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Isothermal section of the Al–Dy–Ge ternary system at 673 K

Pingli Qin [a,b,*], Zhongping Xu [b], Zhongli Qin [c], Duanyong Li [a], Lingmin Zeng [b], Wei He [b]

[a] School of Science, Wuhan Institute of Technology, Wuhan, Hubei, 430073, PR China
[b] Key Laboratory of Nonferrous Metal Materials and New Processing Technology, Ministry of Education, Guangxi University, Nanning, Guangxi, 530004, PR China
[c] Department of Chemical and Environmental Engineering, Wuhan Bioengineering Institute, Wuhan, Hubei, 430415, PR China

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ABSTRACT

The isothermal section of the phase diagram of the Al–Dy–Ge ternary system at 673 K has been investigated by X-ray powder diffraction and scanning electron microscope equipped with energy dispersive X-ray spectroscopy in backscattered electron imaging modes. The existence of thirteen binary compounds including Dy_3Ge_4 in the system Dy–Ge has been confirmed. Four ternary compounds, namely AlDyGe, $Al_3Dy_2Ge_4$, $AlDy_2Ge_3$, and $AlDy_2Ge_2$ were observed, and five new ternary compounds, i.e., $Al_{0.33}DyGe_2$, $AlDy_2Ge_6$, Al_2DyGe_2, $AlDy_3Ge_3$, and $Al_{3-x}Dy_{11}Ge_{7+x}$ ($x \leq 0.7$), and one pseudo-binary compound $Al_{3-x}DyGe_x$ were found in this system at 673 K. The maximum solid solubility of Ge in the pseudo-binary compounds $Al_{3-x}DyGe_x$ is about 7.5 at.% with $x = 0.3$ at 673 K.

1. Introduction

Al-based amorphous alloys have attracted considerable attention in recent years due to their outstanding mechanical and physical properties, such as high mechanical strength, good corrosion resistance, and unique magnetic properties. Especially they are attractive candidates for advanced high-strength lightweight materials [1,2]. As an important technological application in materials, rare earths have been commonly recognized as favorable additives because they have good effects on corrosion resistance, tensile strength and heat resistance of alloys [3]. Attentions are also paid to Germanium using as an addition to Aluminum alloys. Aluminum mechanically alloyed with Germanium exhibits improved super plastic elongation [4]. Properties of these alloys are strongly related with the formation of the intermetallic compounds. Therefore, it is necessary to investigate the phase diagram and thermodynamic description of RE–Al–Ge systems in order to develop alloys with required properties. At present, investigation on the phase relations for the RE–Al–Ge systems have not been investigated except the RE–Al–Ge (RE = Y, La, Ce, Sm, Tb) [5–9] ternary systems, which have been determined only in the region with the compositions in the range of 0–40 at.% RE.

A total of seven type intermetallic compounds in the RE–Al–Ge systems have been reported in references, i.e., REAlGe (RE = Y, La–Nd, Sm, Eu–Er, Lu) [10], $RE_2Al_3Ge_4$ (RE = La–Nd, Sm, Gd–Er) [10] RE_2AlGe_6 (RE = La–Nd, Sm, Gd) [10], $REAl_2Ge_2$ (RE = Y, La, Ce, Eu, Gd, Er, Yb) [10–13] RE_2AlGe_3 (RE = Y, La, Nd, Sm, Tb, Dy, Ho, Er, Tm) [10,14–16], $REAl_{3-x}Ge_x$ (RE = Gd, Tb, Ho, $X = 0.10–0.30$) [17], $REAl_xGe_2$ (RE = Y, Gd, Dy, Ho, Er, $X = 0.27–0.35$) [18–22], and RE_2AlGe_2 (RE = Gd, Dy) [23,24].

The phase diagrams of the binary systems Al–Dy, Dy–Ge and Al–Ge in the Al–Dy–Ge system have been presented in Ref. [25]. At 673 K, there are five intermetallic phases (Al_3Dy, Al_2Dy, AlDy, Al_2Dy_3 and $AlDy_2$) reported in the Al–Dy system [25–28]. Seven intermetallic phases, i.e., Dy_5Ge_3, Dy_5Ge_4, DyGe, Dy_2Ge_3, Dy_3Ge_5, $DyGe_2$ and $DyGe_3$ were found in the Dy–Ge system [25,26]. The Al–Ge system [25] is a simple eutectic system with three phases of the liquid, the Al-fcc solid solution and the Ge-diamond cubic solid solution. No intermetallic phase exists in the Al–Ge system. In this paper we report the investigations on the phase relations in the Al–Dy–Ge ternary system at 673 K.

2. Experimental details

The ingots of aluminum (99.99 wt.%), dysprosium (99. 8 wt.%) and germanium (99.99 wt.%) were used as starting materials. Samples were prepared by arc melting on a water-cooled copper crucible with a non-consumable tungsten electrode under high pure argon atmosphere. All samples were remelted three times and turned around after melting for better homogeneity. Weight

* Corresponding author at: School of Science, Wuhan Institute of Technology, Wuhan, Hubei, 430073, PR China. Tel.: +86 027 87992045; fax: +86 027 87992214.
E-mail addresses: qinpingli2008@163.com, qpl2008@sohu.com (P. Qin).

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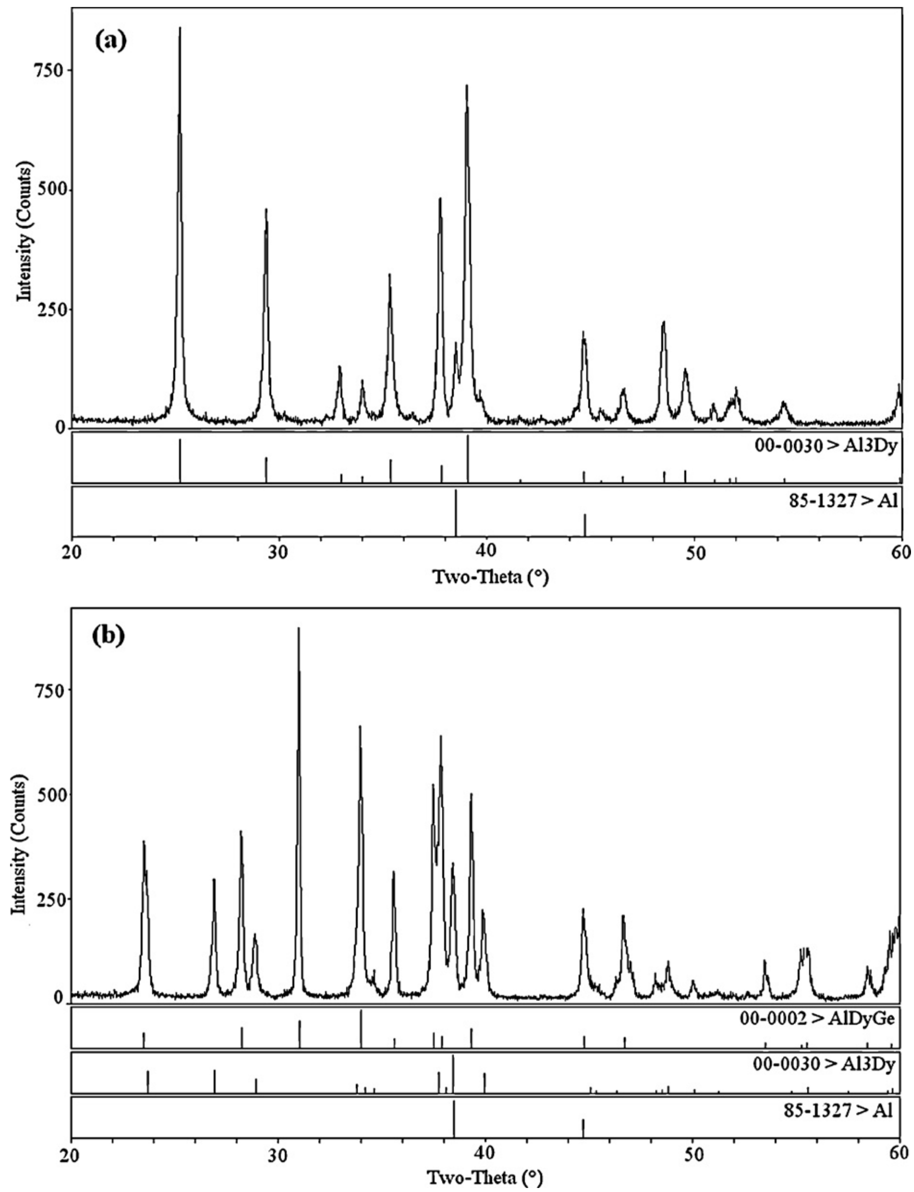

