordan*

[b]*Mechanical Engineering Department, Faculty of Engineering, The Hashemite University, Zarqa 13115, Jordan*

Received 16 Jul 2014 *Accepted 21 Oct 2014*

Abstract

Sn-Sr system is critically evaluated and the most reliable experimental data are incorporated in thermodynamic modeling. Thermodynamic properties of the binary liquid solution are estimated using the modified quasichemical model (MQM). The optimized Sn-Sr phase diagram and the corresponding thermodynamic properties are found to be in fair agreement with the experimental data in the previous related literature. For all the compounds in Sn-Sr system, a comparison between the calculated enthalpy of formation and that calculated by Miedema and first-principles has been reported. Combining Sn-Sr with the self-established thermodynamic database of Mn-Sr and Mn-Sn was used to calculate liquidus projection of Mn-Sn-Sr ternary system.

Keywords: *Modified Quasichemical Model, Magnesium Alloys, Thermodynamic Modeling*.

1. Introduction

Magnesium alloys have a great potential for structural applications because of their significant weight savings, superior damping capacity and good castability [1]. Therefore, the automotive industry leads the way in the growing interest in Mg alloys in order to decrease fuel consumption and reduce emissions [1-3]. Recently, research activities have been carried out to improve the elevated temperature properties of the magnesium alloys through precipitation hardening and/or solid solution hardening [4-8]. The most common magnesium alloys for automotive industry contain aluminum as a major alloying element (AZ91 and AM60). Aluminum improves the mechanical properties at room temperature; however the loss of the mechanical strength at service temperature (above 120°C) of Mg alloys is reported due to the discontinuous precipitation of γ-$Mg_{17}Al_{12}$ [9-15]. Alloying Mg with Ca, Zn, Sr, Mn and Sn are found to improve the elevated temperature properties of Al containing Mg alloys by delaying or inhibiting the formation of γ and/or precipitating of thermally stable compounds such as Al_2Ca or Al_4Sr intermetallic phase [9-19]. Strontium is an important element in multi-component magnesium and aluminum alloys. Alloying magnesium with strontium refines the microstructure and improves the mechanical properties. Moreover, Sr enhances the corrosion resistance of Mg and Al-based alloys [20-23]. On the other hand, tin addition to magnesium based alloys has a potential to improve creep and corrosion resistance of these alloys. Tin is also a reasonably cheap element as compared to RE elements and has a low melting point and is known to improve castability [24-26]. Mn addition to Mg-Sr alloys enhances creep resistance by precipitation of α-Mn at the interdendritic regions and Mn dissolves in the Mg matrix and $Mg_{17}Sr_2$ phase [27, 28].

An understanding of thermodynamic characteristics and equilibrium phase diagram for magnesium and its alloys will allow a better control in developing and designing a new Mg-alloy with desired properties. The present study deals with thermodynamic modeling of the Mn–Sn-Sr system which is one of the important systems in Mg-Mn multi-component systems. Sn-Sr binary system will be critically evaluated and optimized using the available phase equilibrium and thermodynamic data. The latest published journal article on thermodynamic modeling of the Sn-Sr system used Bragg-Williams model [29]. In their work [29], the enthalpies of formation for the stoichiometric compounds at 0 K were computed by first-principles calculations. In the present study, this system will be optimized using the modified quasi-chemical model (MQM). The MQM is considered more physically sound than other models such as the associate solution model [30]. Sn-Sr and Mn-Sr binary systems have been optimized using most up-to-date experimental data. Each of the phases in any binary system has been critically assessed based on the thermodynamic properties.

* Corresponding author. e-mail: maljarrah@hu.edu.jo.

In this research article, the experimental phase diagram and thermodynamic properties of Sn-Sr binary system will be critically evaluated and the most reliable data will be used in optimization. Sn-Sr phase diagram will be optimized and combined with the self-established thermodynamic database of the Mn-Sn and Mn-Sr systems. The optimized parameters of the constituent binary sub-systems will be used to draw liquidus projections of the Mn-Sn-Sr ternary phase diagram.

