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Review

Mechanical Properties of Magnesium-Rare Earth Alloy Systems: A Review

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Abstract: Magnesium-rare earth based alloys are increasingly being investigated due to the formation of highly stable strengthening phases, activation of additional deformation modes and improvement in mechanical properties. Several investigations have been done to study the effect of rare earths when they are alloyed to pure magnesium and other Mg alloys. In this review, the mechanical properties of the previously investigated different magnesium-rare earth based binary alloys, ternary alloys and other higher alloys with more than three alloying elements are presented.

Keywords: magnesium; rare earth; binary alloys; ternary alloys; higher alloys and mechanical properties

1. Introduction

Magnesium is the sixth most abundant element in the earth's crust and is the lightest of all structural metals with a high specific stiffness. This is one of the prime reasons automobile manufacturers are in a quest to replace denser materials with magnesium (Mg) based materials. However, poor formability (ductility) and secondary processing induced crystallographic asymmetry (texture effects) due to the hexagonal closed pack (HCP) crystal structure represent the major limitations of Mg. It has limited slip systems and the activation of non-basal slip is difficult at room temperature, thereby limiting the ductility [1,2]. This limitation is being overcome with the development of new magnesium based alloys [3]. Amongst the several common alloying elements, rare earth (RE) addition has given promising results in terms of weakening the texture and improving the deformability of Mg [4,5]. Further, the hard eutectic phases formed as a result of RE addition also aid in increasing the strength of the alloy [6]. Thus, besides improving the ductility and formability, REs also act as effective strengtheners. Generally, the strengthening of Mg by the addition of RE is believed to be by a solid solution strengthening mechanism and a precipitation hardening mechanism [7].

The Mg-RE based alloys serve a useful purpose in automotive industry as superior light metal-alloys in cast or wrought condition [8,9]. Moreover, the Mg-RE alloys also gained prominence in biomedical applications as biodegradable implant materials that aid in healing of the tissues and leaving no implant residues e.g., bone implants, stents [10–12]. In order to serve such applications, the Mg-RE alloys are to be fabricated economically with minimum alloying compositions and simple processing. The Mg-RE phase diagrams suggest that each RE behaves uniquely when it is added as a dominant alloying element [13]. Hence, we study the effects of alloy compositions and processing on microstructure and texture and their effects on the tensile properties. This will in turn help to design alloy systems at the least cost to meet the requirements of the industry. The present article will give an in-detail review of the tensile and compressive properties of different magnesium-rare earth (Mg-RE) alloy systems.

2. Binary Systems

2.1. Yttrium

Addition of yttrium (Y) as an alloying element in Mg has been tested and tried by many researchers owing to the fact that there exists a large difference in the atomic radii of Mg (145 pm) and Y (212 pm) which allows strengthening of Mg by both solid solution strengthening and precipitation-strengthening (upon decomposition of the supersaturated solid solution). Zhao *et al.* [14] reported that Y with max solubility of 4.7 at.% (15.28 wt.%) in Mg can effectively strengthen Mg by solid solution strengthening. Similar observations regarding solution strengthening effects of Y in Mg have been made by Gao *et al.* [7]. In this study, cast Mg-Y alloys containing different Y concentrations ranging between 0.7 wt.% and 6.5 wt.% (below the solubility limit) were investigated. The properties of those Mg-Y alloys after heat treatment at 525 °C for 2–12 h are summarized in Table 1. It can be seen that the addition of Y resulted in the enhancement of strength properties, however, at the expense of ductility.

Table 1. Tensile properties of Mg-Y binary alloys produced by Gao *et al.* [7].

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-0.7Y	39	150	14	As cast + heat treated at 525 °C for 2–12 h [7]
Mg-1.23Y	45	155	13	
Mg-3.1Y	70	160	11	
Mg-4.67Y	89	175	10	
Mg-6.5Y	110	230	8	

Xuenan *et al.* [15] investigated Mg-1%Y alloy in as cast and rolled conditions and reported that by rolling, the strength is improved and the elongation is decreased as compared to the as-cast Mg-1Y alloy. The authors also reported that Y has a negative effect on magnesium corrosion properties and Mg-1Y indicated no significant toxicity to osteoblasts and can be considered for biomedical alloy design. Zhou *et al.* [16] investigated the room temperature mechanical properties of as-extruded Mg-3%Y (extruded at 350 °C) and reported a tensile ductility as high as 33%. It is also interesting that the incremental tensile elongation has occurred without compromising the strength properties (Table 2) and the reason for such mechanical characteristics was reported to be due to the activation of multiple deformation modes. Similar observations of increases in both strength and ductility (Table 2) simultaneously were made by Edassiqi *et al.* [17] for Mg-2%Y and Sandlobes *et al.* [18] for Mg-3%Y where both the alloys were hot rolled and annealed. Contrarily, Wu *et al.* [19] reported increase in elongation to failure from 15% in pure Mg to 30% in Mg-4%Y alloy but this increase in elongation occured at the expense of strength (Table 2). This is reported to be due to the texture effects in case of Mg-2%Y and Mg-4%Y alloys extruded at 420 °C after heat treatment at 480 °C for 12 h. It has also been reported that the addition of Y to Mg as a solute in case of ultra-rapidly solidified and extruded Mg-alloys reduces critically resolved shear stress (CRSS) required to operate the pyramidal slip system. This activation of pyramidal slip system is believed to produce extensive plasticity. Hence, the ductility seems to increase in Mg-10%Y as compared to Mg-5%Y in reference [20]. The increase in strength from 5 wt%–10 wt% (Table 2), in this study, is reported to be due to the precipitation of β' phase from supersaturated solid solution [20].

Table 2. Tensile properties of Mg-Y binary alloys after secondary processing.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-1Y	25	75	10	As-Cast [15]
Mg-1Y	148	200	9.3	Cast + Hot Rolled at 400 °C [15]
Mg-3Y	120	200	33	Cast + Extruded at 350 °C [16]
Mg-2Y	92	189	21	Cast + Heat treated at 480 °C for 12 h + Extruded at 420 °C [19]
Mg-4Y	87	177	30	Cast + Heat treated at 480 °C for 12 h + Extruded at 420 °C [19]
Mg-2Y	146	228	30.5	Cast + Hot Rolled at 450 °C + Annealed [17]
Mg-3Y	92	165	24	Gravity cast + Hot rolled + Annealed at 500 °C for 15 min [18]

Table 2. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks: Processing Condition and Reference
Mg-5Y	-	350	7	Powder Metallurgy + Cold pressed (540 MPa) + Extruded at 420 °C [20]
Mg-10Y	-	440	9	Powder Metallurgy + Cold pressed (540 MPa) + Extruded at 420 °C [20]

2.2. Cerium

Cerium has almost negligible solid solubitlity in Mg at room temperature and is a eutectic forming solute (α-Mg + $Mg_{12}Ce$) [21]. Previous investigation [21] has shown that the addition of Ce as an alloying element not only produces the dispersion hardening effects but also contributes towards the intergranular percolation strengthening. Mishra *et al.* [22] investigated the microstructure, texture and mechanical properties of Mg-0.2 wt.%Ce alloy. In this study, the addition of 0.2%Ce to Mg has improved the tensile ductility of Mg from 9.1%–31% (Table 3). The increase in ductility however occurred alongside reduction in 0.2% offset yield strength. The reported mechanical properties were attributed to the favourable crystallographic orientation (rare earth assisted texture randomization) of Mg grains achieved upon dynamic recrystallization during extrusion. The ductility enhancement, in this study, was also accompanied with a little increase in the ultimate tensile strength as compared to pure Mg due to the reduction in the grain size upon Ce addition. Chino *et al.* [23] claimed that the improvement in ductility due to 0.2%Ce addition as compared to pure Mg is due to the increase in stacking fault energy unlike reduction in c/a ratio that led towards basal/non basal slip activation. Luo *et al.* [24] reported that the addition of 0.5% Ce to Mg resulted in more surface oxidation during extrusion and reduction in ductility and increase in strength. The authors also suggested that Ce concentration should not be higher than 0.5% in extruded alloys due to the excessive surface oxidation during extrusion. For Mg-1%Ce alloy [25], significant increase in ductility from 2.7%–11.9% was observed after annealing at 350 °C (Table 3). Chia *et al.* [6] have reported that when Cerium is added as an alloying element to Mg, an intermetallic $Mg_{12}Ce$ forms and the effect of increase in volume fraction of intermetallic is more than the effect of morphology of the intermetallic in increasing the strength and reducing the ductility of the alloy.

