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### The Yb-Zn-In system at 400 °C: Partial isothermal section with 0-33.3 at.% Yb

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### ABSTRACT

The phase relations in the ternary system Yb–Zn–In have been established for the partial isothermal section in the 0–33.3 at.% ytterbium concentration range at 400 °C, by researching of more than forty alloys. X-ray powder diffraction (XRPD), optical microscopy (OM) and scanning electron microscopy (SEM), complemented with energy dispersive X-ray spectroscopy (EDS), were used to study the microstructures, identify the phases and characterize their crystal structures and compositions. The phase equilibria of this Yb–Zn–In partial section at 400 °C are characterized by the presence of three extended homogeneity ranges, indium solubility in Yb<sub>13</sub>Zn<sub>58</sub> and YbZn<sub>2</sub> and of zinc solubility in Ybln<sub>2</sub>, and the existence of one ternary intermetallic compound, YbZn<sub>1–x</sub>In<sub>1+x</sub>, x = ~0.3. This new compound crystallizes in the UHg<sub>2</sub> structure type (space group *P6/mmm*), with a = 4.7933(5)Å, c = 3.6954(5)Å. The studied partial isothermal section has eight ternary phase fields at 400 °C.

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### 1. Introduction

The introduction of new technologies requires the improvement of traditional and synthesis of new materials with specified properties. Promising sources of new materials are intermetallic compounds and alloys. The stock of experimental data on the conditions of their formation, structure and properties can provide expanded databases that will allow not only more accurate predict, but also produce materials for modern technology with pre-defined physical and chemical properties. The main method for finding and studying the conditions of the formation of compounds remains the construction of state diagrams, which reflect the phase composition of the alloys and the nature of the interaction among the components in the metallic systems. In this case, rare-earth based intermetallic compounds are both scientifically and technologically important, and their crystal and physical properties have been being widely studied so far.

Ternary rare-earth transitional metals indides have been extensively examined due to their diverse structure and properties [1]. However, the R–Zn–In systems have not been studied systematically; only the existence of a certain number of isostructural ternary compounds of the discussed systems were reported [2]. Among these compounds of specific interest are those containing Ce, Eu, or Yb, which, in addition to interesting crystal structures, they can exhibit unusual physical properties (like heavy fermion behaviour, Kondo effect, mixed valency, etc.).

The Yb–Zn–In ternary system was up to now very poorly explored: only one compound, YbZnIn, is reported in the literature [3,4]. The purpose of the present work was to build the partial isothermal section of the Yb–Zn–In system in the 0–33.3 at.% ytterbium concentration range at 400 °C, to identify the existing compounds and to determine their crystal structures.

### 2. Literature data

A brief summary of the literature data focusing on phase equilibria of the binary Yb–Zn–In subsystems is presented in the following. A list of the solid phases formed in the three binary systems involved is given in Table 1.

The Yb–Zn phase diagram has been established by Mason and Chiotti [5]. Six binary compounds exist in this system: YbZn (CsCl-type), YbZn<sub>2</sub> (CeCu<sub>2</sub>-type), Yb<sub>3</sub>Zn<sub>11</sub> (La<sub>3</sub>Al<sub>11</sub>-type), Yb<sub>13</sub>Zn<sub>58</sub> (Gd<sub>13</sub>Zn<sub>58</sub>-type), Yb<sub>2</sub>Zn<sub>17</sub> (Th<sub>2</sub>Zn<sub>17</sub>-type) and YbZn<sub>11</sub> (BaCd<sub>11</sub>-type). Five of them, YbZn, YbZn<sub>2</sub>, Yb<sub>13</sub>Zn<sub>58</sub>, Yb<sub>2</sub>Zn<sub>17</sub> and YbZn<sub>11</sub> melt congruently at 650, 751, 752, 754 and 755 °C, respectively. The Yb<sub>3</sub>Zn<sub>11</sub> is obtained by the peritectic reaction L+Yb<sub>13</sub>Zn<sub>58</sub> = Yb<sub>3</sub>Zn<sub>11</sub> at 695 °C. The YbZn<sub>2</sub> and Yb<sub>2</sub>Zn<sub>17</sub>, according to [5,6], have two polymorphic modification (of unknown-type and Th<sub>2</sub>Ni<sub>17</sub>-type, respectively). Also, authors [6] pointed out the existence of the Yb<sub>3</sub>Zn<sub>17</sub> (Ru<sub>3</sub>Be<sub>17</sub>-type) and YbZn<sub>13</sub> (NaZn<sub>13</sub>-type) intermetallics.