2. Experimental data

2.1. Sn-Sr phase diagram

Ray [31] tracks the thermal history of twelve tin-strontium alloys within the composition range of 0-29.65 at.% Sr using thermal analysis and optical microscopy. In Ray's study, alloys were prepared by electrolysis of a mixture of sodium and strontium chlorides over molten tin in an iron crucible. During electrolysis, strontium reacted with iron crucible and the fused salts were rapidly volatilized. Therefore, Ray's [31] thermal data were in error and will not be used in the current optimization. Phase equilibria of thirteen tin-strontium alloys were investigated by Marshall and Chang [32] using DTA, XRD and optical microscopy from pure tin up to 65 at.% Sn. They reported that Sn_3Sr forms peritectically at 598 ± 1^0C which is in contrast with the work of Ray who showed that Sn_3Sr melted congruently at 607^0C and forming a eutectic at 26.5 at% Sr and 580^0C. Marshall and Chang also reported that Sn_4Sr is in equilibrium with Sn instead of Sn_5Sr as reported by Ray [31] and Sn_4Sr decomposes peritectically at 334 ± 4^0C. They [32] found that Sn_4Sr and Sn form an eutectic at 230 ± 2^0C and 1 at.% Sr. Widra and Schafer [33] studied Sn-Sr phase diagram in the composition range of 35-100 at.% Sr using DTA and XRD. Five intermetallic compounds, which are Sr_2Sn, Sr_5Sn_3, SrSn, $SrSn_3$ and $SrSn_5$, were reported in their phase diagram, of which only the first four phases were melted congruently. The assessment proposed by Massalski *et al.* [34] is the summary of the work of Marshall and Chang [32], and Widra and Schafer [33]. In the composition range of 11.6 to 43 at.% Sr, Hoffmann *et al*. [35,36] tracked phase transformation temperatures during cooling and heating for seven Sn-Sr alloys using DTA. Phase stability of Sr_3Sn_5 intermetallic compound were shown from the works of Hoffmann *et al*. [35,36] and Zürcher *et al*. [37]. The phase equilibria over the whole composition range in the Sn-Sr system were investigated by Palenzona and Pani [38] using XRD, DTA and optical composition. According to their work, five intermetallic compounds were confirmed namely; Sr_2Sn, SrSn, Sr_5Sn_3, $SrSn_3$ and $SrSn_4$, where, Sr_2Sn and SrSn melt congruently. In their work, three eutectic reactions were detected in the Sr-Sn system and $SrSn_4$ was confirmed instead of $SrSn_5$ as reported by Ray [31] and Widra and Schafer [33]. Experimental phase diagram data of Palenzona and Pani [38] and Hoffmann and Fassler [37] were in agreement. Those experimental data were the most recent and in good agreement; therefore, they will be used in the current optimization. Crystal structures of the compounds in the Sn-Sr system were reported by [35-37, 39-45].

Limited thermodynamic data for the Sn–Sr system could be found in previous literature. Strontium is highly reactive and, hence, it is very difficult to handle the alloys during high temperature experiments. However, enthalpy of mixing of the Sn-Sr liquid was measured by Esin *et al*. [46] using high temperature calorimeter at 1773 K within the composition range from 0 – 50 at.% Sr. Enthalpy of mixing from Esin *et al*. [46] will be used in the current optimization. Morozova *et al*. [47] estimated the enthalpy of formation of $SrSn_2$ compound to be -82.7±1 kJ/mole.atom at 25^0C. Zhao *et al*. [29] calculated the enthalpy of formation for all compounds in the Sn-Sr system using first-principles method and Miedema model and these data will be used only for comparison. Activity of Sr in Sn-Sr system was measured by Klebanov *et al.* [48] at 900 K.

2.2. Mn-Sr System

Based on the experimental data of Obinata *et al.* [49], Peng *et al*. [50] modeled all phases in the Mn-Sr binary system as completely disordered solutions. In order to construct a self-consistent thermodynamic database of the Mn-Sn-Sr ternary system, the optimized parameters of Mn-Sr binary system by Aljarrah *et al*. [56] will be adopted in the current calculations.

2.3. Mn-Sn-Sr Ternary System

There is no experimental data for Mn-Sn-Sr system could be found in the literature.

3. Thermodynamic Modeling

3.1. Pure Elements

The Gibbs free energy of a pure element with a certain structure φ is described as a function of temperature as:

$$^{\circ}G_A^{\varphi}(T) = a + bT + cT\ln T + dT^2 + eT^3 + fT^{-1} + gT^7 + hT^{-9}$$

The parameters *a* through *h* are taken from the SGTE compilation by Dinsdale [51].

3.2. Stoichiometric Compounds

The intermetallic compounds in the Sn-Sr phase diagram are considered stoichiometric and the Gibbs free energy of these compounds is described by the following equation:

$$G^{phase,\,\varphi} = x_i\,{}^{\circ}G_i^{\varphi} + x_j\,{}^{\circ}G_j^{\varphi} + \Delta G_f$$

Where $^{\circ}G_i^{\varphi}$ and $^{\circ}G_j^{\varphi}$ denote Gibbs free energy of element *i* and *j* in their standard state and $\Delta G_f = a + bT$ is the Gibbs energy of formation of the stoichiometric compound. Where a and b are the model parameters to be optimized based on experimental data of phase equilibria and thermodynamic properties.

3.3. Liquid Phase

In the present work, the liquid phase is modeled using the MQM where the pair approximation is utilized to describe the short range ordering in the liquid. A detailed description of the MQM for binary and multi-components solutions is available elsewhere [52-54]. Only a brief description will be presented here. The molar Gibbs energy of the liquid phase, derived from the modified quasichemical theory [52], is described by the following equation:

$$G^{liq} = n_i {}^{\circ}G_i^{liq} + n_j {}^{\circ}G_j^{liq} - T\Delta\Delta^{config} + \frac{n_{ij}}{2}\Delta^{exs}G^{liq}$$

Where n_i and n_j are the number of moles of the component i and j, n_{ij} is the number of (i-j) pairs, ΔS^{config} is the configurational entropy of mixing given for randomly distributing the (i-i), (j-j), and (i-j) pairs.

$$\Delta S^{config} = -R[n_i \ln(x_i) + n_j \ln(x_j)] - R[n_{ii} \ln(\frac{x_{ii}}{y_i^2}) + n_{jj} \ln(\frac{x_{jj}}{y_j^2}) + n_{ij} \ln(\frac{x_{ij}}{2y_i y_j})]$$

Where x_i and x_j are the overall mole fractions of the components i and j, respectively.