Table 3. Tensile properties of Mg-Ce binary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks: Processing Condition and Reference
Mg-0.2Ce	68.6	170	31	Cast + Extruded at 400 °C [22]
Mg-0.2Ce	110–135	200–220	14–16	Cast + Extruded at 300 °C + Rolled at 400 °C [23]
Mg-0.2Ce	100	215	20.6	Cast+ Homogenized at 400 °C +
Mg-0.5Ce	130	230	8	Extrusion at 350 °C [24]
Mg-0.4Ce	140	160	20	As cast [21]
Mg-0.4Ce	90	120	29	Cast + Annealed at 520 °C for 1 h + water quenched [21]

Table 3. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-0.53Ce	80	140	5.5	High Pressure Die Cast [6]
Mg-0.93Ce	90	-	5	
Mg-1.48Ce	100	-	4	
Mg-2.87Ce	135	160	1.5	
Mg-4.78Ce	150	-	0.9–1	
Mg-1Ce	146 ± 5.5	168.5 ± 3	7.1	Cast + hot rolled at 400 °C [25]
Mg-1Ce	134 ± 2.5	205.5 ± 7	2.7	Cast + hot rolled at 400 °C and annealed for 1 h at 250 °C + Water Quenched [25]
Mg-1Ce	124.6 ± 1.5	212.7 ± 4.7	3.3	Cast + hot rolled at 400 °C and annealed for 1 h at 300 °C + Water Quenched [25]
Mg-1Ce	106 ± 4.7	197.6 ± 4.2	11.9	Cast + hot rolled at 400 °C and annealed for 1 h at 350 °C + Water Quenched [25]
Mg-1Ce	101.5 ± 1.6	203.1 ± 2.6	14.9	Cast + hot rolled at 400 °C and annealed for 1 h at 400 °C + Water Quenched [25]
Mg-1Ce	99 ± 2.1	203.3 ± 4.4	16.9	Cast + hot rolled at 400 °C and annealed for 1 h at 450 °C + Water Quenched [25]

2.3. Gadolinium

Gadolinium has a solublity of 23.49 wt.% at eutectic temperature [26] in Mg and thus contributes to solid solution strengthening when alloyed with Mg [12]. Hort *et al*. [12] reported that property profile of Mg-Gd alloys is similar to that of the cortical bone and can be adjusted over a wide range. They also reported that these alloys have better elongation to fracture compared to other metallic implant materials like stainless steels, *etc*. Gao *et al*. [27] studied the effects of Gd on the solid solution strengthening of Mg alloys. In this study, it was reported that Gd (due to size misfits and valency effects) is an effective solid solution strengthener in Mg as compared to Al and Zn. Peng *et al*. [28] reported that melt spun Mg-20Gd alloy contained mostly the supersaturated α-Mg solid solution while the as-cast Mg-20Gd alloy comprised of α-Mg + Mg_5Gd. In this study, the melt spun alloy exhibited fine grain morphology thus having higher strength when compared to that of the as-cast aloy containing metastable phases (Table 4).

Table 4. Tensile properties of Mg-Gd binary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-2Gd	37.992	103.73	6.362	As-cast [12]
Mg-2Gd	33.430	87.002	4.928	As-cast + solutionized (T4) [12]
Mg-2Gd	41.274	101.368	5.686	As-cast + solutionized + artificially aged (T6) [12]
Mg-5Gd	54.752	128.468	6.620	As-cast [12]
Mg-5Gd	44.850	98.012	6.042	As-cast + solutioned (T4) [12]
Mg-5Gd	42.604	78.658	4.270	As-cast + solutionized + artificially aged (T6) [12]

Table 4. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-10Gd	84.110	131.152	2.500	As-cast [12]
Mg-10Gd	69.120	111.650	3.152	Cast + solutioned(T4) [12]
Mg-10Gd	85.430	132.258	2.182	Cast + solutionized + artificially aged (T6) [12]
Mg-15Gd	127.646	175.220	0.950	As-Cast [12]
Mg-15Gd	118.052	186.844	2.440	Cast + solutionized(T4) [12]
Mg-15Gd	201.396	250.918	0.740	Cast + solutionized + artificial aged (T6) [12]
Mg-3.11Gd	60	160	13	Cast + Solution treatment at 535 °C/1.5 h [27]
Mg-5.73Gd	80	180	11	Cast + Solution treatment at 535 °C/4 h [27]
Mg-9.28Gd	100	190	9	Cast + Solution treatment at 535 °C/6.5 h [27]
Mg-14.2Gd	130	225	8	Cast + Solution treatment at 535 °C/9 h [27]
Mg-19.6Gd	150	255	7.5	Cast + Solution treatment at 540 °C/9.5 h [27]
Mg-20Gd	308	308	12	Melt Spun [28]
Mg-20Gd	254	254	13	As-cast [28]

Stanford *et al*. [29] investigated the microstructure-texture-mechanical property relationships in Mg-Gd alloys containing upto 4.5% Gd. They reported that the addition of Gd upto 1% was shown to significantly weaken the recrystallization texture. However, with further addition of Gd, it remained largely unchanged. Similarly, the strength values (Table 5) also increased until 1% Gd addition and remained unchanged thereafter. The authors stated that upon recrystallization annealing, the Gd solute locks the dislocation movement and causes matrix hardening. However, it is reported that such a mechanism did not affect the ducility of the developed Mg-Gd alloys. The same authors in [30] reported that Gd addition to Mg weakens the texture and produces the rare earth texture-component thereby resulting in extended plasticity when tested along the extrusion direction. They further reported that Mg-1.55Gd alloys exhibited high ductility when extruded at 450 °C as compared to 510 °C due to the suppression of formation of RE texture component at higher extrusion temperature. It is also interesting to note that the tensile ductility of Mg-1 wt.%Gd alloy was increased from 4.8%–30% upon annealing between 350 °C and 450 °C [25]. The properties of the Mg-Gd alloys available in literature are shown in Table 5.

Table 5. Tensile properties of Mg-Gd binary alloys after secondary processing.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-0.22Gd	120	190	6	Cast + hot rolled at 400 °C and annealed for 1 h at 380 °C [29]
Mg-0.75Gd	145	210	12	Cast + hot rolled at 400 °C and annealed for 1 h at 380 °C [29]
Mg-2.75Gd	160	205	21	Cast + hot rolled at 400 °C and annealed for 1 h at 380 °C [29]
Mg-4.65Gd	165	210	26	Cast + hot rolled at 400 °C and annealed for 1 h at 380 °C [29]
Mg-1Gd	138.2 ± 1.7	173.3 ± 4	4.8	Cast + hot rolled at 400 °C [25]
Mg-1Gd	129.3 ± 4.9	191.2 ± 5.9	3.4	Cast + hot rolled at 400 °C and annealed for 1 h at 250 °C + Water Quenched [25]
Mg-1Gd	124.5 ± 1.4	225 ± 2.6	4.2	Cast + hot rolled at 400 °C and annealed for 1 h at 300 °C + Water Quenched [25]
Mg-1Gd	111 ± 4.8	240 ± 22	29.7	Cast + hot rolled at 400 °C and annealed for 1 h at 350 °C + Water Quenched [25]
Mg-1Gd	71.3 ± 3.4	184.9 ± 2.5	29.6	Cast + hot rolled at 400 °C and annealed for 1 h at 400 °C + Water Quenched [25]
Mg-1Gd	70.4 ± 2.4	220.6 ± 2.9	29.6	Cast + hot rolled at 400 °C and annealed for 1 h at 450 °C + Water Quenched [25]
Mg-1.55Gd	102	214	23.9	Cast + Solution treated at 530 °C for 3 h + 560 °C for 5 h + Extruded at 450 °C [30]
Mg-1.55Gd	130	210	15.8	Cast + Solution Treated at 530 °C for 3 h + 560 °C for 5 h + Extruded at 510 °C [30]

2.4. Lanthanum

Lanthanum has limited solid solubility in Mg and has a very high eutectic temperature of 612 °C. Due to its poor solid solubility in Mg, Mg-La alloys do not undergo age hardening [31]. Chia *et al.* [6] reported that Mg-La eutectic is lamellar and with the increase in La content, strength (Table 6) is seen to increase due to the $Mg_{12}La$ intermetallic. This was observed with the reduction in ductility. The have also reported [6] that La is largely believed to be an effective grain refiner as well as an effective texture modifier in Mg alloys . In a study by Stanford *et al*. [30], it was reported that Mg-La alloys extruded at 450 °C exhibited new texture component that is similar to “Rare Earth Texture” along $\langle 11\bar{2}1 \rangle$ direction parallel to the extrusion direction. However, the development of such texture components was suppressed in those Mg-La alloys extruded at higher temperatures thus resulting in lowering of the ductility (Table 6).