Fig. 1. XRD patterns of (a) the sample No. 21 ($Al_{80}Dy_{20}$) contained the phases of Al_3Dy and Al and (b) the sample No. 56 ($Al_{55}Dy_{25}Ge_{20}$) located in the phase region of AlDyGe + Al_3Dy + Al.

losses of alloy buttons during arc melting were less than 1% of the total mass. All alloy samples after melting were subjected to a homogenizing annealing in evacuated quartz. The homogenization temperatures were chosen on the basis of the binary phase diagrams of the Al–Dy, Dy–Ge, and Al–Ge systems. Samples with compositions less than 20 at.% Dy were annealed at 673 K for 600 h. The Al-rich and Dy-rich samples were annealed at 873 K and 1173 K for 480 h, respectively. Samples with composition in the range of 30–70 at.% Ge were annealed at 1273 K for 480 h. Subsequently, all of the samples were cooled down to 673 K with a rate of 10 K/h and kept at 673 K for 240 h, and then quenched in liquid nitrogen.

Samples for X-ray diffraction (XRD) analyses were ground into powders. The XRD data were collected on a Rigaku D/Max 2500 V diffractometer with Cu k_α radiation and graphite monochromator operated at 40 kV, 200 mA. The Materials Data Inc. software Jade 5.0 [29] and Powder Diffraction File (PDF release 2002) [28] were used for phase identification. Selected samples were examined by optical microscopy (Leica DMLP, Germany) and then analyzed by scanning electron microscope equipped with energy dispersive X-ray spectroscopy (VEGA3 TESCAN CZECH) in backscattered electron (BSE) imaging modes for microstructure observation and composition measurement.

3. Results and discussion

3.1. Binary compounds

Table 1 gives the crystallographic data of the binary and ternary compounds in the Al–Dy–Ge system. Five intermetallic compounds, i.e., $AlDy_2$, Al_2Dy_3, AlDy, Al_2Dy and Al_3Dy presented in the Al–Dy binary phase diagram in the Refs. [25,30,31] have been confirmed to exist in our work. Pop et al. [32] reported a binary compound $Al_{17}Dy_2$ with hexagonal $Ni_{17}Th_2$ type structure (space group $P6_{3/mmc}$, a = 1.1788 nm, and c = 1.1322 nm) in the Al–Dy system. In order to identify the existence of the phase $Al_{17}Dy_2$, a series of alloy samples with composition in the Al-rich region of the Al–Dy–Ge system were prepared. The calculated XRD pattern of $Al_{17}Dy_2$ was obtained from the crystallographic data in Ref. [32] using the LAZY program [33]. By analyzing the XRD patterns of these samples by

Table 1
Crystallographic data of the compounds in the Al–Dy–Ge system at 673 K.

Phase	Space group	Structure type	Lattice parameter			Reference
			a (nm)	*b* (nm)	*c* (nm)	
Al	$Fm\bar{3}m(225)$	Cu	0.4050(2)	–	–	[39]
Dy	$P6_3/mmc(194)$	Mg	0.3458	–	0.5466	[40]
Ge	$Fd\bar{3}m(227)$	C	0.56512	–	–	[41]
Al_2Dy	$Fd\bar{3}m(227)$	Cu_2Mg	0.7826	–	–	[10]
AlDy	$Pbcm(57)$	AlDy	0.5822	1.1369	0.5604	[10]
Al_2Dy_3	$P4_2nm(102)$	Al_2Gd_3	0.8170	–	0.7523	[10]
$AlDy_2$	$Pnma(62)$	Co_2Si	0.6543	0.5075	0.9397	[10]
αAl_3Dy	$P6_3/mmc(194)$	Ni_3Ti	0.6097(9)	–	0.9534(8)	[28]
Dy_5Ge_3	$P6_3/mcm(193)$	Mn_5Si_3	0.842(2)	–	0.632(1)	[26]
Dy_5Ge_4	$Pnma(62)$	Ge_4Sm_5	0.7603(5)	1.4640(5)	0.7680(5)	[26]
DyGe	$Cmcm(63)$	BCr	0.4254(1)	1.0623(2)	0.3904(1)	[26]
Dy_3Ge_4	$Cmcm(63)$	W_3CoB_3	0.4027(1) 0.4204	1.0599(3)	1.4169(5)	[34]
Dy_2Ge_3	$P6/mmm(191)$	AlB_2	0.3936(1)	–	0.4143(1)	This work
Dy_3Ge_5	$Fdd2(43)$	Ge_5Y_3	0.5729(1)	1.7190(2)	1.3678(1)	[26]
$DyGe_2$	$Cmmm(65)$	Ge_2Tb	0.4091(1)	2.9807(4)	0.3987(1)	[26,27]
Dy_6Ge_{11}	$Cmc2_1(36)$		0.41027	2.9705	0.39316	[36]
$DyGe_3$	$Cmcm(63)$	$DyGe_3$	0.40278(5)	2.0710(3)	0.38997(5)	[26]
AlDyGe	$Cmcm(63)$	AlDyY	0.4035(4)	1.0396(9)	0.5752(3)	[10]
$Al_3Dy_2Ge_4$	$Cmca(64)$	$Ba_3Bi_2Cd_4$	0.5881(2)	1.4800(4)	0.7690(2)	[10]
$AlDy_2Ge_3$	$Pnma(62)$	Y_2AlGe_3	0.6785	0.4171	1.7665	[14]
			0.67907(8)	0.41386(6)	1.7695(2)	This work
Al_2DyGe_2	$P\bar{3}ml(164)$	La_2O_3	0.4204(3)	–	0.6681(2)	This work
$Al_{0.33}DyGe_2$	$Cmcm(63)$	$CeNiSi_2$	0.41018(2)	1.62323(6)	0.39463(1)	[20], This work
$AlDy_2Ge_6$	$Amm2(38)$	Ce_2CuGe_6	0.4144(4)	0.3992(3)	2.0576(3)	This work
$Al_{3-x}DyGe_x (x=0)$	$P6_3/mmc(194)$	Ni_3Ti	0.6095(1)	–	0.9531(1)	This work
$AlDy_2Ge_2$	$P4/mbm(127)$	Mo_2FeB_2	0.7019	–	0.4291	[24]
$AlDy_3Ge_3$	$Pmcn(62)$	unknown	1.7266(8)	0.8175(2)	0.5999(3)	This work
$Al_{3-x}Dy_{11}Ge_{7+x} (x=0)$	$I4/mmm(139)$	unknown	1.09816(4)	–	1.61037(8)	This work