The phase diagram of binary Yb–In system has been determined in [7]. The existence of five compounds has been established: YbIn<sub>3</sub> (AuCu<sub>3</sub>-type), YbIn<sub>2</sub> (CaIn<sub>2</sub>-type), YbIn (CsCl-type), Yb<sub>2</sub>In (Co<sub>2</sub>Si-type) and Yb<sub>8</sub>In<sub>3</sub> (Yb<sub>8</sub>In<sub>3</sub>-type). Three compounds, namely, Yb<sub>5</sub>In<sub>2</sub>,

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### Table 1

Literature data on binary and ternary phases of the Yb-Zn-In system.

Phase	Transformation	ormation Structure type Space group		Lattice parameters (Å)			Reference
	Temperature (°C) <sup>a</sup>			a	b	с	
YbZn	650, mp	CsCl	Pm3m	3.629	-	-	[5]
YbZn <sub>2</sub> ( $\alpha$ )	751, mp	-	-	-	-	-	[5]
$YbZn_2(\beta)$	630, pc	CeCu <sub>2</sub>	Imma	4.570	7.290	7.562	[5]
Yb <sub>3</sub> Zn <sub>11</sub>	695, p	La <sub>3</sub> Al <sub>11</sub>	Immm	4.421	8.891	13.127	[5]
Yb <sub>13</sub> Zn <sub>58</sub>	752, mp	Gd <sub>13</sub> Zn <sub>58</sub>	P6 <sub>3</sub> mc	14.32	-	14.15	[6]
Yb <sub>3</sub> Zn <sub>17</sub>	?	Ru <sub>3</sub> Be <sub>17</sub>	Im3	14.291	-	-	[6]
$Yb_2Zn_{17}(\alpha)$	754, mp	Th <sub>2</sub> Ni <sub>17</sub>	P6 <sub>3</sub> /mmc	9.022	-	8.798	[2]
$Yb_2Zn_{17}(\beta)$	?	Th <sub>2</sub> Zn <sub>17</sub>	R3m	9.040	-	13.216	[5]
YbZn <sub>11</sub>	755, mp	BaCd <sub>11</sub>	I41/amd	10.637	-	6.822	[5]
YbZn <sub>13</sub>	?	NaZn <sub>13</sub>	Fm3c	12.172	-	-	[2]
YbIn₃	810, p	AuCu <sub>3</sub>	Pm3m	4.6146	-	-	[2]
YbIn <sub>2</sub>	820, p	CaIn <sub>2</sub>	P6 <sub>3</sub> /mmc	4.8908	-	7.6406	[7]
YbIn	1067, mp	CsCl	Pm3m	3.8076	-	-	[7]
$Yb_2 In(\alpha)$	890, mp	-	-	-	-	-	[7]
$Yb_2 In(\beta)$	675, pc	Co <sub>2</sub> Si	Pnma	7.072	5.340	9.866	[7]
Yb <sub>8</sub> In <sub>3</sub> <sup>b</sup>	630, p	Yb <sub>8</sub> In <sub>3</sub>	RĴc	9.47	-	54.05	[7]
YbZnIn	?	CaIn <sub>2</sub>	P6 <sub>3</sub> /mmc	4.725	-	7.382	[3]
YbZnIn	?	CeCu <sub>2</sub>	Imma	4.734	7.370	8.191	[4]

<sup>a</sup> mp = melting point, p = peritectic reaction; pc = polymorphic reaction.