Table 6. Tensile properties of Mg-La binary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-0.51La	80	135	5	High pressure die-cast [6]
Mg-0.94La	90	-	4.5	High pressure die-cast [6]
Mg-1.71La	110	-	3.72	High pressure die-cast [6]
Mg-3.44La	140	170	1	High pressure die-cast [6]
Mg-5.07La	168	-	0.75	High pressure die-cast [6]
Mg-0.22La	115	232	19.4	Cast + Solution treated at 560 °C for 8 h + Extruded at 450 °C [30]
Mg-0.22La	150	220	13.8	Cast + Solution treated at 560 °C for 8 h + Extruded at 520 °C [30]

2.5. Erbium

Erbium is one of the rare earths that is well soluble in Mg. Wu *et al*. [32] investigated the strengthening of the extrusion texture component <0 0 0 1> parallel to the direction of extrusion occured with the addition of Er. This developed to RE texture after complete recrystallization in Mg-6Er. The tensile ductility (Table 7) of the Mg-Er alloys was reported to be due to the reduction in the c/a ratio and development of texture that led to the activation of different modes of plastic deformation. A high tensile ductility of about 30% was observed in Mg-6Er alloy. In Mg-3.6%Er [33], the authors reported that ageing at 200 °C led to the dynamic strain ageing that gave rise to the serrated flow behaviour.

Table 7. Tensile properties of Mg-Er binary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-3.6Er	90	140	20	Cast + solution treated at 500 °C for 8 h, + aged at 200 °C for 8 h [33]
Mg-2Er	83 **47.0 ± 1.5 ***	251 **205.0 ± 5.0 ***	19.6 **33.0 ± 3.0 ***	Die cast + homogenized at 520 °C for 48 h + Extruded at 400 °C + annealed at 400 °C/60 min [32]
Mg-4Er	80 **47.0 ± 1.3 ***	184 **176.0 ± 3.4 ***	28.4 **35.0 ± 3.8 ***	Die cast + homogenized at 520 °C for 48 h + Extruded at 440 °C + annealed at 450 °C/20 min [32]
Mg-6Er	72 **47.0 ± 1.5 ***	195 **170.0 ± 4.2 ***	29.4 **42.3 ± 3.3 ***	Die cast + homogenized at 520 °C for 48 h + Extruded at 440 °C + annealed at 450 °C/30 min [32]

* indicates the compressive properties of the same alloy.

2.6. Neodymium

Neodymium has the highest solid solubility in Mg and lowest eutectic temperature of about 552 °C and shows best response to age hardening when added to Mg due to its high solid solubility [6]. Chia *et al*. [6] reported that unlike Ce and La, Nd forms Mg_3Nd phase which is a very hard phase and not $Mg_{12}Nd$ phase. They have attributed the same for better strength of Nd containing Mg alloys as compared to that of Ce and La containing Mg alloys. In contrast, Jingli *et al.* [34] reported that the microstructure of Mg-Nd alloys consists of dendritic α-Mg and divorced eutectic $Mg_{12}Nd$. The improvement in strength with increase in Nd content was attributed to both solid solution hardening and precipitation hardening. Seitz *et al.* [35] studied Mg-2 Nd alloys in different extruded and heat treated conditions and reported that the high elongation ratios combined with the low yield strength (Table 8) and low degradation of the Mg-2Nd alloys make them promising for resorbable stent applications and comparable to the conventional WE 43 alloys.

Table 8. Tensile properties of Mg-Nd binary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-0.47Nd	81	189	9.5	High Pressure Die-cast [6]
Mg-0.76Nd	85	-	6.75	High Pressure Die-cast [6]
Mg-1.25Nd	92	-	4.8	High Pressure Die-cast [6]
Mg-2.60Nd	115	-	4.1	High Pressure Die-cast [6]
Mg-3.53Nd	130	140	2.5	High Pressure Die-cast [6]
Mg-1.2Nd	95	123	4.61	As-cast [34]
Mg-1.85Nd	121.2	155.8	2.76	As-cast [34]
Mg-3.59Nd	141.2	153.6	1.08	As-cast [34]
Mg-2Nd	77 **102 ***	193 **327 ***	30 -	Cast +Extruded at 380 °C [35]
Mg-2Nd	123 **106 ***	240 **340 ***	26 -	Cast + Extruded at 380 °C + annealing at 204 °C for 16 h (T5(1)) [35]
Mg-2Nd	102 **110 ***	242 **340 ***	27.5 -	Cast + Extruded at 380 °C + annealing at 204 °C for 48 h (T5(2)) [35]
Mg-2Nd	125 **105 ***	220 **320 ***	15 -	Cast + Extruded at 380 °C + solution treatment at 510 °C for 3 h + annealing at 204 °C for 16 h (T6(1)) [35]
Mg-2Nd	70 **85 ***	230 **335 ***	18.5 -	Cast + Extruded at 380 °C + solution treatment at 510 °C for 3 h + annealing at 204 °C for 48 h (T6(2)) [35]

* indicates the compressive properties of the same alloy.

2.7. Dysprosium

Dysprosium has a high solid solubility in Mg and the melting point of the intermetallic $Mg_{24}Dy_5$ is 560 °C [36]. It is expected to improve the room temperature mechanical properties of Mg by solid solution strengthening and precipitation hardening as the solubility decreases drastically with decrease in temperature. The ductility decreases with increase in Dy content and is very poor at room temperature [37,38]. The authors [37] reported that of all the alloys, Mg-10Dy can be developd further for biomedical applications due to its mechanical and corrosion properties. They also suggested in reference [38] that ageing treatment at 200 °C can be selected for applicability of the Mg-Dy alloys as bone fictures as low ducility and high strength are required. The mechanical properties of various Mg-Dy binary alloys are shown in Table 9.

Table 9. Tensile properties of Mg-Dy binary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks: Processing Condition and Reference
Mg-5Dy	48	77	4.6	As-Cast(F) [37]
Mg-5Dy	40	76	3.3	Cast + Solutionized at 520 °C for 24 h + Water Quenched (T4) [37]
Mg-10Dy	82	130	5.5	As-Cast(F) [37]
Mg-10Dy	63	104	4	Cast + Solutionized at 520 °C for 24 h + Water Quenched (T4) [37]
Mg-10Dy	65	108	3.8	Cast + Solutionized at 520 °C for 24 h + Water Quenched + aged at 250 °C for 16 h (T6-1) [38]
Mg-10Dy	70	95	4.2	Cast + Solutionized at 520 °C for 24 h + Water Quenched + aged at 200 °C for 168 h (T6-2) [38]
Mg-15Dy	105	125	1.9	As-Cast(F) [37]
Mg-15Dy	68	125	3	Cast + Solutionized at 520 °C for 24 h + Water Quenched (T4) [37]
Mg-15Dy	72	113	2	Cast + Solutionized at 520 °C for 24 h + Water Quenched + aged at 250 °C for 16 h (T6-1) [38]
Mg-15Dy	104	137	2.2	Cast + Solutionized at 520 °C for 24 h + Water Quenched + aged at 200 °C for 168 h (T6-2) [38]
Mg-20Dy	120	142	1.5	As-Cast(F) [37]
Mg-20Dy	110	148	1.25	Cast + Solutionized at 520 °C for 24 h + Water Quenched (T4) [37]
Mg-20Dy	120	140	0.6	Cast + Solutionized at 520 °C for 24 h + Water Quenched + aged at 250 °C for 16 h (T6-1) [38]
Mg-20Dy	168	223	0.9	Cast + Solutionized at 520 °C for 24 h + Water Quenched + aged at 200 °C for 168 h (T6-2) [38]
Mg-12.1Dy	83	114	2.8	As-Cast [36]

3. Ternary Systems

Several compositions are tried where rare earths are major as well as minor alloying elements in order to investigate the influence of the rare earths on the properties of the Mg based alloy. In this section, properties of such investigated Mg-RE based ternary alloys containing magnesium, rare earth element and another alloying element *i.e.*, Mg-X-RE (X = RE, Al, Zn, Zr, Sn, Mn, Cu) are discussed.