4. Results and Discussions

4.1. Sn-Sr Phase Diagram

Figure 1 shows the calculated Sn-Sr phase diagram in relation with the experimental data from the previous literature. A good agreement with the liquidus line between the calculated values in this work and the experimental values of Palenzona and Pani [38], Marshall and Chang [32], and Hoffman [35] is found in Figure 1. The calculated invariant points of Sn-Sr phase diagram in comparison with the experimental data are listed in Table 1. The activity of Sr in Sn-Sr liquid reported by Klebanov *et al*. [48] was used in the optimization of the Sn-Sr system. Comparison between the calculated activity of Sr from Klebanov *et al*. [48] is shown in Figure 2. The calculated activity shows a good agreement with the experimental data. The optimized model parameters of the stable phases in the Sn-Sr binary system are summerized in Table 2.

The data of enthalpy of mixing by Esin *et al*. [46] was used in the optimization and matched the calculated enthalpy of mixing curve seen in Figure 3. As can be seen from this figure, the calculated enthalpy of mixing of liquid Sn-Sr is in fair agreement with the experimental data. The lowest point of the curve is located where thermally high stable compounds are formed. This indicates stronger atomic interactions in the liquid at the composition of the intermetallic compounds.

Figure 4 shows a comparison between the calculated enthalpy of formation for all phases in Sn-Sr system and that reported by Zhao *et al*. [29]. The current enthalpies of formation for intermetallic compounds are in fair agreement with that obtained by Miedema model.

4.2. Mn-Sn-Sr Ternary System

The Gibbs energy of the liquid phase was calculated using the symmetric Kohler-like approximation [55] with no ternary interaction parameters for the liquid phase. The invariant reactions for the Mn-Sn-Sr system are listed in Table 3. The liquidus projection of the Mn-Sn-Sr ternary system is shown in Figure 5. The miscibility gap covers most of the composition triangle, as shown in Figure 5. Since there is no ternary experimental data available for the entire Mn-Sn-Sr system, it is possible that the size of the miscibility gap is over or underestimated by the extrapolation.

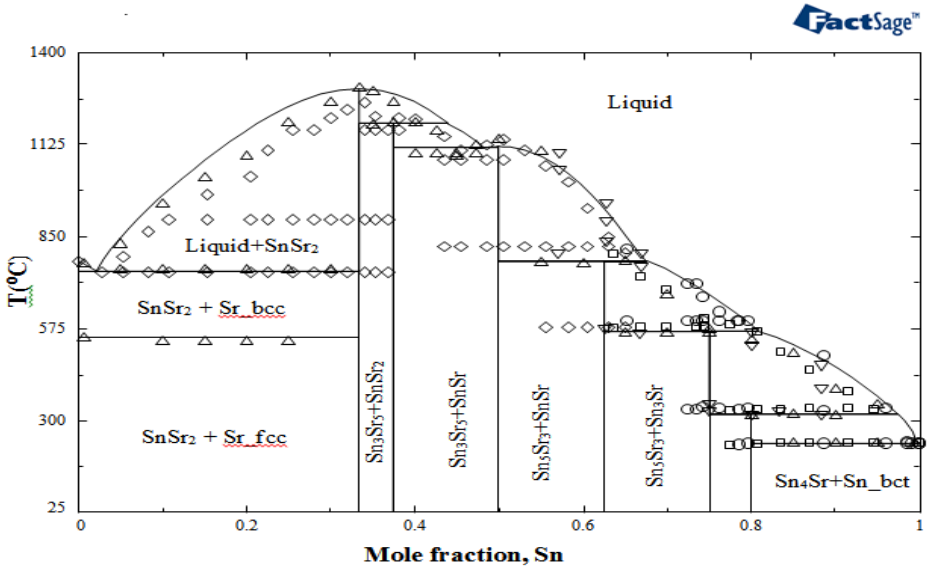

Figure 1. Re-optimized Sn-Sr phase diagram in comparison with experimental data from literature: Palenzona and Pani △ , Marshall and Chang ○ , Ray □ , Widra and Schafer ◇ and Hoffman ▽

  - Volume 8, Number 6 (ISSN 1995-6665)