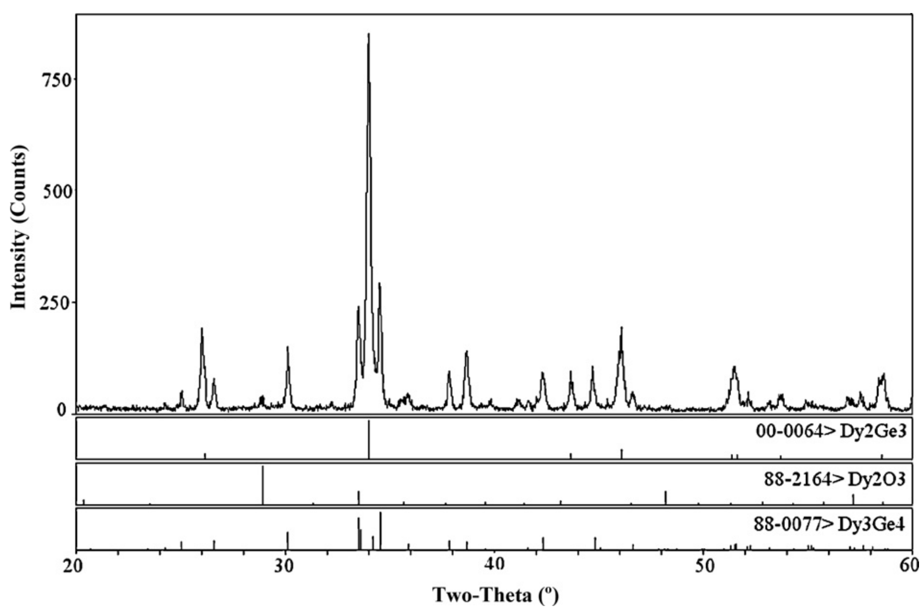

Fig. 2. XRD pattern of the sample No. 8 ($Dy_{41.5}Ge_{58.5}$) located in the phase region of $Dy_2Ge_3 + Dy_3Ge_4 + Dy_2O_3$. (There is a minor impure phase of Dy_2O_3, and the peak at $2\theta = 29°$ belongs to the phase of Dy_2O_3.)

using the database of PDF [28] and the calculated XRD pattern of $Al_{17}Dy_2$, we were able to identify the phases in each sample. Fig. 1 shows the XRD patterns of two selected alloy samples of No. 21 ($Al_{80}Dy_{20}$) and No. 56 ($Al_{55}Dy_{25}Ge_{20}$) indicating the absence of the compound $Al_{17}Dy_2$. From Fig. 1, it can be seen that the sample No. 21 ($Al_{80}Dy_{20}$) consists of the two phases of Al and Al_3Dy and the sample No. 56 ($Al_{55}Dy_{25}Ge_{20}$) contained the phases of Al, Al_3Dy (or $Al_{3-x}DyGe_x$) and AlDyGe. No evidence was found to confirm the existence of $Al_{17}Dy_2$ under our experimental conditions. This is in good agreement with Ref. [25].

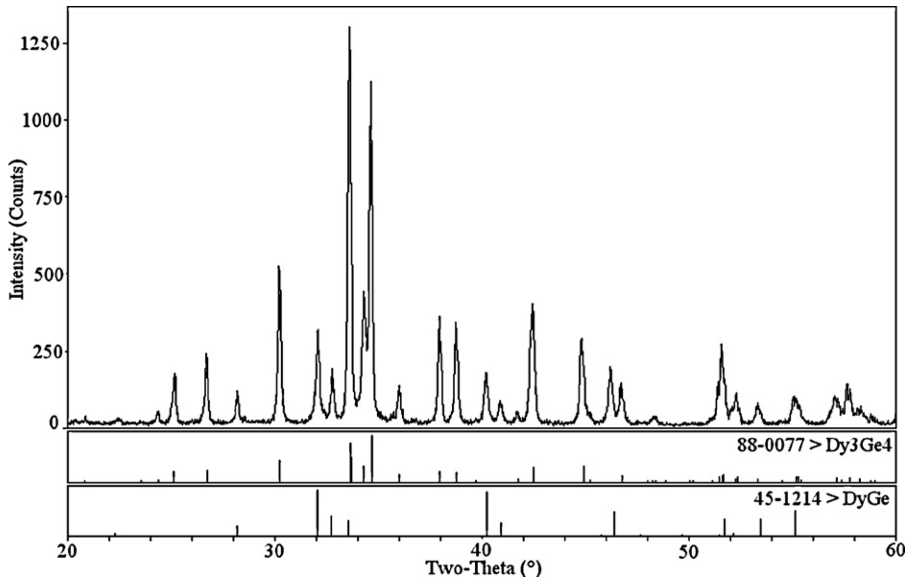

Fig. 3. XRD pattern of the sample No. 9 ($Dy_{47}Ge_{53}$) consisted of the phases of Dy_3Ge_4 and DyGe.

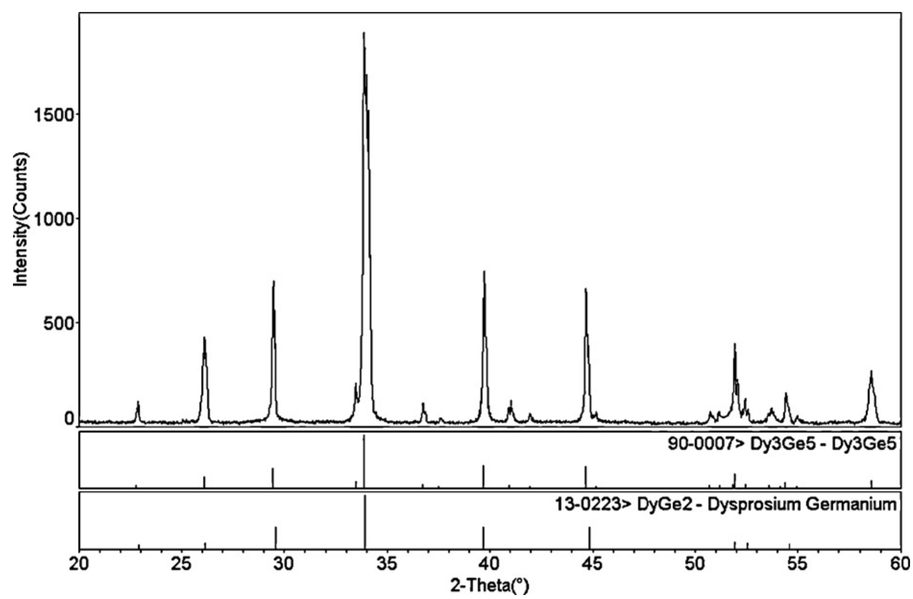

Fig. 4. XRD pattern of the sample No. 72 ($Al_5Dy_{35}Ge_{60}$) contained the phases of $Al_{0.33}DyGe_2$, Dy_3Ge_5 and $AlDy_2Ge_3$.

Seven binary compounds (Dy_5Ge_3, Dy_5Ge_4, DyGe, Dy_2Ge_3, Dy_3Ge_5, $DyGe_2$ and $DyGe_3$) in the Dy–Ge system were confirmed to exist at 673 K, which is consistent with the results that presented in Refs. [25,34]. However, the compound Dy_3Ge_4 in this system reported in Ref. [35] was observed under our experimental conditions. The XRD patterns of the samples No. 8 ($Dy_{41.5}Ge_{58.5}$) and No. 9 ($Dy_{47}Ge_{53}$) with composition near Dy_3Ge_4 clearly proves the existence of the compound Dy_3Ge_4, as shown in Figs. 2 and 3. The samples No. 8 ($Dy_{41.5}Ge_{58.5}$) consists of the phases of Dy_2Ge_3, Dy_3Ge_4 and impurity phase Dy_2O_3 and No. 9 ($Dy_{47}Ge_{53}$) contained the phases of Dy_3Ge_4 and DyGe. Mokra et al. [36] claimed that the compound Dy_6Ge_{11} crystallized in an orthorhombic structure (space group $Cmc2_1$, a = 0.41027 nm, b = 2.9705 nm, and c = 0.39316 nm). By comparing the experimental X-ray diffraction patterns of some alloys with the calculated XRD pattern of the compound Dy_6Ge_{11} obtained from the crystallographic data in Ref.