<sup>b</sup> Identical to so-called Yb<sub>5</sub>In<sub>2</sub>.

Yb<sub>2</sub>In and YbIn<sub>3</sub> form peritectically at 810, 820 and 630 °C, respectively. However, the YbIn<sub>2</sub> and YbIn melt congruently at 890 and 1067 °C. Additionally, polymorphic transformation for the Yb<sub>2</sub>In compound has been found at 675 °C (unknown-type).

Generalized In–Zn phase diagram based on experimental data and thermodynamic calculation is presented in paper [8]. There are no binary compounds in the In–Zn system. Only one eutectic reaction, with the 3.8Zn:96.2In composition, is observed in the In–Zn system at 143.5 °C.

Up to the authors' best knowledge, there is no data in the literature on the interaction of the components in the Yb–Zn–In system. Only one compound, YbZnIn [3], has been described up to now on this system. YbZnIn was first reported to crystallize in the CaIn<sub>2</sub> type structure [3], but later studies indicate that this compound crystallizes in the CeCu<sub>2</sub> type [4]. No information on the melting characteristics of this compound was given.

#### 3. Experimental details

A total number of forty-two binary and ternary samples have been prepared and analysed in the present work, and their compositions are shown in Fig. 1. The starting materials for the preparation of the Yb–Zn–In alloys were ingots of ytterbium and zinc, and indium tear drops, all with stated purities better than 99.95 wt.%. The samples were prepared by directly melting the elements inside quartz ampoules under vacuum ( $10^{-5}$  Torr). The ampoules were heated up to 900 °C and hold at that temperature for 1 h. After that period they were cooled in air and further under running water. Obtained products with metallic-like lustres were removed from the ampoules and analysed by X-ray powder diffraction technique (XRPD). No reaction with the quartz was observed. Finally, fragments of the as-prepared ingots were wrapped in tantalum foil and sealed in evacuated quartz tubes. The annealing procedure has been carried out in a vertical oven at 400 °C during 25 days. After the heat treatments, the samples were quenched by submerging the quartz tubes in cold





water. Special care was taken with the samples manipulation (work inside silicon oil) due to their susceptibility to oxidation in contact with air.

For the X-ray phase and structural analyses polycrystalline products were crushed, powdered with agate mortar and examined using a Panalytical X'Pert Pro diffractometer (Cu K $\alpha$ -radiation). The scans were taken in the  $\theta/2\theta$  mode with the following parameters:  $2\theta$  region 15–120°, step scan 0.03°, counting time per step 5–20 s. Theoretical powder patterns were calculated with the help of the Powder-Cell program [9] and used for the identification of the phases. The lattice parameters were obtained by least-squares fitting, using the Latcon program [10]. Rietveld refinements of X-ray diffraction data were performed using the FullProf program [11].

The microstructure of the samples was first studied, on polished and etched surfaces, by using an optical microscope Olympus OM150. Selected samples were then observed by electron microscopy, by using a Hitachi S2400 scanning electron microscope operated at 25 kV. The composition of the phases was analysed by semi-quantitative energy dispersive X-ray spectroscopy (EDS) using a Röntec detector with a protective beryllium window. At least three valid EDS points were measured for each phase in order to guarantee a good analysis of their compositions. These measurements were carried out with a spatial resolution of ~2  $\mu$ m and a collection time of 100 s. Automated matrix corrections were carried out using the Röntec Edwin EDS software package.

### 4. Results and discussion

Samples from the indium-rich region usually contain the binary YbIn<sub>3</sub> and YbIn<sub>2</sub> compounds, in agreement with the literature data, which indicate that these two binary intermetallics are stable at 400 °C. The existence of other five binary phases from the Yb–Zn system (YbZn<sub>11</sub>, Yb<sub>2</sub>Zn<sub>17</sub>, Yb<sub>13</sub>Zn<sub>58</sub>, Yb<sub>3</sub>Zn<sub>11</sub> and YbZn<sub>2</sub>), previously reported to be stable at that temperature, were also confirmed, their crystallographic analysis agreeing with the reported data. The two previously described YbZn<sub>13</sub> and Yb<sub>3</sub>Zn<sub>17</sub> compounds were not detected in the present work, which indicates that they are not stable at 400° C.