3.1. Mg-RE Ternary Systems

The Mg-10Y-2.5Sm alloy was investigated by Zhang *et al*. [39] and it was reported that $Mg_{24}Y_5$ phase was distributed in α-Mg matrix uniformly and no phases contained Sm. The tensile properties, in the study, are attributed to the solid solution strengthening effect of Sm and strengthening by $Mg_{24}Y_5$. In the Mg-8.3Gd-1.9Er alloy, the strength increased with ageing due to the β' phase that has formed by precipitation mechanism. Gavras *et al*. [40] investigated Mg-La-(Y,Gd,Nd) systems and reported that the tensile strength of Mg-2.5La-3.6Nd system is highest of all the investigated Mg-La-(Y,Gd,Nd) alloys with a value of 195 MPa. It was reported to be due to the higher amount of intermetallics in the eutectic that settled at the grain boundaries. The tensile properties of the above discussed alloys are shown in Table 10.

Table 10. Tensile properties of Mg-RE ternary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-10Y-2.5Sm	-	207	2.53	Cast + Solution treated at 540 °C for 6 h + Water Quenched+ Aged at 250 °C for 2 h [39]
Mg-8.3Gd-1.9Er	112	246	6.5	As-Cast [41]
Mg-8.3Gd-1.9Er	190	308	4.9	Cast + solution treated at 570 °C for 6 h + Isothermally aged at 200 °C [41]
Mg-2.5La-3.6Nd	195	-	2.2	High Pressure Die Cast [40]
Mg-2.5La-2.5Y	170		5	
Mg-2.5La-4.1Y	186	-	4	
Mg-2.4La-5.2Gd	184	-	3.9	

3.2. Mg-Al-RE Ternary Systems

Luo *et al*. [24] reported that the addition of 0.2 or 0.5% Ce to Mg-3Al did not show significant improvement in tensile properties due to the affinity of Ce for Al thus forming $Al_{11}Ce_3$ in Mg-Al-Ce ternary alloys resulting in the properties as shown in Table 11.

Table 11. Tensile properties of Mg-Zn-RE ternary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-3Al-0.2Ce	120	235	18	Cast + Homogenized at 400 °C + Extrusion at 350 °C [24]
Mg-3Al-0.5Ce	125	230	20	

3.3. Mg-Zn-RE Ternary Systems

Luo *et al*. [42] investigated the Mg-Zn-Ce alloys and reported that the addition of Zn to Mg-0.2Ce alloys has improved the strength significantly with a slight reduction in ductility and attributed it to the independent effect of solid solution strengthening by Zn. The authors also reported that Zn does not react with Ce thereby producing random texture in extrusion. Le *et al*. [43] investigated Mg-2Zn-0.4RE alloys and reported that the highest strength was seen in Ce containing alloy and highest ductility in Y containing alloy. Wu *et al*. [44] reported that the excellent ductility of the rolled Mg-Gd-Zn alloy sheets is due to the texture weakening effects of Gd. The effects of ultrasonic treatment was studied on Mg-5Zn-2Er alloys [45] and it was reported that the improved mechanical properties are a result of cavitation and acoustic streaming during ultrasonic treatment. The properties of cast Mg-5Zn-0.63Er alloy were studied under heat treated and peak aged conditions [46]. In this study, it was reported that the properties were high in aged condition due to the presence of rod-like $MgZn_2$ particles. Wang *et al*. [47] suggested that the texture of as-extruded Mg-*x*Zn-*x*Er was weakened by the recrystallization via particle stimulated nucleation (PSN). Srinivasan *et al*. [48] investigated Mg-Gd-Zn alloys and reported that the Mg-10Gd-*x*Zn alloys (x = 2, 6) exhibited good strength due to the 14H-type LPSO phases present in the matrix while those alloys containing lower Gd exhibited good ductility due to the lower fraction of LPSO. Singh *et al*. [49] attributed the high strength of the Mg-Zn-Y alloy to the nano-quasi-crystalline phase that has formed during extrusion. The properties of all the alloys that are discussed/investigated are listed in Table 12.

Table 12. Tensile properties of Mg-Zn-RE ternary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-2Zn-0.2Ce	135	225	27	Cast + Extruded at 400 °C [42]
Mg-5Zn-0.2Ce	135	247	15	
Mg-8Zn-0.2Ce	136	289	16	
Mg-1.11Zn-1.68Gd	129.9	233.4	40.3	Cast + homogenized at 500 °C for 10 h + Rolled at 430 °C + annealed at 400 °C for 1 h (Tested in Rolling Direction) [44]
Mg-1.11Zn-1.68Gd	113.8	221.2	44.5	Cast + homogenized at 500 °C for 10 h + Rolled at 430 °C + annealed at 400 °C for 1 h (Tested in 45° to Rolling Direction) [44]
Mg-1.11Zn-1.68Gd	110.1	218.4	44.6	Cast + homogenized at 500 °C for 10 h + Rolled at 430 °C + annealed at 400 °C for 1 h (Tested in Transverse Direction) [44]
Mg-1.06Zn-2.74Gd	130.6	220.0	40.3	Cast + homogenized at 500 °C for 10 h + Rolled at 430 °C + annealed at 400 °C for 1 h (Tested in Rolling Direction) [44]
Mg-1.06Zn-2.74Gd	121.0	220.3	47.3	Cast + homogenized at 500 °C for 10 h + Rolled at 430 °C + annealed at 400 °C for 1 h (Tested at 45° to Rolling Direction) [44]
Mg-1.06Zn-2.74Gd	118.0	220.9	45.1	Cast + homogenized at 500 °C for 10 h + Rolled at 430 °C + annealed at 400 °C for 1 h (Tested in Transverse Direction) [44]
Mg-2Zn-0.4Ce	190	255	18	Cast + Extruded at 310 °C [43]
Mg-2Zn-0.4Gd	125	220	26	
Mg-2Zn-0.4Y	160	240	30	
Mg-2Zn-0.4Nd	175	245	28	
Mg-2Zn-2Gd	71	135	5.5	Gravity permanent mold cast [48]
Mg-6Zn-2Gd	89	170	4.5	
Mg-2Zn-10Gd	119	146	1.5	
Mg-6Zn-10Gd	116	144	1	
Mg-0.2Zn-12.12Dy	92	125	6.3	As-Cast [36]
Mg-1.2Zn-12Dy	100	145	5.2	
Mg-2.4Zn-11.9Dy	95	128	1.2	

Table 12. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-2Zn-2.3Er	310 ± 6.5	320 ± 7.9	12.8 ± 1.2	Cast + annealed at 400 °C for 10 h + Extruded at 300 °C [47]
Mg-2Zn-2.3Er	247 ± 6.2	279 ± 6.8	12.1 ± 1.6	Cast + annealed at 400 °C for 10 h + Extruded at 400 °C [47]
Mg-3.7Zn-4Er	295 ± 2.8	330 ± 3.0	13.7 ± 2.1	Cast + annealed at 400 °C for 10 h + Extruded at 300 °C [47]
Mg-3.7Zn-4Er	278 ± 2.9	319 ± 3.1	17.6 ± 2.0	Cast + annealed at 400 °C for 10 h + Extruded at 400 °C [47]
Mg-5.5Zn-6.2Er	299 ± 6.3	343 ± 7.0	16.8 ± 1.2	Cast + annealed at 400 °C for 10 h + Extruded at 300 °C [47]
Mg-5.5Zn-6.2Er	283 ± 2.2	328 ± 2.5	19.7 ± 1.2	Cast + annealed at 400 °C for 10 h + Extruded at 400 °C [47]
Mg-4Zn-0.1Ce	109 ± 2.6	234 ± 4.0	17.3 ± 0.94	Cast + homogenized for 3 h at 300 °C + 24 h at 400 °C + hot rolled at 400 °C + annealed at 400 °C for 30 min [50]
Mg-3Zn-0.3Er	70	180	12.5	As-Cast [51]
Mg-3Zn-0.38Er	75	185	13	
Mg-3Zn-0.5Er	77	186	13.5	
Mg-3Zn-0.75Er	80	155	11.5	
Mg-3Zn-2.5Er	82	164	8	
Mg-3Zn-3Er	104	184	7.5	
Mg-3Zn-3.8Er	103	162	6	
Mg-5Zn-0.5Er	94	205	11.5	
Mg-5Zn-0.63Er	96	210	12.5	
Mg-5Zn-0.83Er	97	209.52	11	
Mg-5Zn-1.25Er	98	187.6	10.5	
Mg-5Zn-2.5Er	99	185	9	
Mg-5Zn-5Er	124	213.7	8.5	
Mg-5Zn-6.25Er	117	186.03	7.5	
Mg-7Zn-0.7Er	102.11	195	6.5	
Mg-7Zn-0.88Er	120	197	7.5	
Mg-7Zn-1.17Er	124	196	7	
Mg-7Zn-1.75Er	126	158	6.5	
Mg-7Zn-3.5Er	128	169	6	
Mg-7Zn-7Er	130.24	210	5.5	
Mg-7Zn-8.75Er	128.49	176	3.5	
Mg-5Zn-0.63Er	112.5	223	11.5	As-Cast [46]
Mg-5Zn-0.63Er	106	206.8	13.6	Cast + solution heat-treated at 440, 460, 480 and 500 °C for 10 h (T4) [46]
Mg-5Zn-0.63Er	124	261	10.5	Cast + solution heat-treated at 440, 460, 480 and 500 °C for 10 h + isothermally aged at 175 °C (T6) [46]
Mg-5Zn-2Er	-	151	7	As-Cast [45]