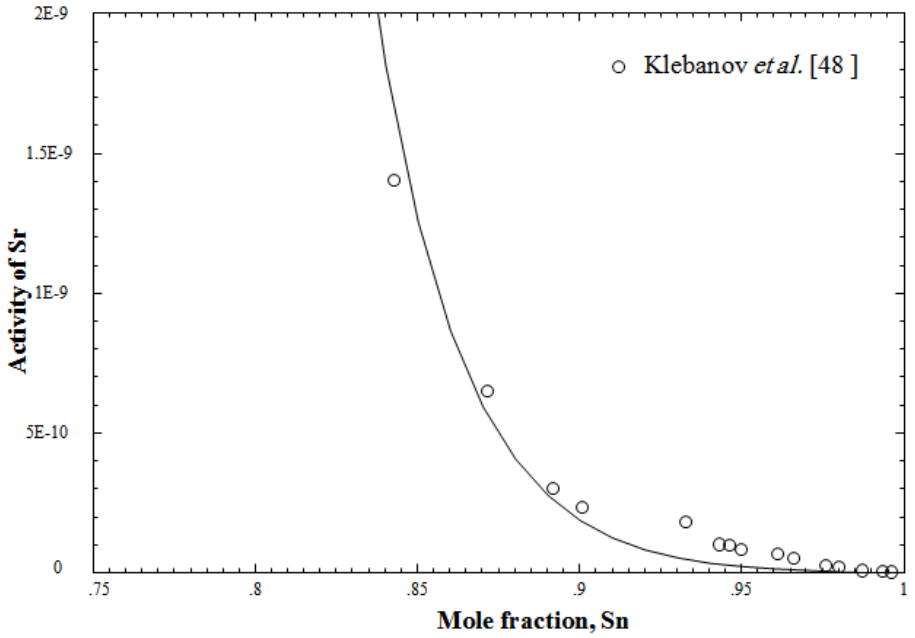

Figure 2. Plot of calculated activity of Sr against mole fraction Sn for the Sn-Sr liquid at 900 K in comparison with experimental data of Klebanov et al. [48]

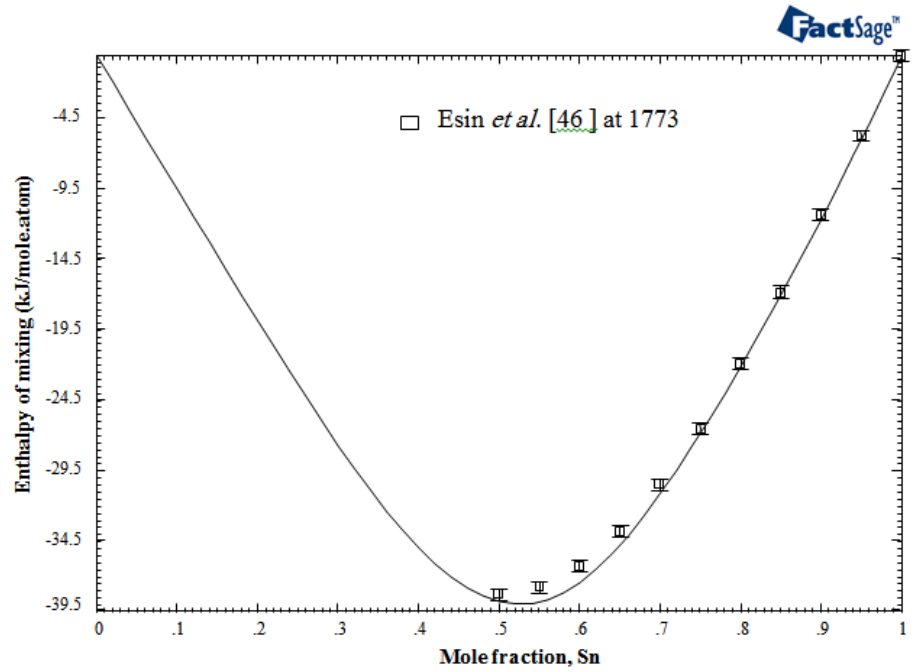

Figure 3. Calculated enthalpy of mixing against mole fraction Sn for the Sn-Sr liquid at 1773 K in comparison with the experimental data of Esin et al. [46]

Table 1: Comparsion between calculated and experimental values of the invariant reactions in the Sn-Sr system.

Reaction type	Reaction	Composition (at.%Sn)	T(^{0}C)	Reference
		2.22	741	This work
Eutectic	Liquid ↔ Sr_BCC + Sr_2Sn	2.7	745	[33]
		2.5	752 ± 5	[38]
		33.3	1288	This work
Congruent	L1↔ Sr_2Sn		1295± 5	[38]
			1255	[33]
		37.5	1185	This work
Peretictic	Liquid + Sr_2Sn↔ Sr_5Sn_3	39.9	1190 ± 5	[38]
		36.7	1170	[33]
		50	1141	This work
Congruent	L1↔ SrSn	50	1140	[33]
		50	1140 ± 5	[38]
		62.5	776	This work
		65	775 ± 5	[38]
Peretictic	Liquid + SrSn↔ Sr_3Sn_5		780	[36]
			810	[37]
		75	557	This work
		79.7	598±1	[32]
Peretictic	Liquid + Sr_3Sn_5↔ $SrSn_3$		563	[36]
			560± 5	[38]
		73.5	580	[31]
		80	320	This work
		95.1	338	Ray
Peretictic	Liquid + $SrSn_3$↔ $SrSn_4$	96	334±4	[32]
		95.8	315±5	[38]
			316	[36]
Eutectic	Liquid ↔ Sn_BCC + $SrSn_4$	99.8	231	This work
		99.7	232	[31]
		99	230±2	[32]
		99	230±5	[38]
			212	[32]
Eutectic	Liquid ↔ SrSn + Sr_5Sn_3	48.7	1144	This work
		45.6	1100±5	[38]
		46.1	1080	[33]