The binary Yb<sub>13</sub>Zn<sub>58</sub> compound dissolves about 7 at.% indium in annealed samples and up to 15 at.% indium in as-prepared alloys. The evolution of the lattice parameters and volume of this hexagonal phase (as-prepared samples) versus indium content is presented in Fig. 2. An almost linear increase of the lattice parameters can be observed when increasing the indium content, in agreement with the bigger atomic dimensions of indium with respect to zinc (the atomic radii of zinc and indium are equal 1.39 and 1.66, respectively [12]). Negligible indium solubility is observed in the YbZn<sub>11</sub>, Yb<sub>2</sub>Zn<sub>17</sub> and Yb<sub>3</sub>Zn<sub>11</sub> compounds.

According to the X-ray phase analysis of the 18Yb:72Zn:10In alloy (Fig. 3a), it consists of three phases, namely,  $Yb_{13}Zn_{58-x}In_x$ 

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**Fig. 2.** Lattice parameters of as-prepared  $Yb_{13}Zn_{58-x}In_x$  as a function of the Incontent.

(main phase), Yb<sub>2</sub>Zn<sub>17</sub> and YbZn<sub>x</sub>In<sub>2-x</sub>. The microstructure of this alloy (Fig. 3b) agrees with the X-ray diffraction data, showing a major phase and small grained secondary phases. The composition of the majority grey phase, found by SEM/EDX analysis, is Yb<sub>18</sub>Zn<sub>76</sub>In<sub>6</sub> (Yb<sub>13</sub>Zn<sub>53.7</sub>In<sub>4.3</sub>), in agreement with the X-ray diffraction results. Some secondary phases with different dark–grey colour are also displayed in the microstructure too, which probably correspond to the Yb<sub>2</sub>Zn<sub>17</sub> and YbZn<sub>x</sub>In<sub>2-x</sub> compounds. However, it was not possible to check their compositions by EDS due to the small grain size.

Fig. 4a and b shows the X-ray diffraction pattern and microstructure of the 30Yb:65Zn:5In alloy, respectively. The microstructure consists of two different types of regions, dark dendrites and a grey eutectic. X-ray diffraction results indicate the presence of  $YbZn_{2-x}In_x$  and  $Yb_3Zn_{11}$ . In accordance with the binary Yb–Zn phase diagram, the first one should crystallize as dendrites,  $Yb_3Zn_{11}$  mainly existing in the eutectic region. SEM/EDS results are in agreement with the X-ray diffraction data, the normalized average compositions for dark and grey phases being equal to  $Yb_{33.3}Zn_{64.1}In_{2.6}$  (YbZn<sub>1.92</sub>In<sub>0.08</sub>) and Yb<sub>21.4</sub>Zn<sub>77.5</sub>In<sub>1.1</sub> (Yb<sub>3</sub>Zn<sub>10.86</sub>In<sub>0.15</sub>), respectively.

In order to study the solid solution ranges of the ternary  $Yb(Zn,In)_2$  phases, ten Yb-Zn-In alloy samples with 33.3 at.% ytterbium and different Zn:In ratios have been examined. The  $YbZn_2-YbIn_2$  section shows an extended homogeneity range for the binary  $YbZn_2$  compound, dissolving up to 40 at.% indium. Therefore, the reported YbZnIn (i.e.  $Yb_{33,3}Zn_{33,3}In_{33,3}$ ) is not an individual compound, but it is a part of this solid solution





**Fig. 3.** X-ray diffraction pattern (a) and microstructure  $(500 \times)(b)$  of the annealed Yb<sub>18</sub>Zn<sub>72</sub>In<sub>10</sub> alloy.



Fig. 4. X-ray diffraction pattern (a) and microstructure (b) of the annealed  $Yb_{30}Zn_{65}In_5$  alloy.