Table 12. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing Condition and Reference
Mg-5Zn-2Er	-	210	11	Ultrasonic Treatment for 100 s and power 600 W + Cast [45]
Mg-6Zn-0.3Er	72	210	12	As-Cast [52]
Mg-6Zn-0.3Er	138	289	25	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C [52]
Mg-6Zn-0.3Er	157	291	18	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C + aged at 200 °C [52]
Mg-6Zn-0.5Er	87	184	12	As-Cast [52]
Mg-6Zn-0.5Er	155	310	17	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C [52]
Mg-6Zn-0.5Er	183	329	12	Cast+ homogenized at 400 °C for 10 h+ extruded at 300 °C + aged at 200 °C [52]
Mg-6Zn-1.0Er	104	224	11	As-Cast [52]
Mg-6Zn-1.0Er	187	295	18	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C [52]
Mg-6Zn-1.0Er	193	302	14	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C + aged at 200 °C [52]
Mg-6Zn-1.5Er	100	203	10	As-Cast [52]
Mg-6Zn-1.5Er	175	296	17	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C [52]
Mg-6Zn-1.5Er	188	300	15	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C + aged at 200 °C [52]
Mg-6Zn-2.0Er	110	198	6	As-Cast [52]
Mg-6Zn-2.0Er	194	304	16	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C [52]
Mg-6Zn-2.0Er	193	301	12	Cast + homogenized at 400 °C for 10 h + extruded at 300 °C + aged at 200 °C [52]
Mg-14.4Zn-3.3Y	171 **213 ***	320 **530 ***	12 **14 ***	Cast + solutionized at 480 °C for 24 h + extruded at 430 °C [49]
Mg-14.4Zn-3.3Y	365.0 ± 3.5 **267.7 ± 0.7 ***	380 **550 ***	8 **12 ***	Cast + solutionized at 480 °C for 24 h + extruded at 430 °C + aged at 150 °C [49]

* indicates the compressive properties of the same alloy.

3.4. Mg-Zr-RE Ternary Systems

Huang *et al*. [4] reported the effect of multi-micro alloying of RE on the ductility of Mg alloys. Different rare earths were studied in the ternary system and the best ductility was observed with Gd addition to Mg-0.5Zr. Investigations on Mg-0.6Zr-8Gd were done in [53] and the properties were attributed to the precipitate β-Mg5RE (Gd/Er) and dispersed β'-$Mg_{15}RE_3$ (Gd/Er) metastable phase. The properties are shown in Table 13.

Table 13. Tensile properties of Mg-Zr-RE ternary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-0.5Zr-0.4Y	20.9 ± 1.0	119.3 ± 7.2	4.3 ± 2.5	As-Cast [4]
	25.6 ± 2.0 *	**200.8 ± 16.6 ***	**15.6 ± 3.6 ***	
Mg-0.5Zr-0.4Gd	52.2 ± 3.8	144.6 ± 1.7	22.1 ± 1.6	
	40.2 ± 1.1 *	**231.3 ± 8.7 ***	**24.4 ± 1.5 ***	
Mg-0.5Zr-0.4Dy	53.7 ± 3.0	140.7 ± 0.4	17.5 ± 0	
	32.5 ± 2.6 *	**231.6 ± 16 ***	**22.7 ± 2.0 ***	
Mg-0.5Zr-0.4Sm	51.6 ± 3.1	144.2 ± 6.5	17.0 ± 2.5	
	36.2 ± 1.6 *	**237.1 ± 3.0 ***	**22.9 ± 2.6 ***	
Mg-0.6Zr-8Gd	82	141	6.2	Cast + solution treated at 530 °C for 10 h + Aged at 230 °C [53]
Mg-0.6Zr-8Gd	81	155	6.4	

* indicates the compressive properties of the same alloy.

3.5. Mg-Sn-RE Ternary Systems

The properties of Mg-Sn-RE system have been investigated by Zhao *et al*. [54]. In this study, Y was used as the rare earth element and it was reported that when Y is 1.5%, MgSnY phase forms and with increase of Y to 3%, MgSnY+Sn_3Y_5 phases form and at 3.5%Y, Sn_3Y_5 phase forms. The combined effect of intermetallics in Mg-3%Y is responsible for the higher properties as shown in Table 14. Wang *et al*. [55] reported that Mg-8.23Sn-2Nd exhibited the best tensile properties. This was related to the microstructure as α-Mg, Mg_2Sn and Mg-Sn-Nd phases were present in the microstructure of the alloys and the strength was attributed to the change in morphology of the Mg-Sn-Nd phase and size of the Mg_2Sn phase. The properties of the different Mg-Sn-RE alloys that are investigated are shown in Table 14.

Table 14. Tensile properties of Mg-Sn-RE ternary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ducility (%)	Remarks Processing Condition and Reference
Mg-1Sn-1.5Y	165	199	12.8	Cast + Homogenized at 480 °C for 12 h + Extruded at 350 °C [54]
Mg-1Sn-3Y	295	305	2.4	
Mg-1Sn-3.5Y	136	225	14	
Mg-1.65Sn-2Nd	-	115	8	As-Cast [55]
Mg-4.92Sn-2Nd	-	132.5	8.5	
Mg-8.23Sn-2Nd	-	140	10	
Mg-11.52Sn-2Nd	-	135	8.75	

3.6. Other Ternary Systems

The addition of Er to Mg-1.8Mn resulted in the increase in ductility and this was attributed to the resistance to recrystallize and retard the grain growth with the addition of Er [56]. The highest tensile properties were found in alloy containing 0.7% Er. Du *et al*. [57] reported that 18R LPSO phase is formed in Mg-10Er-2Cu alloy that resulted in the properties as shown in Table 15.

Table 15. Tensile properties of other ternary alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks
				Processing Condition and Reference
Mg-1.8Mn-0.1Er	173	255	7	Cast + homogenized at 450 °C for 4 h + Extruded at 450 °C + Annealed at 390 °C for 1 h [56]
Mg-1.8Mn-0.4Er	224	276	9	
Mg-1.8Mn-0.7Er	228	275	12.5	
Mg-10Er-2Cu	320	380	15	Cast + homogenized at 450 °C for 24 h + Extruded at 430 °C [57]

4. Higher Alloy Systems

In this section, magnesium rare earth alloys containing more than three elements are discussed. The alloying elements whose effect is studied include REs, Al, Li, Zr, Zn, Sn, Mn, Cu, Ca and V.

4.1. Mg-RE Higher Alloy Systems

Zhang *et al*. [58] reported the properties of WE43 degradable biomaterial in extruded conditions as reported in Table 16. In reference [59], the authors reported the properties of Mg-4Y-3.2RE at room temperature and reported that ageing improved the strength of the alloy significantly. Su *et al*. [60] reported the properties of peak aged WE43 alloy as shown in Table 16. Mukai *et al*. [61] reported the properties of the WE43 alloys in annealed, extruded and aged conditions and reported that the extruded alloy exhibits superior properties in terms of strength and ductility due to the fine grained microstructure and transition from intergranular to transgranular fracture with grain refinement. Panigrahi *et al*. [62] studied the effects of forging and ageing on the mechanical properties of WE43 alloys and reported that the improvement in strength is due to the combined effect of grain refinement, work hardening and precipitation strengthening. The improvement in ductility is also reported to be due to the limited intergranular fracture and activation of non-basal slip prior to twinning.