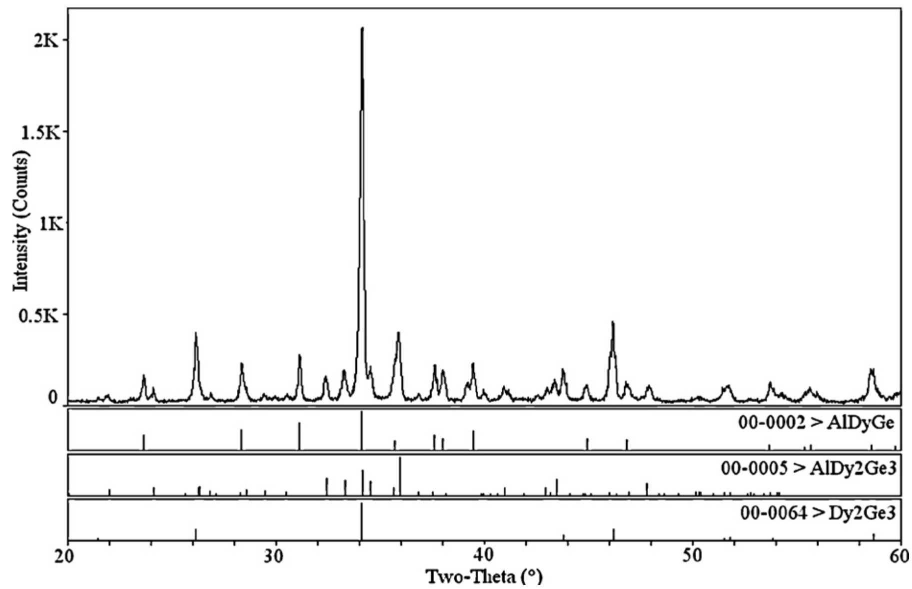

Fig. 5. XRD pattern of the sample No. 65 ($Al_{15}Dy_{35}Ge_{50}$) located in the phase region of $AlDy_2Ge_3$ + AlDyGe + Dy_2Ge_3.

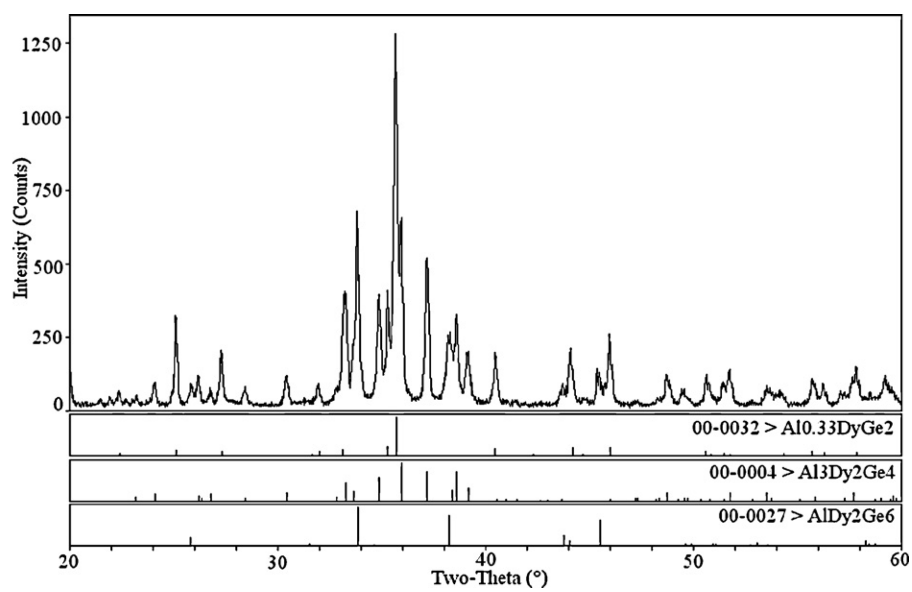

Fig. 6. XRD pattern of the sample No. 76 ($Al_{20}Dy_{25}Ge_{55}$) located in the phase region of $Al_{0.33}DyGe_2$ + $Al_3Dy_2Ge_4$ + $AlDy_2Ge_6$.

[36], the absence of the compound Dy_6Ge_{11} at 673 K was confirmed. The experimental XRD of the sample is more close to that of $DyGe_2$ [27], therefore, the existence of $DyGe_2$ is considered at 673 K.

No compound was found in the Al–Ge system.

3.2. Ternary compounds

Four ternary compounds reported in literature, i.e., AlDyGe [10], $Al_3Dy_2Ge_4$ [10], $AlDy_2Ge_3$ [16], and $AlDy_2Ge_2$ [24] were confirmed to exist at 673 K. Five new ternary compounds ($Al_{0.33}DyGe_2$, Al_2DyGe_2, $AlDy_2Ge_6$, $AlDy_3Ge_3$, and $Al_{3-x}Dy_{11}Ge_{7+x}$) were found in the Al–Dy–Ge system at 673 K. Crystallographic data of all ternary compounds are summarized in Table 1. The ternary compound $Al_{0.33}DyGe_2$ crystallizes in the orthorhombic $CeNiSi_2$-type structure [37] with space group *Cmcm* (No. 63) and a = 0.41018(2) nm, b = 1.62323(6) nm, c = 0.39463(1) nm [20]. The compound Al_2DyGe_2 has a La_2O_3-type [38] structure with space group $P\bar{3}ml$ (No. 164), and a = 0.4204 nm and c = 0.6681 nm. The new ternary compound $AlDy_2Ge_6$ was found to crystallize in the orthorhom-

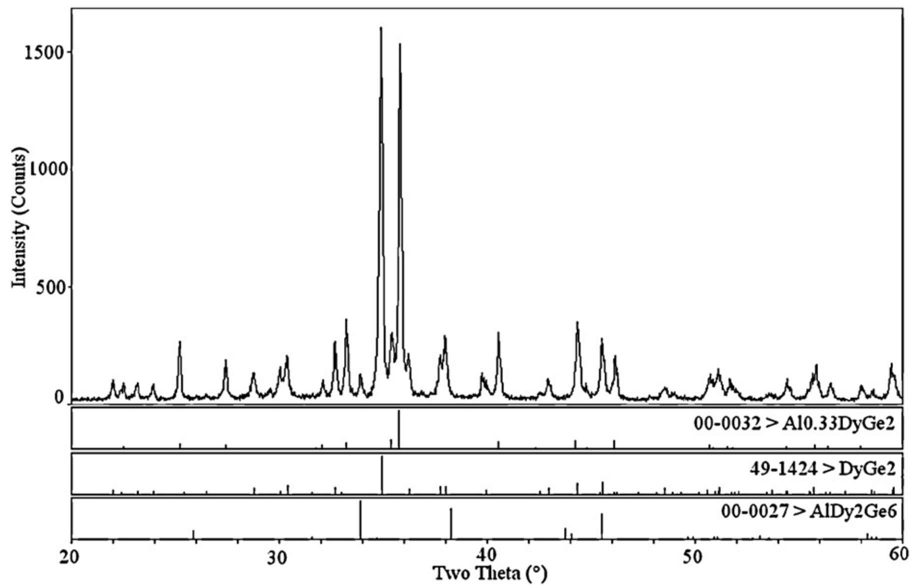

Fig. 7. XRD pattern of the sample No. 85 ($Al_5Dy_{30}Ge_{65}$) consisted of the three phases of $Al_{0.33}DyGe_2$, $DyGe_2$ and $AlDy_2Ge_6$.