Table 2: Optimized parameters of all phases in Sn-Sr and Mn-Sr systems.

Phase		Thermodynamic parameters
Liquid		$Z_{SnSr}^{Sn} = 5;\ Z_{SnSr}^{Sr} = 5$
	Sn-Sr Liquid	$\Delta g_{SnSr}^{0} = -2127.2 - 1.55T;\ \Delta g_{SrSn}^{10} = -478 - 2.39T$
		$\Delta g_{SrSn}^{01} = -1.43T$
Sn-Sr intermetallic phases	SrSn	$^{\circ}G_{298.15K}^{SrSn} = -93500 + 8.13\mathrm{T}$
	Sr_2Sn	$^{\circ}G_{298.15K}^{\mathrm{Sr\,2Sn}} = -80666.7 + 17.4\mathrm{T}$
	$SrSn_3$	$^{\circ}G_{298.15K}^{\mathrm{SrSn\,3}} = -59500 + 0.78\mathrm{T}$
	Sr_5Sn_3	$^{\circ}G_{298.15K}^{\mathrm{Sr\,5Sn\,3}} = -90875 + 8\mathrm{T}$
	$SrSn_4$	$^{\circ}G_{298.15K}^{\mathrm{SrSn\,5}} = -47880 + 0.61\mathrm{T}$
	Sr_3Sn_5	$^{\circ}G_{298.15K}^{\mathrm{Sr\,3Sn\,5}} = -83375 + 1.05\mathrm{T}$

Table 3. The calculated enthalpies of formation for all the stable compounds in the Sn–Sr system in comparison with literature.

Compound	Miedema Model	First-principle method	MQM
$SnSr_2$	−68.02	−63.40	-66.00
Sn_3Sr_5	−75.47	−64.47	-75.75
SnSr	−90.55	−68.88	-90.00
Sn_5Sr_3	−88.83	−57.93	-83.38
Sn_3Sr	−67.84	−41.74	-59.5
Sn_4Sr	−55.32	−33.96	-47.88

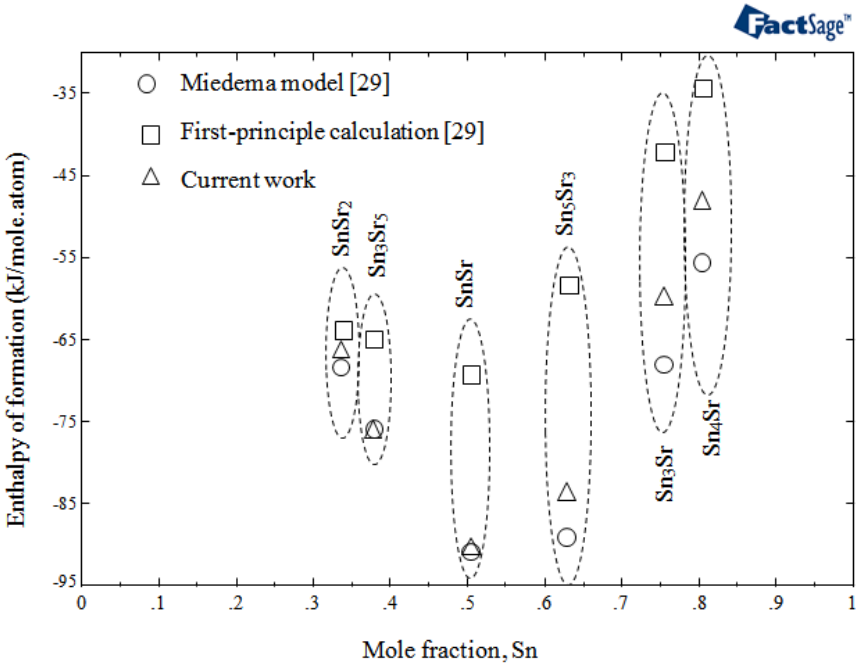

Figure 4. The calculated enthalpy of formation of all intermetallic compounds in comparison with work of Zhao *et al*. [29].