Table 16. Tensile properties of Mg-RE based higher alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks
				Processing condition and Reference
Mg-4Y-2.3Nd-0.88Gd	221 ± 1.7	295 ± 3.1	10.7 ± 0.8	Cast + Extruded at 350 °C [58]
Mg-4Y-3.2RE	-	240	-	Cast + Annealed at 525 °C [59]
Mg-4Y-3.2RE	-	320	-	Cast + Annealed at 525 °C + Aged at 200 °C [59]
Mg-4Y-3RE	165	250	2.0	T6 [60]
Mg-4Y-3RE (2.2Nd)	-	230	16	Annealed at 525 °C/5 h [61]
Mg-4Y-3RE (2.2Nd)	-	300	6	Annealed at 525 °C/5 h + Aged at 200 °C [61]
Mg-4Y-3RE (2.2Nd)	-	320	20	Annealed at 525 °C/5 h + Extruded at 300 °C [61]
Mg-4Y-3RE	185 ± 12	261 ± 5	31 ± 1	As-Received [62]
Mg-4Y-3RE	270 ± 15	348 ± 6	16 ± 3	As Received + T5 [62]
Mg-4Y-3RE	263 ± 7	311 ± 11	23 ± 3	Forged [62]
Mg-4Y-3RE	318 ± 9	368 ± 10	17 ± 1	Forged + Aged at 210 °C/32h [62]
Mg-4Y-3RE	344 ± 11	388 ± 12	23 ± 1	Forged + Aged at 180 °C/60 h [62]
Mg-4Y-3RE	286 ± 10	341 ± 4	28 ± 1	Forged + Aged at 150 °C/104 h [62]

4.2. Mg-Al-RE Higher Alloy Systems

Rzychoń *et al*. [63], in their study on Mg-Al-RE alloys, reported that when RE/Al ratio is >0.5, no $Mg_{17}Al_{12}$ phase forms. The $Mg_{17}Al_{12}$ phase has lower melting temperature compared to the other $Al_{11}RE_3$, Al_2RE phases and thus when the ratio between RE and Al is maintained at an optimum level, the thermal stability of Mg alloys can be improved. In reference [64], the authors investigated the microstructure and mechanical properties of Mg-10Gd-3Y-0.8Al alloys and reported that the microstructure of cast Mg-10Gd-3Y alloy was refined with the addition of 0.8%Al and when solution treated at 520 °C for 6 h + 550 °C for 7 h, the ductility improved from 5%–13%. Further, they also discussed the effect of ageing on the properties of the alloy. The strength increased due to the precipitation strengthening and solute dissolution of the intermetallic particles in the solute. Zhang *et al*. [65] investigated the properties of Mg-3.0Al-1.8Ce-0.3Y-0.2Mn alloy and found that it exhibited high structural stability and strength due to the presence of dendrite boundaries with $Al_{11}(Ce,Y)_3$ intermetallics. The strength enhancement, in this study, is also thought to be due to the solid solution strengthening effects of Y. Similar strengthening mechanism was reported in reference [66] by the same authors wherein Ce was mostly present in the $Al_{11}RE_3$ and Y was observed to exist in Al_2RE. Rzychoń *et al*. [67] investigated the properties of AE44 alloys and reported that the high pressure die cast alloys exhibited better properties when compared to the sand cast alloys. They attributed the same to the low solidification rates in the sand cast alloys that led to the unfavorable morphology of the intermetallics $Al_{11}RE_3$ (needle shaped) and Al_2RE (polyhedral) and coarse grained structure. Zhang *et al*. [68] also reported that when La substitutes Ce rich misch metal, α-Mg and $Al_{11}La_3$ phases are observed instead of $Al_{11}RE_3$ and Al_2RE. It was reported that La containing alloy exhibits better properties due to the stability of $Al_{11}La_3$ phase in Mg-4Al-4RE-0.4Mn alloy. The same author also reported in [69] that with an increase in Ce content, the strength was improved and was attributed to the acicular morphology of the main strengthening phase, $Al_{11}Ce_3$. A similar trend was observed with La, Pr and Nd in [70–72]. Wang *et al*. [73] also observed that Mg-5Al-0.3Mn-1.5Ce alloy exhibited the best tensile strength due to the presence of optimized content of $Al_{11}Ce_3$ + β-$Mg_{17}Al_{12}$. Chen *et al*. [74] reported that the addition of Nd led to the formation of higher melting Al-Nd intermetallic and also improved the room temperature strength of the Mg-6Al-2Ca-*x*Nd (x = 1,2) alloys. Wu *et al*. [75] reported that the addition of REs and Ca to AZ91 alloys led to the improvement in strength as well as corrosion resistance due to the presence of Al_2Ca phases. The properties of the above discussed alloys are given in Table 17.

Table 17. Tensile properties of Mg-Al-RE based higher alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiliy (%)	Remarks
				Processing Condition and Reference
Mg-10Gd-3Y-0.8Al	136	215	4.8	As-Cast [64]
Mg-10Gd-3Y-0.8Al	126	226	13	Cast + solution treated at 520 °C for 6 h + 550 °C for 7 h (T4A) [64]
Mg-10Gd-3Y-0.8Al	227	353	3.5	Cast + solution treated at 520 °C for 6 h + 550 °C for 7 h + peak-aged at 200 °C (T6A) [64]

Table 17. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiliy (%)	Remarks Processing Condition and Reference
Mg-10Gd-3Y-0.8Al	213	301	12.1	Cast + solution treated at 520 °C for 6 h + 550 °C for 7 h + peak-aged at 225 °C (T6B) [64]
Mg-3Al-1.8Ce-0.3Y-0.2Mn	158	255	10	Die-cast [65]
Mg-3.4Al-2.4Cemm-0.3Ymm-0.3Mn	166 **158***	267 **372***	11 **17***	Die-cast [66]
Mg-4Al-4RE-0.18Mn	47	146	7.1	Sand Cast [67]
(2.35%Ce, 1.07%La, 0.59%Nd, 0.16%Pr)	178	241	10.8	High Pressure Die Cast [67]
Mg-4Al-4RE-0.4Mn (RE = 52–55Ce, 3–5La, 16–20Nd, 5–6Pr)	140	247	11	Die-cast [68]
Mg-4Al-4La-0.4Mn	146	264	13	Die-cast [68]
Mg-4Al-1Ce-0.3Mn	146	232	9	As-Cast [69]
Mg-4Al-2Ce-0.3Mn	148	247	12	As-Cast [69]
Mg-4Al-4Ce-0.3Mn	157	250	11	As-Cast [69]
Mg-4Al-6Ce-0.3Mn	161	254	10	As-Cast [69]
Mg-4Al-1La-0.3Mn	133	236	12	As-Cast [70]
Mg-4Al-2La-0.3Mn	140	245	13	As-Cast [70]
Mg-4Al-4La-0.3Mn	155	265	12	As-Cast [70]
Mg-4Al-6La-0.3Mn	171	257	7	As-Cast [70]
Mg-4Al-1Pr-0.3Mn	145	241	13	As-Cast [71]
Mg-4Al-2Pr-0.3Mn	148	248	13	As-Cast [71]
Mg-4Al-4Pr-0.3Mn	165	262	16	As-Cast [71]
Mg-4Al-6Pr-0.3Mn	155	251	10	As-Cast [71]
Mg-4Al-1Nd-0.3Mn	150	244	12	As-Cast [72]
Mg-4Al-2Nd-0.3Mn	154	248	13	As-Cast [72]
Mg-4Al-4Nd-0.3Mn	156	258	15	As-Cast [72]
Mg-4Al-6Nd-0.3Mn	165	261	12	As-Cast [72]
Mg-5Al-0.3Mn-0.5Ce	71	173	9	As-Cast [73]
Mg-5Al-0.3Mn-1.0Ce	82	184	15	As-Cast [73]
Mg-5Al-0.3Mn-1.5Ce	88	203	20	As-Cast [73]
Mg-5Al-0.3Mn-1.5Ce	225	318	9	Cast + Hot Rolled at 400 °C [73]
Mg-5Al-0.3Mn-2.0Ce	75	177	13	As-Cast [73]
Mg-5Al-0.3Mn-3.0Ce	68	165	6	As-Cast [73]
Mg-6Al-2Ca-1Nd	180	286	9.5	Cast + Homogenised at 460 °C for 24 h + Extruded at 330 °C [74]
Mg-6Al-2Ca-2Nd	186	306	12.3	
Mg-6Al-2Ca-3Nd	205	310	13	
Mg-6Al-2Ca-4Nd	210	319	12.8	
Mg-9Al-0.5Zn-0.5RE	91	158	1.65	As-Cast [75]
Mg-9Al-0.5Zn-1.0RE	90	165	1.62	
Mg-9Al-0.5Zn-1.2RE	88	170	1.6	
Mg-9Al-0.5Zn-1.5RE	93	174	1.5	
Mg-9Al-0.5Zn-1Ca-1RE	90	169	1.6	
Mg-9Al-0.5Zn-2Ca-1RE	78	150	1.4	
Mg-9Al-0.5Zn-3Ca-1RE	75	129	1.3	
Mg-9Al-0.5Zn-4Ca-1RE	70	115	0.9	

* indicates the compressive properties of the same alloy.