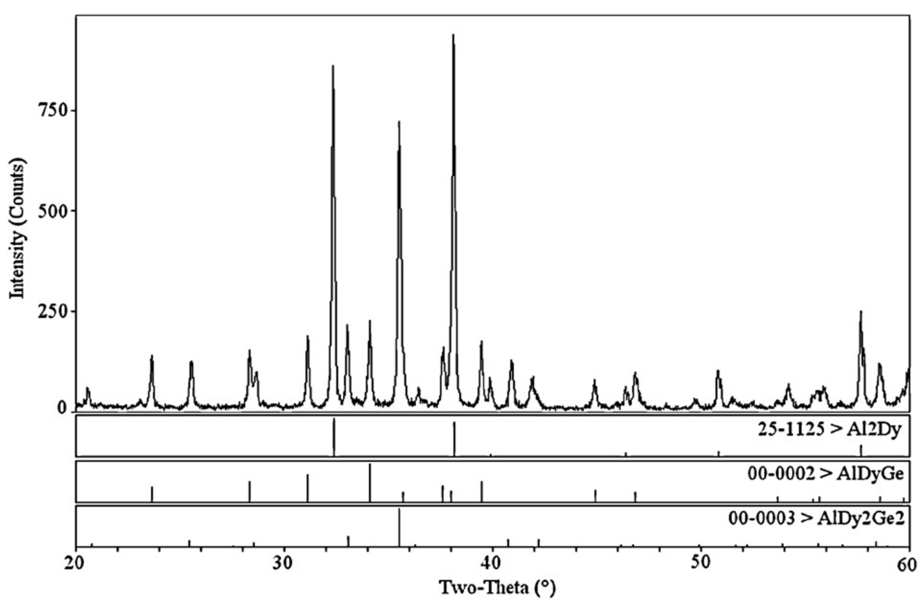

Fig. 8. XRD pattern of the sample No. 46 ($Al_{40}Dy_{36}Ge_{24}$) sit in the phase region of $Al_2Dy + AlDyGe + AlDy_2Ge_2$.

bic Ce_2CuGe_6-type structure with space group *Amm*2 (No. 38) and $a = 0.4144$ nm, $b = 0.3992$ nm and $c = 2.0576$ nm. The new ternary compound $AlDy_3Ge_3$ crystallizes in an orthorhombic structure with space group *Pmcn* (No. 62) and unit-cell parameters $a = 1.7266(8)$ nm, $b = 0.8175(2)$ nm, and $c = 0.5999(3)$ nm. The analysis of the X-ray powder diffraction patterns revealed that the new ternary compound $Al_{3-x}Dy_{11}Ge_{7+x}$ has a solid solution range of $0 \leq x \leq 0.7$ at 673 K. The new ternary compound $Al_{3-x}Dy_{11}Ge_{7+x}$ with $x = 0$ crystallizes in a tetragonal structure with space group *I*4/*mmm* (No. 139) and unit-cell parameters $a = 1.09816(4)$ nm, and $c = 1.61037(8)$ nm. The unknown crystal structure needs additional study.

The existence of the above ternary compounds can be proved by the X-ray diffraction patterns of the samples located in the three-phase regions. Phase identification of several selected ternary alloys using X-ray powder diffraction technique is shown in Figs. 4–11. Fig. 4 presents the X-ray diffraction pattern of the sample No. 72 ($Al_5Dy_{35}Ge_{60}$) contained the phases of $Al_{0.33}DyGe_2$, Dy_3Ge_5 and

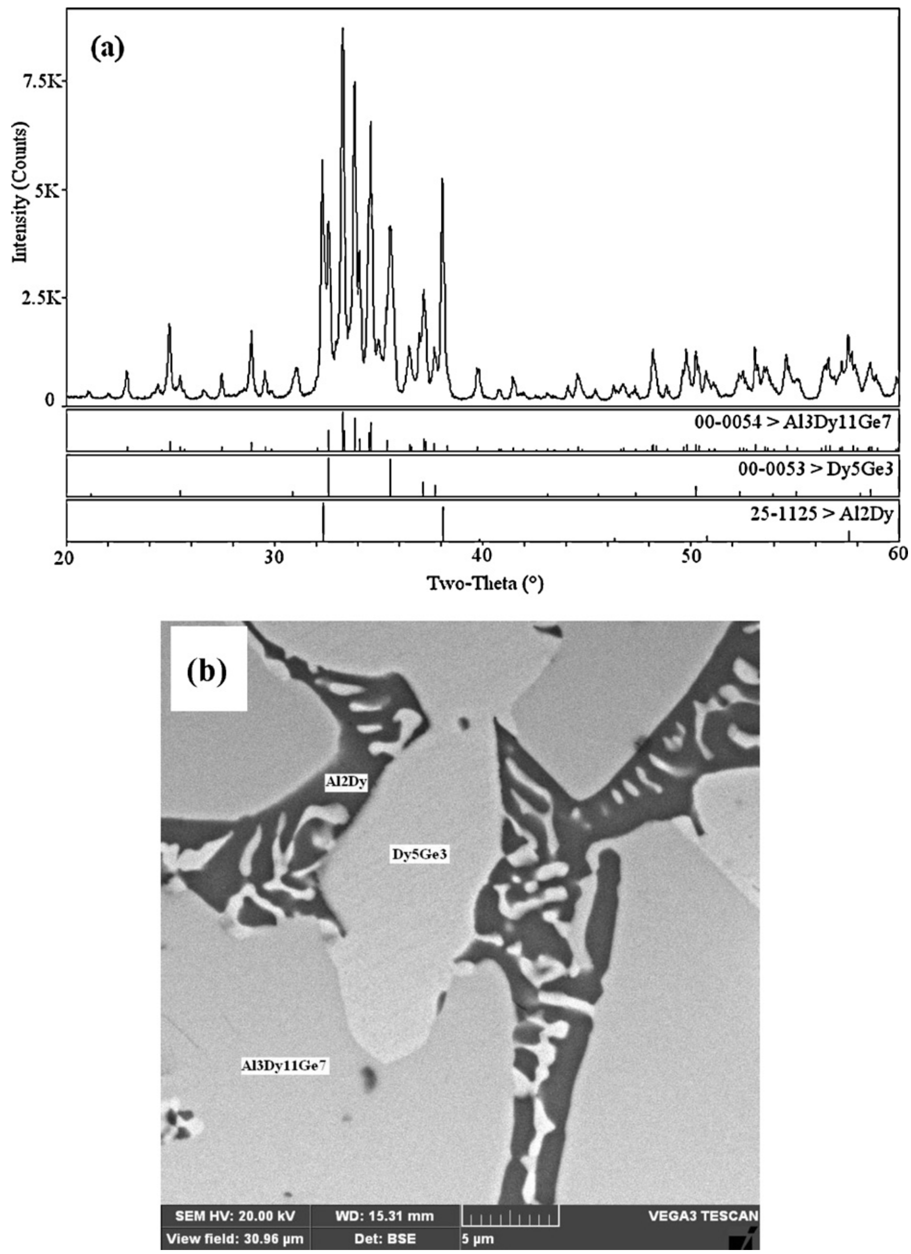

Fig. 9. XRD pattern (a) and SEM image (b) of the sample No. 40 ($Al_{20}Dy_{52}Ge_{28}$) located in the three phase region of $Al_3Dy_{11}Ge_7 + Dy_5Ge_3 + Al_2Dy$.