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Fig. 5. X-ray diffraction pattern of the annealed  $Yb_{33}Zn_{27}In_{40}$  alloy.

(YbZn<sub>2-x</sub>In<sub>x</sub>, x = 0 - 1.2). This can be critical for the physical properties characterization of the compounds, as materials belonging to the homogeneity range but with different compositions can present different physical behaviours. The X-ray diffraction pattern of the 33Yb:27Zn:40In alloy is plotted in Fig. 5. This phase is almost monophasic, the X-ray diffraction data indicate a main CeCu<sub>2</sub>-type phase and small peaks belonging to Yb<sub>2</sub>O<sub>3</sub> and In. Microscopic observations are in agreement with the X-ray diffraction data, showing a major granular compound surrounded by minor amounts of an intergranular phase. SEM/EDS analysis made on the same sample confirmed the composition of the main phase. which is closed to the 1Yb:1Zn:1In, and revealed the composition of the secondary phase, which corresponds to the  $Yb_{13}Zn_{58-x}In_x$ compound. The composition change of the as-prepared  $YbZn_{2-x}In_x$ (0 < x < 1.2) lattice parameters are plotted in Fig. 6. Substituting the smaller Zn atoms by the larger In atoms in the binary YbZn<sub>2</sub> compound leads, as expected, to an increase of the cell dimensions.

In order to investigate crystal structure of this  $YbZn_{2-x}In_x$  extended homogeneity range, structure refinement using the Rietveld method was made for the  $Yb_{33,3}Zn_{58,7}In_8$  alloy. Details of data refinement, atomic coordinates and interatomic distances are given in Tables 2 and 3. Atoms of ytterbium occupy the positions of cerium atoms, while zinc and indium atoms are statistically distributed over the positions of copper in the structure of CeCu<sub>2</sub>. The

#### Table 2

Crystallographic data, details of experimental conditions and structure refinement for the phase  $YbZn_{2-x}In_x$  (x = 0.24).

Phase	YbZn <sub>1.76</sub> In <sub>0.24</sub>
Structure type	CeCu <sub>2</sub>
Space group	Imma (No. 74)
Pearson symbol, Z	ol12, 4
Lattice parameters (Å)	
а	4.5946(3)
Ь	7.3254(5)
с	7.7859(6)
V (Å <sup>3</sup> )	262.05(3)
Diffractometer	Panalytical X'Pert Pro
$2\theta$ (°), step, time (s)	15–120, 0.03, 15
R <sub>B</sub>	8.93
Rp	10.0
$\chi^2$	3.33
Atom	Site
Yb	4e(0, 1/4, z) = 0.5489(4)
М	8h(0, y, z) y = 0.0535(5), z = 0.1672(5)
Overall B (Å <sup>2</sup> )	1.08(7)
Composition of M	0.88Zn+0.12In



Fig. 6. Lattice parameters from various as-prepared alloys  $YbZn_{2-x}In_x$  versus In content.

M (zinc and indium) atoms form three dimensional networks in form of jointed slightly distorted hexagons (Fig. 7.). Intralayer M–M bonds (2.634 and 2.719 Å) are shortest in comparison with interlayer M–M distances (2.879 Å). The ytterbium atoms form a zig-zag chain along Y axis. The shortest Yb–Yb distances are equal to 3.741 and 3.884 Å and close to the Yb–Yb bonds (3.86 Å) in pure metal [12]. The shortest Yb–M touches range from 3.135 to 3.327 Å.

In the YbIn<sub>2</sub> extreme composition (crystallizing in the Caln<sub>2</sub>type structure) zinc also substitutes indium, but its solubility range is much smaller, extending only up to the  $\sim$ YbZn<sub>0.3</sub>In<sub>1.7</sub> composi-

#### Table 3

Interatomic distances in the structure of  $YbZn_{2-x}In_x$  (x = 0.24).