4.3. Mg-Li-RE Higher Alloy System

Krausse *et al*. [76] investigated the biodegradation behavior of LAE442 alloys and reported that the alloys have sufficient initial strength to be used in weight bearing applications in bones. In reference [77], the authors characterized Mg-1.21Li-1.12Ca-1Y alloy and reported that the alloy exhibited better tensile properties in extruded state due to the refinement of microstructure. The authors also indicated that the corrosion resistance of extruded alloy is better than the as-cast alloy due to the delay of the initiation of the corrosion pits. Tao *et al*. [78] investigated the structural and mechanical properties of Mg-Li-Al-Zn-*x*RE alloys containing varying RE content between 0.2% and 1%. In this study, it was reported that the microstructure of the alloys mainly comprised of α-phase, β-phase, $Mg_{17}Al_{12}$ phase, $Mg_{64.5}Li_{34.3}Al_{0.9}Zn_{0.3}$ and $A1_2Zn_2La$ intermetallic compounds. They also reported that besides reducing the laminar spacing of the matrix, RE also acted as an effective grain refiner. The improvement of strength at both room temperature and high temperature was attributed to the formation of $A1_2Zn_2La$ strengthening phase. Zhou *et al*. [79] studied the Mg-Li-Al-RE alloys and reported that the high properties of the alloys are due to the addition of Al and rare earths that result in grain refinement, solid solution strengthening and dispersion strengthening. They also reported the applicability of the alloys for cardiovascular stent materials due to the good corrosion resistance and good cytotoxicity test results. Wang *et al*. [80] studied the Mg-8Li-1Al-1Ce alloy in as-cast and extruded condition and reported that the α(Mg) phase and β(Li) phase are refined after extrusion and the long rod-like Al_2Ce present in the as-cast state becomes short and rod-like after extrusion which is responsible for the properties as shown in Table 18.

Table 18. Tensile properties of Mg-Li-RE based higher alloys.

Alloy (RE = 85% La, 10% Pr, 5% Ce) (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-1.21Li-1.12Ca-1Y	44.00	51.71	1.47	As-Cast [77]
Mg-1.21Li-1.12Ca-1Y	115.02	183.72	14.45	Cast + Extruded [77]
Mg-7Li-6A1-6Zn-0.2 RE	-	194	2.8	
Mg-7Li-6A1-6Zn-0.4 RE	-	200	2.4	
Mg-7Li-6A1-6Zn-0.6 RE	-	204	2.6	As-cast [78]
Mg-7Li-6A1-6Zn-0.8 RE	-	205	2.5	
Ma-7Li-6A1-6Zn-1RE	-	209	2.1	
Mg-3.5Li-2Al-2RE	95	190	22	
Mg-5.5Li-2Al-2RE	140	235	23	Cast + Extruded [79]
Mg-8.5Li-2Al-2RE	100	150	32	
Mg-8Li-1Al-1Ce	141	160	16	As-Cast [80]
Mg-8Li-1Al-1Ce	175	187	33	Cast + Extruded at 220 °C [80]
Mg-8Li-7Al-Si-4.5RE	200	260	14	Wrought [81]

4.4. Mg-Zr-RE Higher Alloy Systems

For Mg-10Gd-3Y-0.4Zr, the mechanism of strengthening is similar to as discussed in the case of Mg-10Gd-3Y-0.8Al [64]. Mg-*x*Y-1.5LPC-0.4Zr (*x* = 0, 2, 4, 6) (LPC = 85% La, 8% Ce, 7% Pr) alloys were investigated in [82]. In this study, the authors showed that the tensile properties of the Mg-Zr-RE alloys improved with an increase in Y content and it was attributed to the distribution of the cubic β-$Mg_{24}Y_5$ precipitate phases and prismatic β′ phases in Mg matrix. Mohri *et al.* [83] investigated the Mg-4Y-3Re-0.5Zr alloy in different conditions and reported that the material extruded at 400 °C exhibited the best properties due to the presence of fine spherical precipitates in the grains. Zhang *et al.* [84] reported that the solution treatment and ageing treatment can enhance the strength of the alloy. The authors also reported that the *in vitro* degradation rate of the alloy increases by solution treatment and decreases by aging due to coarse microstructure and relief of internal stresses in the precipitation phase, respectively. Zhang *et al.* [58] reported that Mg-0.44Zr-3.09Nd, 0.22Zn (JDBM) alloy exhibited superior mechanical properties (due to finer grain size) as well as biocorrosion properties as compared to WE43 and AZ31 alloys and thus is a promising degradable biomaterial. Su *et al.* [60] reported the age hardening behavior and mechanical properties of the Mg-4Y-2.4Nd-0.2Zn-0.4Zr alloy and suggested that the presence of fine β" precipitates in the matrix result in the high mechanical properties in the peak aged condition. Zhang *et al.* [85] reported that the cyclic extrusion resulted in better mechanical properties and bio corrosion of the Mg-2.73Nd-0.16Zn-0.45Zr alloy. In reference [86], the authors studied the mechanical properties and biocorrosion behavior of the Mg-Nd-Zr-Zn alloys at different extrusion ratios. With extrusion ratio 8, the alloys exhibited high strength and moderate elongation while with extrusion ratio 25, the alloys exhibited high elongation and moderate strength. Thus, the authors suggested the optimal properties of the alloy when the alloy undergoes dynamic recrystallization and the growth is suppressed. The authors also indicated that the corrosion properties and cytotoxicity of the alloy meet the requirement of the cell toxicity and hence this makes it a potential biomaterial. Zhang *et al.* [87] reported the effect of double extrusion on the improved mechanical properties and improved corrosion resistance of the biodegradable Mg-Nd-Zn-Zr alloy due to the grain refinement. Kielbus *et al.* [88] investigated Mg-4Y-3RE and Mg-3Nd-1Gd alloys and reported that Mg-4Y-3RE alloys exhibit higher tensile and creep properties due to the presence of higher stable Y containing phases in Mg-4Y-3RE alloys. Zheng *et al.* [89] investigated the effect of thermomechanical treatment on Mg-6Gd-2Nd-0.5Zr and reported that cold deformation increase from 5%–10% accelerated the age hardening response of the alloy and improved the strength. They also reported that hot extrusion and ageing lead to the very high tensile properties of the alloy as reported in Table 19. Xiao *et al.* [90] investigated the Mg-10Gd-3Y-0.5Zr and reported that the Friction Stir processing (FSP) led to grain refinement and dissolution of the eutectic Mg5(Gd,Y) thereby improving the ductility. Ageing treatments done after the FSP led to the improvement in the strengths. Similarly, Li *et al.* [91] studied the effects of FSP on WE43 alloy and reported that the improvement in mechanical properties is due to the refinement of grains in the alloy's microstructure. He *et al.* [92] studied WE 93 alloy and it was observed that the extruded and aged alloy exhibited the best combination of tensile properties. This was reported to be due to the $Mg_{24}Y_5$ phase that is completely dissolved in Mg_{12}(MM) (MM = Misch Metal) which is present around the grain boundaries. In [93], the authors reported that the rolling process has effectively reduced the grain size and improved the mechanical properties. The properties of the different alloys discussed above are reported in Table 19.