$AlDy_2Ge_3$. The sample No. 65 ($Al_{15}Dy_{34}Ge_{50}$ alloy) consists of the three phases of $AlDy_2Ge_3$, AlDyGe, and Dy_2Ge_3 seen in Fig. 5. The sample No. 76 ($Al_{20}Dy_{25}Ge_{55}$ alloy) consists of the phases $Al_{0.33}DyGe_2$, $Al_3Dy_2Ge_4$, and $AlDy_2Ge_6$ seen in Fig. 6. The XRD analysis of the samples $Al_5Dy_{30}Ge_{65}$ shows the existence of the three-phase region of $Al_{0.33}DyGe_2 + DyGe_2 + AlDy_2Ge_6$ as shown in Fig. 7. The XRD pattern of the sample No. 46 ($Al_{40}Dy_{36}Ge_{24}$) located in the phase region of Al_2Dy + AlDyGe + $AlDy_2Ge_2$ is given in Fig. 8. Fig. 9 presents the X-ray diffraction pattern (a) and the SEM image (b) of the sample No. 40 ($Al_{20}Dy_{52}Ge_{28}$) contained of the three phases of $Al_{3-x}Dy_{11}Ge_{7+x}$, Dy_5Ge_3, and Al_2Dy. Fig. 10 shows the X-ray diffraction pattern (a) and the SEM image (b) of the sample No. 42 ($Al_{20}Dy_{45}Ge_{35}$). The X-ray diffraction analysis for the sample gives the same result with that of SEM analysis. It can be clearly seen from Fig. 10 that the sample consisted of the three phases of $Al_{3-x}Dy_{11}Ge_{7+x}$, $AlDy_2Ge_2$ and Al_2Dy. The X-ray diffraction pattern of the sample No. 52 ($Al_8Dy_{44}Ge_{48}$) is shown in Fig. 11 proving the existence of the compound $AlDy_3Ge_3$.

3.3. Pseudo-binary compound

A series samples with compositions of $Al_{3-x}DyGe_x$ with x = 0.1, 0.2, 0.3, 0.4, 0.5 were prepared by arc-melting. The XRD patterns of the series samples of $Al_{3-x}DyGe_x$ are shown in Fig. 12. The XRD analysis pointed out that the obtained samples $Al_{3-x}DyGe_x$ with

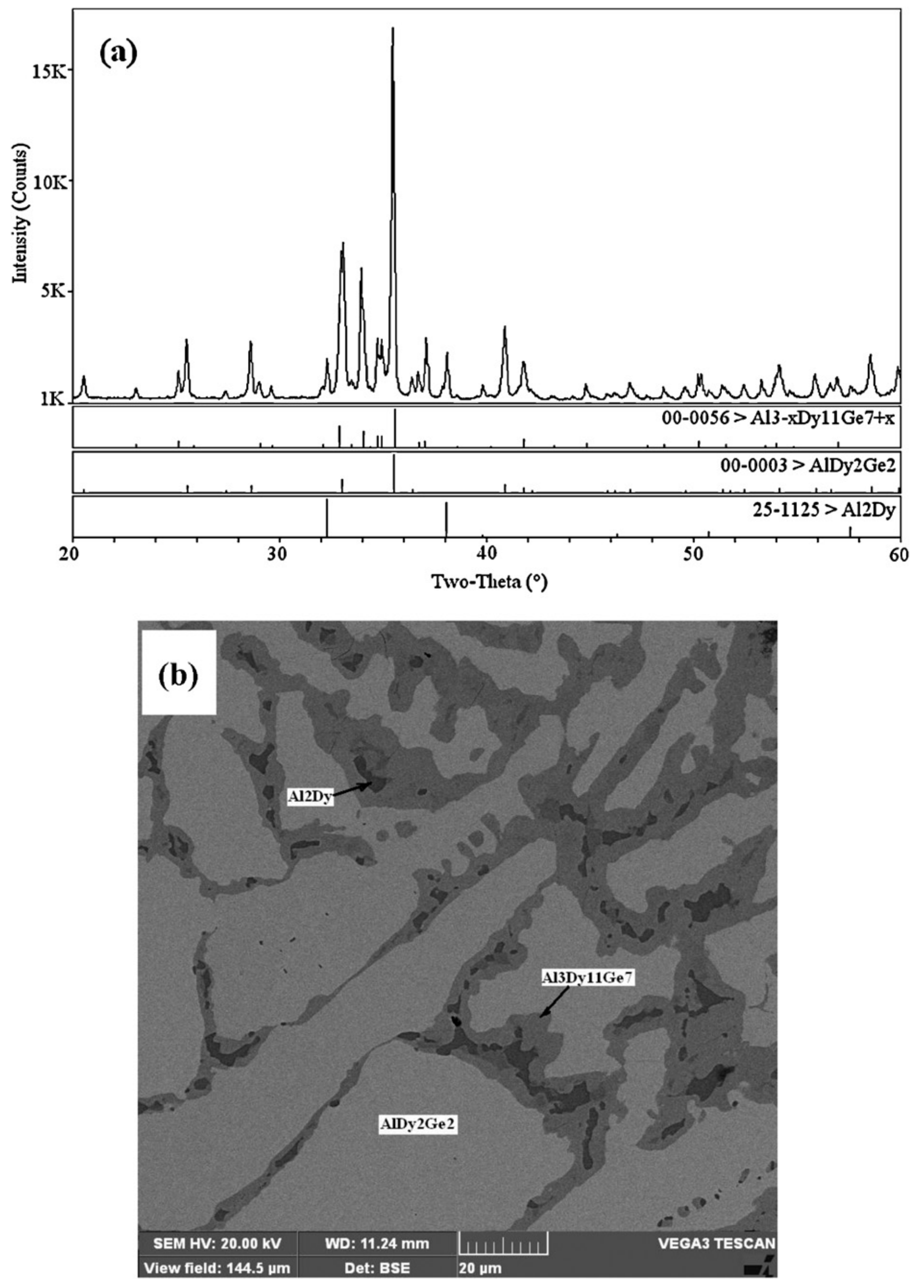

Fig. 10. XRD pattern (a) and SEM image (b) of the sample No. 42 ($Al_{20}Dy_{45}Ge_{35}$) in the three phase region of $Al_3Dy_{11}Ge_7$ + $AlDy_2Ge_2$ + Al_2Dy.

$x \leq 0.3$ contained the single phase of $Al_{3-x}DyGe_x$. It also can be seen from Fig. 12, the samples $Al_{3-x}DyGe_x$ with $x > 0.3$ consisted of a small amount second and third phases of Al_2DyGe_2 and AlDyGe. Therefore, the pseudo-binary compound $Al_{3-x}DyGe_x$ existed in the range of $x \leq 0.3$ (with maximum of 7.5 at.% Ge), which are in agreement with Ref. [17].

3.4. Isothermal section at 673 K

The isothermal section of the Al–Dy–Ge system at 673 K has been determined by comparing and analyzing the X-ray diffraction patterns of 92 binary and ternary alloys combined with the aid of the scanning electron microscopy in the present work. The isothermal section consists of 25 single-phase regions, 56 two-phase regions and 32 three-phase regions, as shown in Fig. 13. There are nine ternary compounds AlDyGe, $Al_3Dy_2Ge_4$, $AlDy_2Ge_3$, $AlDy_2Ge_2$, $Al_{0.33}DyGe_2$, $AlDy_2Ge_6$, Al_2DyGe_2, $AlDy_3Ge_3$, $Al_{3-x}Dy_{11}Ge_{7+x}$ ($x \leq 0.7$) and one pseudo-binary compound $Al_{3-x}DyGe_x$ existing in the system. The nominal composition and phase components of each sample in the isothermal section of the Al–Dy–Ge ternary system at 673 K are given in Table 2.