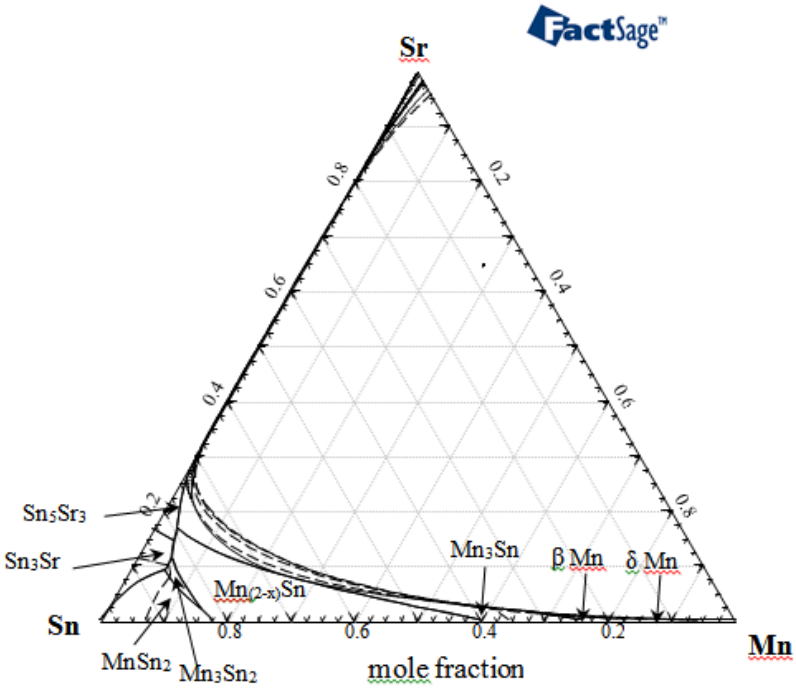

Figure 5. Liquidus projection of Mn-Sn-Sr ternary phase diagram

5. Conclusions

The experimental phase diagram data and thermodynamic properties of the Sn-Sr binary system was evaluated and optimized to obtain self-consistent model parameters for the Gibbs energy of all phases. The calculated liquidus line of Sn-Sr phase diagram was compared with the experimental data and found to be in a good agreement. The calculated thermodynamic properties such as activity and enthalpy of mixing of the Sn-Sr system were in accord with the experimental data in the literature. By combining self-consistent set of optimized parameters of the phases of the constituent binary sub-systems, liquidus projection of the ternary Mn-Sn-Sr phase diagram was obtained.

6. Acknowledgment

Financial support from the Deanship of Scientific Research and Graduate Studies, The Hashemite University, Jordan, is gratefully acknowledged**.** Authors would like to thank Prof. M. Medraj, Mechanical and Industrial Engineering Department, Concordia University, Canada, for useful discussions and suggestions.

References

[1] E. F. Emely "*Principles of Magnesium Technology*", Pergamon Press Ltd., New York,1966.

[2] H. Mao, *et al.*, "Microstructural Characteristics of Die Cast AZ91D and AM60 Magnesium Alloys," *SAE Technical Paper*, 1999.

[3] R. Gradinger and P. Stolfig, "Magnesium wrought alloys for automotive applications," in *Proceedings of the Minerals, Metals & Materials Society (TMS)*, (2003), pp. 231-236.

[4] E. Aghion, *et al.*, "Dead sea magnesium alloys newly developed for high temperature applications," in *Proceedings of the Minerals, Metals & Materials Society (TMS)*, (2003), pp. 177-182.

[5] M. O. Pekguleryuz, *et al.*, "Creep resistant Mg-Al-Sr alloys," *J. Adv. Mater.*, Vol. 35 (2003), pp. 32-38.

[6] E. Ma and J. Xu, "The glass window of opportunities," *Nat. Mater.*, Vol. 8 (2009), pp. 855-857.

[7] Humble P., "Toward a cheap creep resistant magnesium alloy", *Material forum*, 21 (1997), pp. 45-56.

[8] Greenfield P., "Magnesium", Mills and Boo Limited, London, pp. 7-19, 1972.

[9] A.A. Luo, "Recent magnesium alloy development for elevated temperature applications", International Materials Reviews, Vol 49 (2004) No. 1, 13-30.

[10]M. Pekguleryuz, M. Celikin, "Creep Mechanisms in Magnesium Alloys", Int. Mater. Rev., Vol. 55 (2010) No. 4, pp. 197-217.

[11] A. Suzuki, N.D. Saddock, J.W. Jones, T.M. Pollock, "Solidification paths and eutectic intermetallic phases in Mg–Al–Ca ternary alloys" Acta Mater., Vol. 53 (2005), pp. 2823–2834.

[12] M. Celikin, F. Zarandi, M. Pekguleryuz, "Compressive Creep and Texture Evolution in Cast-Pure Magnesium at Stresses above the Yield Strength," Can. Met. Quart. Vol.48 (2009), No. 4, pp. 419-432

[13] N. Ishimatsu, Y. Terada, T. Sato, K. Ohori, "Internal Stress during Creep in a Die-Cast AM50 Magnesium Alloy at 473 K", Materials Transactions, Vol. 47 (2006), No. 10, pp.2493-2496

[14]I.P. Moreno, T.K. Nandy, J.W. Jones, J.E. Allison, T.M. Pollock, "Microstructural stability and creep of rare-earth containing magnesium alloys", Scripta Materialia, Vol. 48 (2003), 1029–1034

[15] J. Zhang, K. Liu,D. Fang, X. Qiu, D. Tang, J. Meng, "Microstructure, tensile properties, and creep behavior of high pressure die-cast Mg-4Al-4RE-0.4Mn (RE=La, Ce) alloys", J. Mater Sci, Vol. 44 (2009) No. 8, 2046−2054

[16] M. Aljarrah "Thermodynamic modeling and experimental investigation of the Mg-Al-Ca-Sr system" Ph.D. thesis 2008, Concordia University, Montreal, QC, Canada.