Atoms		d (Å)	Atoms		d (Å)
Yb	-2M -4M -2M -4M -2Yb -2Yb	3.135(4) 3.191(3) 3.302(5) 3.327(3) 3.741(1) 3.884(4)	М	-2M -M -Yb -2Yb -2Yb -2Yb	2.634(3) 2.719(5) 2.879(5) 3.135(4) 3.191(3) 3.302(5) 3.327(3)

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**Fig. 7.** Unit cell (dotted line) and three dimensional networks (bold line) in the structure of  $YbZn_{2-x}In_x$  (x = 0.24). Ytterbium atoms and mixture of Zn and In atoms marked by blue and cyan circles, respectively.



Fig. 8. X-ray diffraction pattern of the annealed Yb<sub>33</sub>Zn<sub>24</sub>In<sub>43</sub> alloy.

tion. The lattice parameters for  $YbZn_xIn_{2-x}$  with x = 0.24 are given in Table 2. The  $YbIn_3$  compound was found to be formed with a non-existing, or negligible, homogeneity range.

One new ternary phase,  $YbZn_{1-x}In_{1+x}$ , with a small homogeneity range around the x=0.3 composition, was identified in the Yb–Zn–In system. The comparison between the experimental and simulated patterns indicates that this phase crystallizes in the UHg<sub>2</sub> structure type (Fig. 8). Herein, we present only the lattice parameters of this compound (see Table 2). Its crystal structure determination and physical properties will be published in a further paper.

The crystallographic data on the new ternary Yb–Zn–In phases are collected in Table 4.

The isothermal section at 400 °C of the Yb–Zn–In phase diagram (0–33.3 at.% ytterbium), constructed by using the experimental results obtained from the X-ray powder diffraction experiments, is shown in Fig. 9. In this partial isothermal section eight ternary phase fields have been identified, those are listed below in order of increasing of ytterbium contents:

$L + Zn + YbZn_{11},$	(1

 $L + YbIn_3 + YbZn_{11}, (2)$ 



**Fig. 9.** Isothermal section of the ternary Yb–Zn–In phase diagram at 400  $^{\circ}$ C with 0–33.3 at.% Yb (ternary phase fields are indicated by numbers).

$YnZn_{11} + YbIn_3 + YbIn_2,$	(3)
$YbZn_{11} + Yb_2Zn_{17} + YbZn_xIn_{2-x},$	(4)
$Yb_2Zn_{17} + Yb_{13}Zn_{58-x}In_x + YbZn_xIn_{2-x},$	(5)
$Yb_{13}Zn_{58-x}In_x + YbZn_xIn_{2-x} + YbZn_{1-x}In_{1+x},$	(6)

 $Yb_{13}Zn_{58-x}In_{x} + YbZn_{1-x}In_{1+x} + YbZn_{2-x}In_{x},$ (7)

$$Yb_{13}Zn_{58-x}In_{x} + Yb_{3}Zn_{11} + YbZn_{2-x}In_{x}$$
(8)