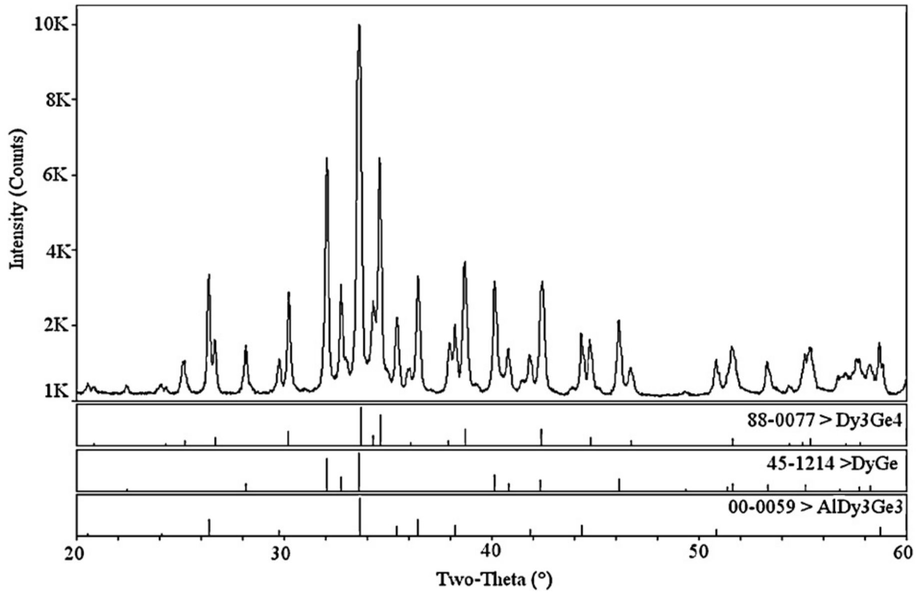

Fig. 11. XRD pattern of the sample No. 52 ($Al_8Dy_{44}Ge_{48}$) contained the three phases of Dy_3Ge_4, DyGe and $AlDy_3Ge_3$.

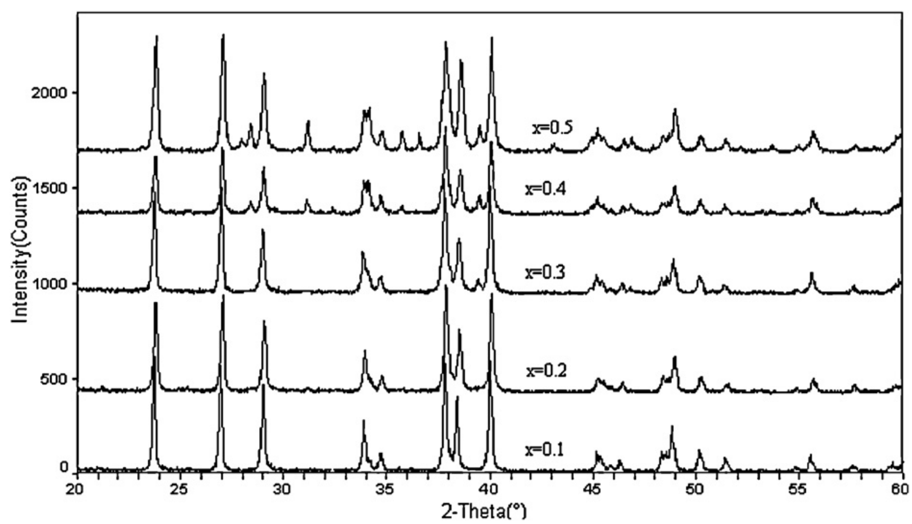

Fig. 12. XRD patterns of the compound $Al_{3-x}DyGe_x$.

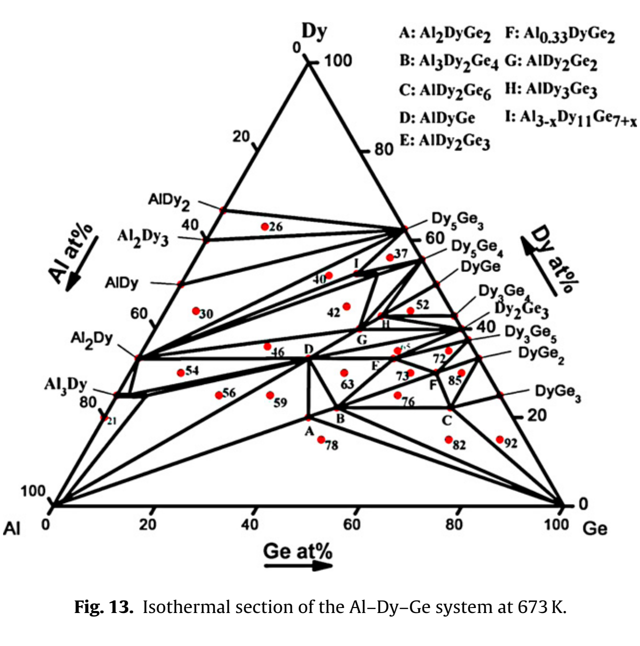

Fig. 13. Isothermal section of the Al–Dy–Ge system at 673 K.

Table 2
The nominal composition and phase components of each sample in the isothermal section of the Al–Dy–Ge ternary system at 673 K.