[17] A. Janz, Thermodynamics and constitution of quaternary Mg-Al-Ca-Sr and the extension to the quinary Mg-Al-Ca-Sr-Mn system, Ph.D. Thesis, Clausthal University of Technology, TU Clausthal, Germany, 2008.

[18] M. Aljarrah, M.A. Parvez, J. Li, E. Essadiqi, M. Medraj, "Microstructural characterization of Mg–Al–Sr alloys", Science and Technology of Advanced Materials, Vol. 8 (2007) No. 4, 237-248.

[19] M. Aljarrah, M. Medraj, X. Wang, E. Essadiqi, A. Muntasar, G. Denes, "Experimental investigation of the MgAlCa system", Journal of alloys and compounds, Vol. 436 (2007) No. 1, 131-141

[20] M.B. Yang, F.S. Pan, R.J. Cheng, J. Shen, "Comparison about effects of Sb, Sn and Sr on as-cast microstructure and mechanical properties of AZ61-0.7Si magnesium alloy", [J]. Mater Sci Eng A, Vol. 489 (2008), No. 1/2, 413−418.

[21] S.K. Guan, S.J. Zhu, L.G. Wang, Q. Yang, W.B. Cao, "Microstructures and mechanical properties of double hot-extruded AZ80+*x*Sr wrought alloys", [J]. Transactions of Nonferrous Metals Society of China, Vol 17 (2007), No. 6, 1143−1151.

[22] M.B. Yang, J. Shen, L. Bai, F.S. Pan, "Effects of Sr on the microstructure, tensile and creep properties of AZ61-0.7Si magnesium alloy", [J]. Inter J Minerals, Metallurgy and Materials, Vol. 16 (2009), No. 1, 89−95.

[23] M.B. Yang, F.S. Pan, R.J. Cheng, A.T. Tang, "Effect of Mg-10Sr master alloy on grain refinement of AZ31 magnesium alloy", [J]. Mater Sci Eng A, Vol. 491 (2008) No. 1/2, 440−445.

[24] Dead Sea Magnesium Ltd., *High Strength and Creep Resistant Magnesium Alloys*, European Patent, EP 1 308 531 A1, 2003.

[25] A. Hitachi Ltd., *High Strength Mg Based Alloy and its Uses*, EP1 108799 A2, European Patent, 2001.

[26] L. Bowles, C. Blawert, N. Hort and K. U. Kainer, "Microstructural investigations of the Mg-Sn and Mg-Sn-Al alloys systems", Magnesium Technology (2004), TMS 2004, pp. 307-310.

[27] M. Celikin and M. Pekguleryuz, "The role of α-Mn precipitation on the creep mechanism of Mg-Sr-Mn", Material Science & Engineering A, Vol. 556 (2012), 911-920.

[28] M. Masoumi and M. Pekguleryuz, "Effect of Sr on the texture of rolled Mg-Mn-based alloys", Material letters, Vol. 71 (2012), 104-107.

[29] J. Zhaoa, Y. Du, L. Zhang, A. Wang, L. Zhou, D. Zhao, J. Liang, "Thermodynamic assessment of the Sn–Sr system supported by first-principles calculations", Thermochimica Acta 529 (2012) , 74– 79.

[30] A.D. Pelton, S.A. Degterov, G. Eriksson, C. Robelin, Y. Dessureault, The modified quasichemical model I-Binary solutions, Metall. Mater. Trans. B 31B (2000) 651–659.

[31] K.W. Ray, Properties of strontium–tin alloys, Ind. Eng. Chem. 22 (1930) 519–522.

[32] D. Marshall, Y.A. Chang, Constitution of the tin-strontium system up to 35 at.% Sr, J. Less-Common Met. 78 (1981) 139–145.

[33] A. Widera, H. Schafer, Das Zustandsdiagramm Sr–Sn und die Verbindung Sr_3SnO (The phase diagram of Sr–Sn system and the compound Sr_3SnO), J. Less-Common Met. 77 (1981) 29–36 (in German).

[34] T.B. Massalski (editor-in-chief), Binary Alloy Phase Diagrams, second ed., Vol.3, Materials Information Soc., Materials Park, OH, 1990.

[35] S. Hoffmann, Darstellung, Struktur und Eigenschaften von Stanniden sowie Tetrelid-Silicaten und Silicaten, Ph.D. Thesis, Humboldt-Universität, Berlin, 2002 (in German).