A direct comparison of the Yb–Zn–In ternary system isothermal section at 400 °C with other related systems (like Yb-d-metals-In) is difficult, because only a limited number of isostructural ternary compounds on the discussed systems were reported. In the rare earth - zinc - indium systems 10 ternary compounds with equiatomic composition, crystallizing with CaIn2 or CeCu2 structure types, have been studied [3,4,15]. Our results indicate that most probably these RZnIn intermetallics are part of a solid solution based on the binary  $RZn_2$  (R=Ce-Lu) or  $RIn_2$  (R=Eu, Yb) compounds, which structures belong to the CeCu<sub>2</sub> and CaIn<sub>2</sub> types, respectively. Concerning other Yb-d-metals-In systems, most attention was devoted so far to the Yb-Cu-In phase diagram: its isothermal section was investigated in the whole concentration region, at 400 °C, and five ternary indides were reported: YbCu<sub>5.1</sub>In<sub>6.9</sub> (ThMn<sub>12</sub>-type), YbCu<sub>4.0-4.8</sub>In<sub>1.0-0.2</sub> (MgCu<sub>4</sub>Sn-type), Yb<sub>2</sub>Cu<sub>2</sub>In (with two reported structures, W<sub>2</sub>CoB<sub>2</sub>-type and Mo<sub>2</sub>FeB<sub>2</sub>-type); and Yb<sub>3</sub>CuIn<sub>2</sub> and Yb<sub>4</sub>CuIn, both with unknown structures [1]. It is interesting to notice that only one homogeneity range (YbCu<sub>4.0-4.8</sub>In<sub>1.0-0.2</sub>) was reported for this system. In general, 28 intermetallics were identified in the ytterbium-d-metal-indium systems. All the above mentioned compounds belong to seventeen structure types: Ho<sub>2</sub>CoGa<sub>8</sub>, HoCoGa<sub>5</sub>, Yb<sub>2</sub>Pd<sub>6</sub>In<sub>13</sub>, YNiAl<sub>4</sub>, LaCoAl<sub>4</sub>, MgCuAl<sub>2</sub>, YbAg<sub>2</sub>In<sub>4</sub>, ThMn<sub>12</sub>, CaIn<sub>2</sub>, CeCu<sub>2</sub>, UHg<sub>2</sub>, TiNiSi, ZrNiAl, Mo<sub>2</sub>FeB<sub>2</sub>, W<sub>2</sub>CoB<sub>2</sub>, MnCu<sub>2</sub>Al and MgCu<sub>4</sub>Sn [1,2,13,14].

Looking to the related systems with gallium and aluminium, in the Yb–Zn–Ga system just the lattice parameters and homogeneity range for the ternary YbZn<sub>x</sub>Ga<sub>4-x</sub> (x=0.25–1) intermetallics, with BaAl<sub>4</sub>-type structure, have been determined [16]; the Yb–Zn–Al was the most explored system, showing a large number of ternary phases: YbZnAl (MgNi<sub>2</sub>-type) [17], Yb<sub>8</sub>Zn<sub>41.4–48.5</sub>Al<sub>24.6–17.5</sub> (Yb<sub>8</sub>Cu<sub>17</sub>Al<sub>49</sub>-type) [17–19], YbZn<sub>1.65</sub>Al<sub>2.35</sub> (BaAl<sub>4</sub>-type) [20], Yb<sub>3.36</sub>Zn<sub>30.94</sub>Al<sub>4.34</sub> (own type, derived from the SmZn<sub>11</sub>-type) [21], Yb<sub>6.4</sub>Zn<sub>46.8</sub>Al<sub>3.4</sub> (own type) [21], Yb<sub>12.4</sub>Zn<sub>96.8</sub>Al<sub>4.4</sub> (own type, derived from the U<sub>2</sub>Zn<sub>17</sub>-type) [21], Yb<sub>3</sub>Zn<sub>17.7</sub>Al<sub>4.3</sub> (Ce<sub>3</sub>Zn<sub>22</sub>-type) [21]. Six homogeneity ranges, based on binary compounds from the Yb–Zn and Yb–Al systems, were also reported in the Yb–Zn–Al system [17]. However, a complete investigation of the interaction among the components in the Yb–Zn–Al system is still missing.

The studied Yb–M–In and Yb–Zn–X systems are rich in variety of the compositions and crystal structures of the ternary compounds. In the case of the partial Yb–Zn–In (0–33.3 at.% Yb) ternary phase diagram at 400 °C, and albeit the small solubility observed in the binary systems, large homogeneity ranges are also observed. All these points to the possibility of existence of new compounds and extended homogeneity ranges, based on the partial substitution of

5

### 6

 Table 4

 New ternary phases in the Yb-Zn-In systems.