Sample No.	Nominal composition (at.%)			Equilibrated phase	Sample No.	Nominal composition (at.%)			Equilibrated phase
	Al	Dy	Ge			Al	Dy	Ge	
1	0	10	90	$DyGe_3 + Ge$	47	50	35	15	$Al_2Dy + AlDyGe + AlDy_2Ge_2$
2	0	20	80	$DyGe_3 + Ge$	48	23	42	35	$Al_2Dy + Al_3Dy_{11}Ge_7 + AlDy_2Ge_2$
3	0	30	70	$DyGe_3 + DyGe_2$	49	30	37	33	$AlDy_2Ge_2 + AlDyGe + Al_2Dy$
4	0	34	66	$Dy_3Ge_5 + DyGe_2$	50	16	41	43	$Dy_2Ge_3 + AlDy_2Ge_2 + AlDy_3Ge_3$
5	0	36	64	$Dy_3Ge_5 + DyGe_2$	51	10	46	44	$DyGe + AlDy_3Ge_3 + Dy_5Ge_4$
6	0	39	61	$Dy_3Ge_5 + Dy_2Ge_3$	52	8	44	48	$DyGe + AlDy_3Ge_3 + Dy_3Ge_4$
7	0	38	62	$Dy_3Ge_5 + Dy_2Ge_3$	53	12	41	47	$Dy_2Ge_3 + AlDy_2Ge_2 + AlDy_3Ge_3$
8	0	41.5	58.5	$Dy_3Ge_4 + Dy_2Ge_3$	54	60	30	10	$Al_{3-x}DyGe_x + AlDyGe + Al_2Dy$
9	0	47	53	$Dy_3Ge_4 + DyGe$	55	45	32	23	$Al_{3-x}DyGe_x + AlDyGe + Al_2Dy$
10	0	52	48	$Dy_5Ge_4 + DyGe$	56	55	25	20	$Al_{3-x}DyGe_x + AlDyGe + Al$
11	0	60	40	$Dy_5Ge_4 + Dy_5Ge_3$	57	70	20	10	$Al_{3-x}DyGe_x + AlDyGe + Al$
12	0	70	30	$Dy + Dy_5Ge_3$	58	53	27	20	$Al_{3-x}DyGe_x + AlDyGe + Al$
13	0	80	20	$Dy + Dy_5Ge_3$	59	45	25	30	$Al_2DyGe_2 + AlDyGe + Al$
14	15	85	0	$Dy + AlDy_2$	60	55	20	25	$Al_2DyGe_2 + AlDyGe + Al$
15	30	70	0	$Dy + AlDy_2$	61	35	25	40	$Al_2DyGe_2 + AlDyGe + Al_3Dy_2Ge_4$
16	35	65	0	$AlDy_2 + Al_2Dy_3$	62	35	28	37	$Al_2DyGe_2 + AlDyGe + Al_3Dy_2Ge_4$
17	45	55	0	$AlDy + Al_2Dy_3$	63	28	30	42	$AlDy_2Ge_3 + AlDyGe + Al_3Dy_2Ge_4$
18	60	40	0	$AlDy + Al_2Dy$	64	23	32	45	$AlDy_2Ge_3 + AlDyGe + Al_3Dy_2Ge_4$
19	70	30	0	$\alpha Al_3Dy + Al_2Dy$	65	15	35	50	$AlDy_2Ge_3 + AlDyGe + Dy_2Ge_3$
20	78	22	0	$\alpha Al_3Dy + Al$	66	20	35	45	$AlDy_2Ge_3 + AlDyGe + Dy_2Ge_3$
21	80	20	0	$\alpha Al_3Dy + Al$	67	23	37	40	$AlDy_2Ge_2 + AlDyGe + Dy_2Ge_3$
22	90	10	0	$\alpha Al_3Dy + Al$	68	26	36	38	$AlDy_2Ge_2 + AlDyGe + Dy_2Ge_3$
23	10	80	10	$Dy_5Ge_3 + AlDy_2 + Dy$	69	9	39	52	$AlDy_2Ge_2 + AlDyGe + Dy_2Ge_3$
24	15	70	15	$Dy_5Ge_3 + AlDy_2 + Dy$	70	10	33	57	$AlDy_2Ge_3 + Dy_3Ge_5 + Al_{0.33}DyGe_2$
25	20	75	5	$Dy_5Ge_3 + AlDy_2 + Dy$	71	13	33	54	$AlDy_2Ge_3 + Dy_3Ge_5 + Al_{0.33}DyGe_2$
26	27	63	10	$Dy_5Ge_3 + AlDy_2 + Al_2Dy_3$	72	5	35	60	$AlDy_2Ge_3 + Dy_3Ge_5 + Al_{0.33}DyGe_2$
27	15	63	22	$Dy_5Ge_3 + AlDy_2 + Al_2Dy_3$	73	15	30	55	$AlDy_2Ge_3 + Al_3Dy_2Ge_4 + Al_{0.33}DyGe_2$
28	20	60	20	$Dy_5Ge_3 + AlDy + Al_2Dy_3$	74	20	30	50	$AlDy_2Ge_3 + Al_3Dy_2Ge_4 + Al_{0.33}DyGe_2$
29	35	55	10	$Dy_5Ge_3 + AlDy + Al_2Dy_3$	75	15	25	60	$AlDy_2Ge_6 + Al_3Dy_2Ge_4 + Al_{0.33}DyGe_2$
30	50	44	6	$Dy_5Ge_3 + AlDy + Al_2Dy$	76	20	25	55	$AlDy_2Ge_6 + Al_3Dy_2Ge_4 + Al_{0.33}DyGe_2$
31	45	45	10	$Dy_5Ge_3 + AlDy + Al_2Dy$	77	50	10	40	$Al_2DyGe_2 + Ge + Al$
32	25	55	20	$Dy_5Ge_3 + AlDy + Al_2Dy$	78	40	15	45	$Al_2DyGe_2 + Ge + Al$
33	25	50	25	$Dy_5Ge_3 + Al_2Dy + Al_3Dy_{11}Ge_7$	79	35	5	60	$Al_2DyGe_2 + Ge + Al$
34	15	55	30	$Dy_5Ge_3 + Al_2Dy + Al_3Dy_{11}Ge_7$	80	35	20	45	$Al_2DyGe_2 + Ge + Al_3Dy_2Ge_4$
35	19	52	29	$Dy_5Ge_3 + Al_2Dy + Al_3Dy_{11}Ge_7$	81	25	15	60	$Al_2DyGe_2 + Ge + Al_3Dy_2Ge_4$
36	14	53	33	$Dy_5Ge_3 + Al_2Dy + Al_3Dy_{11}Ge_7$	82	15	15	70	$AlDy_2Ge_6 + Ge + Al_3Dy_2Ge_4$
37	6	56	38	$Dy_5Ge_3 + Al_3Dy_{11}Ge_7 + Dy_5Ge_4$	83	20	20	60	$AlDy_2Ge_6 + Ge + Al_3Dy_2Ge_4$
38	3	58	39	$Dy_5Ge_3 + Al_3Dy_{11}Ge_7 + Dy_5Ge_4$	84	10	10	80	$AlDy_2Ge_6 + Ge + Al_3Dy_2Ge_4$
39	9	50	41	$Al_3Dy_{11}Ge_7 + AlDy_2Ge_2 + Dy_5Ge_4$	85	5	30	65	$AlDy_2Ge_6 + DyGe_2 + Al_{0.33}DyGe_2$
40	20	52	28	$Al_2Dy + Al_3Dy_{11}Ge_7 + Dy_5Ge_3$	86	10	25	65	$AlDy_2Ge_6 + DyGe_2 + Al_{0.33}DyGe_2$
41	25	45	30	$Al_2Dy + Al_3Dy_{11}Ge_7 + AlDy_2Ge_2$	87	6	32	62	$Dy_3Ge_5 + DyGe_2 + Al_{0.33}DyGe_2$
42	20	45	35	$Al_2Dy + Al_3Dy_{11}Ge_7 + AlDy_2Ge_2$	88	3	34	63	$Dy_3Ge_5 + DyGe_2 + Al_{0.33}DyGe_2$
43	30	44	26	$Al_2Dy + Al_3Dy_{11}Ge_7 + AlDy_2Ge_2$	89	5	27	68	$AlDy_2Ge_6 + DyGe_2 + DyGe_3$
44	16	47	37	$Al_2Dy + Al_3Dy_{11}Ge_7 + AlDy_2Ge_2$	90	5	25	70	$AlDy_2Ge_6 + DyGe_2 + DyGe_3$
45	10	49	41	$Dy_5Ge_4 + Al_3Dy_{11}Ge_7 + AlDy_2Ge_2$	91	5	20	75	$AlDy_2Ge_6 + Ge + DyGe_3$
46	40	36	24	$Al_2Dy + AlDyGe + AlDy_2Ge_2$	92	5	15	80	$AlDy_2Ge_6 + Ge + DyGe_3$

4. Conclusions

The isothermal section of the Al–Dy–Ge system at 673 K has been determined by comparing and analyzing the X-ray diffraction patterns of 92 binary and ternary alloys combined with the aid of the scanning electron microscopy in the present work. The isothermal section consists of 25 single-phase regions, 56 two-phase regions and 32 three-phase regions, as shown in Fig. 13. There are nine ternary compounds AlDyGe, $Al_3Dy_2Ge_4$, $AlDy_2Ge_3$, $AlDy_2Ge_2$, $Al_{0.33}DyGe_2$, $AlDy_2Ge_6$, Al_2DyGe_2, $AlDy_3Ge_3$, $Al_{3-x}Dy_{11}Ge_{7+x}$ ($x \leq 0.7$) and one pseudo-binary compound $Al_{3-x}DyGe_x$ existing in the system. The nominal composition and phase components of each sample in the isothermal section of the Al–Dy–Ge ternary system at 673 K are given in Table 2.

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