[36] S. Hoffman and T.F. Fassler, $SrSn_4$: a superconducting stannide with localized and delocalized bond character, Inorg. Chem., 42(2003), pp. 8748-8754.

[37] F. Zürcher, R. Nesper, S. Hoffmann, T.F. Fässler, Novel arachno-type X56- zintl anions in Sr_3Sn_5, Ba_3Sn_5, and Ba_3Pb_5 and charge influence on zintl clusters, Z. Anorg. Allg. Chem. 627 (2001) 2211–2219.

[38] A. Palenzona, M. Pani, The phase diagram of the Sr–Sn system, J. Alloys Compd. 384 (2004) 227–230.

[39] M.T. Klem, J.T. Vaughey, J.G. Harp, J.D. Corbett, A3Tt5 phases Sr_3Sn_5, Ba_3Pb_5, and La_3Sn_5. Structure and bonding in a series of isotypic metallic compounds with increased electron count and their comparison with the nominal zintl phase La_3In_5, Inorg. Chem. 40 (2001) 7020–7026.

[40] T.F. Fassler, S. Hoffmann, $SrSn_3$—eine superleitende Legierung mit freien Elektronenpaaren ($SrSn_3$—a superconducting alloy with non-bonding electron pairs), Z. Anorg. Allg. Chem. 626 (2000) 106–112 (in German).

[41] A. Widera, H. Schafer, Das Zustandsdiagramm Sr–Sn und die Verbindung Sr_3SnO (The phase diagram of Sr–Sn system and the compound Sr_3SnO), J. Less-Common Met. 77 (1981) 29–36 (in German).

[42] G. Bruzzone, E. Franceschi, On the occurrence of M_2X intermetallic compounds (M = Ca, Sr, Ba; X = Si, Ge, Sn, Pb), J. Less-Common Met. 57 (1978) 201–208.

[43] W. Dorrscheidt, A. Widera, H. Schäfer, Darstellung und Kristallstruktur von Sr_5Sn_3 und Ba_5Sn_3 (Preparation and crystal structure of Sr_5Sn_3 and Ba_5Sn_3), Z. Naturforsch., Teil B: Anorg. Chem., Org. Chem. 32B (1977) 1097–1099 (in German).

[44] W. Rieger, E. Parthé, Alkaline earth silicides germanides and stannides with CrB structure type, Acta Crystallogr. 22 (1967) 919–922.

[45] F. Merloa, M.L. Fornasini, CrB-type equiatomic compounds of europium, ytterbium and alkaline-earth metals with Si, Ge, Sn, Pb, J. Less-Common Met. 13 (1967) 603–610.

[46] Yu.O. Esin, V.V. Litovskii, S.E. Demin, M.S. Petrushevskii, Partial and integral enthalpies of formation of liquid alloys of strontium and barium with tin, Zh. Fiz. Khim. 59 (1985) 766–767 (in Russian).

[48] M.P. Morozova, M. Li, M.V. Golomolzina, Enthalpy of formation of the compounds of strontium with the elements of the main subgroup of group IV, Vestnik Leningradskogo Universiteta, Ser. Fiz. Khim. 14 (1959) 83–86 (in Russian).

[49] E.B. Klebanov, O.O. Tvaradze, A.G. Moroachevskii, Activity of strontium in molten alloys with tin, Izv. Vyssh. Uchebn. Zaved., Tsvetn. Metall. (1985) 106–107 (in Russian).

[50] I. Obinata, Y. Takeuchi, K. Kurihara, and M. Watanabe, "Alloys of Manganese and Silicon with Alkali and Alkaline-Earth Metals", Metallurgy, Vol. 19 (1965), 21-35

[51] Y. Peng, D. Zhao, B. Hu, L. Zhou, Y. Du, T. Gang, S. Liu and K. Chang, Thermodynamic modeling of the Sr-M (M=Fe, Mn, Ni, Ti, V) Systems, J Phase Equilib Diffus Vol. (2011), No. 1, 42-47.

[52] A.T. Dinsdale, SGTE Data for Pure Elements, CALPHAD Vol. 15 (1991) No. 4, 317-425.

[53] A.D. Pelton, P. Chartrand," The modified quasichemical model: Part II. Multicomponent solutions, Metall Mater Trans A, Vol. 32 (2001) No. 6,1355-1360.

[54] A.D. Pelton, M. Blander, Computer assisted analysis of the thermodynamic properties and phase diagrams of slags, in:

Proc. 2nd Int. Symp. On Metall. Slags and Fluxes, TMS-AIME, Warrendlae, PA, USA, (1984), 281-294.

[55] F. Kohler, Estimation of the thermodynamic data for a ternary system from the corresponding binary systems, Monats. Chem. Vol. 91 (1960), 738–740

[56] M. Aljarrah, S. Obaidat, Rami H. Fouad, M. Rababah and A. Almagableh, A. Itradat, "Thermodynamic Calculations of the Mn-Sn,Mn-Sr and Mg-Mn-{Sn, Sr} systems". Accepted in IET, 2014