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Phase	Structure type	Space group	Lattice parameters (Å)			Remark
			a	b	С	
$Yb_{13}Zn_{58-x}In_x$	Gd <sub>13</sub> Zn <sub>58</sub>	P6 <sub>3</sub> /mmc	14.317(2)	-	14.173(3)	$\chi = 0^{a}$
			14.421(3)	-	14.254(3)	$x = 2.86^{a}$
			14.510(3)	-	14.318(4)	$x = 5.68^{a}$
			14.545(5)	-	14.341(6)	$x = 7.10^{a}$
			14.591(3)	-	14.386(4)	$x = 9.94^{a}$
YbZn <sub>2-x</sub> In <sub>x</sub>	CeCu <sub>2</sub>	Imma	4.5668(8)	7.2866(11)	7.5643(12)	$x = 0^a$
			4.5892(10)	7.3153(14)	7.7074(16)	$x = 0.15^{a}$
			4.5946(3)	7.3254(5)	7.7859(6)	$x = 0.24^{a}$
			4.6037(7)	7.3271(10)	7.8172(12)	$x = 0.3^{a}$
			4.6174(11)	7.3385(16)	7.9131(19)	$x = 0.42^{a}$
			4.6614(8)	7.3507(12)	7.9982(15)	$x = 0.6^{a}$
			4.6801(13)	7.3591(17)	8.0437(21)	$x = 0.68^{a}$
			4.6993(14)	7.3643(19)	8.0731(24)	$x = 0.8^{a}$
			4.7553(14)	7.3859(18)	8.1769(21)	$x = 1^{a}$
			4.7827(9)	7.3953(12)	8.2254(14)	$x = 1.1^{a}$
			4.7808(8)	7.3998(8)	8.2590(14)	$x = 1.2^{a}$
			4.6002(4)	7.3359(6)	7.8334(6)	$x = 0.3^{b}$
			4.6294(9)	7.3445(13)	7.9453(15)	$x = 0.42^{b}$
			4.6548(12)	7.3516(16)	8.0195(21)	$x = 0.56^{b}$
			4.6750(6)	7.3559(8)	8.0744(9)	$x = 0.68^{b}$
			4.6873(6)	7.3664(8)	8.1119(14)	$x = 0.8^{b}$
			4.7989(10)	7.4017(14)	8.2595(16)	$x = 1^{b}$
			4.7927(10)	7.4035(9)	8.2757(15)	$x = 1.2^{b}$
$YbZn_{1-x}In_{1+x}$	UHg <sub>2</sub>	P6 <sub>3</sub> /mmm	4.7898(4)	-	3.6988(4)	$x = 0.3^{a}$
			4.7933(5)	-	3.6954(5)	$x = 0.3^{b}$
YbZn <sub>x</sub> In <sub>2-x</sub>	CaIn <sub>2</sub>	P6 <sub>3</sub> /mmc	4.8409(3)	-	7.6331(5)	$x = 0.24^{a}$
			4.8367(7)	-	7.6241(14)	x=0.24 <sup>b</sup>

<sup>a</sup> As-prepared sample.

the *d*- and *p*-atoms, in the yet unexplored Yb–M–In and Yb–Zn–X phase diagrams.

### 5. Conclusion

The Yb–Zn–In alloys have been analysed by mean of X-ray phase analysis and EDX/SEM measurements. Seven compounds belonging to the binary Yb–Zn, Yb–In and Zn–In systems and previously reported to be stable at 400 °C, have been observed in the study of the partial isothermal section of the Yb-Zn-In phase diagram at that temperature. Three solid solution ranges,  $Yb_{13}Zn_{58-x}In_x$ ,  $YbZn_{2-x}In_x$  and  $YbZn_xIn_{2-x}$ , are stable at 400 °C and their lattice parameters have been obtained from the powder X-ray diffraction data. One new compound,  $YbZn_{0.7}In_{1.3}$  (crystallizing in the UHg<sub>2</sub>) structure type), was also found to exist at 400 °C. The study of the 33.3-100 at.% ytterbium region of the Yb-Zn-In system is currently under way. The available data on the studied Yb-M-In and Yb-Zn-X systems point to the possibility of existence of new compounds and extended homogeneity ranges, based on the partial substitution of the *d*- and *p*-atoms, in the yet unexplored Yb-M-X systems.

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<sup>&</sup>lt;sup>b</sup> Annealed sample.