Table 19. Tensile properties of Mg-Zr-RE based higher alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-10Gd-3Y-0.4Zr	151	230	4.4	As-Cast [64]
Mg-10Gd-3Y-0.4Zr	131	247	14.4	Cast + Solution Treated at 500 °C for 6 h (T4) [64]
Mg-10Gd-3Y-0.4Zr	231	349	2.2	Cast + Solution Treated at 500 °C for 6 h + peak-aged at 225 °C [64]
Mg-2Y-1.5LPC-0.4Zr (LPC = 85% La, 8% Ce, 7% Pr)	90	180	25	Cast + Solution treated for 10 h at 525 °C [82]
Mg-4Y-1.5LPC-0.4Zr (LPC = 85% La, 8% Ce, 7% Pr)	110	195	20	
Mg-6Y-1.5LPC-0.4Zr (LPC = 85% La, 8% Ce, 7% Pr)	135	250	10	
Mg-4Y-3RE-0.4Zr	-	235	17	Cast + Annealed at 525 °C/5 h [83]
Mg-4Y-3RE-0.4Zr	-	300	6	Cast + Annealed at 525 °C/5h + Aged at 200 °C [83]
Mg-4Y-3RE-0.4Zr	-	325	20	Cast + Annealed at 525 °C/5 h + Extruded at 100:1 at 400 °C [83]
Mg-4Y-3RE-0.4Zr	-	330	20	Cast + Annealed at 525 °C/5 h + Extruded at 100:1 at 400 °C + Aged at 200 °C [83]
Mg-4Y-3RE-0.4Zr	-	350	13	Cast + Annealed at 525 °C/5 h + Extruded at 2.8:1 at 400 °C [83]
Mg-4Y-3RE-0.4Zr	-	370	5	Cast + Annealed at 525 °C/5 h + Extruded at 2.8:1 at 400 °C + Aged at 200 °C [83]
Mg-4Y-2.4Nd-0.2Zn-0.4Zr	150	197	7.5	As-cast (F) [60]
Mg-4Y-2.4Nd-0.2Zn-0.4Zr	162	240	15	Cast + solution treated at 490 °C+ water quenched (T4) [60]
Mg-4Y-2.4Nd-0.2Zn-0.4Zr	268	339	4.0	Cast + solution treated at 490 °C + water quenched + Aged at 200 °C (T60) [60]
Mg-4Y-2.4Nd-0.2Zn-0.4Zr	265	330	6.5	Cast + solution treated at 500 °C + water quenched + Aged at 225 °C (T61) [60]
Mg-4Y-2.4Nd-0.2Zn-0.4Zr	195	260	3.0	Cast + solution treated at 510 °C + water quenched + Aged at 250 °C (T62) [60]
Mg-2.7Nd-0.2Zn-0.4Zr	363 ± 6.3	376 ± 4.3	8.4 ± 2.2	Cast + solution-treated at 540 °C for 10 h + Water quenched + Extruded at 250 °C [84]
Mg-2.7Nd-0.2Zn-0.4Zr	394 ± 5.2	417 ± 7.6	2.6 ± 0.2	Cast + solution-treated at 540 °C for 10 h + Water quenched + Extruded at 250 °C + Aged at 200 °C for 8 h [84]
Mg-2.7Nd-0.2Zn-0.4Zr	121 ± 4.8	217 ± 3.3	22.2 ± 2.4	Cast + solution-treated at 540 °C for 10 h + Water quenched + Extruded at 250 °C + solution-treated at 530 °C for 30 min [84]

Table 19. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-2.7Nd-0.2Zn-0.4Zr	191 ± 2.6	326 ± 2.8	12.2 ± 1.2	Cast + solution-treated at 540 °C for 10 h + Water quenched + Extruded at 250 °C + solution-treated at 530 °C for 30 min + Aged at 200 °C for 8 h [84]
Mg-0.44Zr-3.09Nd, 0.22Zn	293 ± 5.1	307 ± 1.9	15.9 ± 3.1	Cast + Extruded at 350 °C [58]
Mg-0.45 Zr-2.73Nd-0.16Zn	175	240	11	Cast + solution-treated at 540 °C for 10 h + Water quenched + Extruded at 350 °C [85]
Mg-0.45 Zr-2.73Nd-0.16Zn	260	300	29	Cast + solution-treated at 540 °C for 10 h + Water quenched + Extruded at 350 °C (Cyclic Extrusion and Compression) [85]
Mg-0.4Zr-3Nd-1.6Zn	90 ± 7	194 ± 3	12.0 ± 0.8	Cast + Solution treated at 540 °C for 10 h + Water quenched (T4) [86]
Mg-0.4Zr-3Nd-1.6Zn	308 ± 6	312 ± 2	12.2 ± 0.6	T4 + Extruded at 320 °C with ratio 8 (R8) [86]
Mg-0.4Zr-3Nd-1.6Zn	333 ± 4	334 ± 4	7.9 ± 0.2	R8 + Aging [86]
Mg-0.4Zr-3Nd-1.6Zn	156 ± 1	233 ± 4	25.9 ± 0.8	T4 + Extruded at 320 °C with ratio 25 (R25) [86]
Mg-0.4Zr-3Nd-1.6Zn	177 ± 2	238 ± 3	20.4 ± 0.3	R25 + Aging [86]
Mg-2.25Nd-0.11Zn-0.43Zr	204 ± 5.3	247 ± 4.4	20.6 ± 1.6	Cast + solution-treated at 540 °C for 10 h + Water quenched + Single Extruded at 290 °C [87]
Mg-2.25Nd-0.11Zn-0.43Zr	276 ± 6.0	309 ± 6.4	34.3 ± 3.4	Cast + solution-treated at 540 °C for 10 h + Water quenched + Double Extruded at 320 °C [87]
Mg-2.70Nd-0.20Zn-0.41Zr	163 ± 1.9	245 ± 2.2	14 ± 1.5	Cast + solution-treated at 540 °C for 10 h + Water quenched + Single Extruded at 350 °C [87]
Mg-2.70Nd-0.20Zn-0.41Zr	275 ± 4.7	308 ± 2.3	32.8 ± 1.4	Cast + solution-treated at 540 °C for 10 h + Water quenched + Single Extruded at 320 °C [87]
Mg-4Y-3RE-0.5Zr	225	331	6	Cast + solution-treated at 520 °C for 8 h + Water quenched + Aged at 250 °C for 16 h [88]
Mg-3Nd-1Gd-0.5Zr-0.4Zn	163	293	7	Cast + solution-treated at 520 °C for 8 h + Water quenched + Aged at 200 °C for 16 h [88]
Mg-0.5Zr-0.4Y-0.4Gd	51.7 ± 2.8 **43.7 ± 2.7 ***	140.2 ± 0.6 **242.4 ± 16.2 ***	27.7 ± 1.5 **24.9 ± 0.2 ***	As-Cast [4]
Mg-0.5Zr-0.4Y-0.4Dy	48.9 ± 2.5 **43.8 ± 1.6 ***	132.2 ± 1.5 **247.7 ± 7.1 ***	29.3 ± 1.8 **25.0 ± 0.3 ***	
Mg-0.5Zr-0.4Y-0.4Sm	55.7 ± 2.7 **47.0 ± 5.7 ***	148.6 ± 2.9 **260.8 ± 10.2 ***	27.0 ± 2.3 **25.1 ± 0.2 ***	
Mg-0.5Zr-0.4Gd-0.4Dy	47.6 ± 2.7 **38.1 ± 2.3 ***	143.7 ± 2.4 **243.5 ± 4.7 ***	22.2 ± 2.2 **25.6 ± 0.3 ***	
Mg-0.5Zr-0.4Gd-0.4Sm	51.7 ± 0.3 **44.1 ± 0.8 ***	145.1 ± 3.6 **247.5 ± 1.0 ***	26.4 ± 0.7 **24.8 ± 1.0 ***	

Table 19. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-0.5Zr-0.4Dy-04Sm	49.2 ± 2.1 **38.2 ± 1.0 ***	148.4 ± 2.0 **250.0 ± 9.3 ***	19.6 ± 2.5 **24.7 ± 1.5 ***	
Mg-0.5Zr-0.4Gd-0.4Dy-0.4Sm	57.8 ± 1.9 **50.9 ± 0.4 ***	140.8 ± 4.4 **264.7 ± 2.0 ***	30.8 ± 0.6 **26.5 ± 0.4 ***	
Mg-0.5Zr-0.4Y-0.4Gd-0.4Dy-0.4Sm	49.6 ± 1.1 **45.6 ± 1.6 ***	146.0 ± 1.3 **249.4 ± 7.6 ***	17.4 ± 2.0 **24.2 ± 2.0 ***	
Mg-6Gd-2Nd-0.5Zr	118	220	17	Cast + Solution Treated at 500 °C + Quenched [89]
Mg-6Gd-2Nd-0.5Zr	175	345	7.5	Cast + Solution Treated at 500 °C + Quenched + peak-aged (200 °C for 24 h) [89]
Mg-6Gd-2Nd-0.5Zr	245	340	7	Cast + Solution Treated at 500 °C + Quenched + deformed (5%) and peak-aged at 200 °C for 12 h [89]
Mg-6Gd-2Nd-0.5Zr	270	350	4	Cast + Solution Treated at 500 °C + Quenched + deformed (10%) and peak-aged at 200 °C for 8 h [89]
Mg-6Gd-2Nd-0.5Zr	200	275	21	as-extruded at 450 °C [89]
Mg-6Gd-2Nd-0.5Zr	250	350	8	as-extruded at 350 °C [89]
Mg-6Gd-2Nd-0.5Zr	245	290	29	extruded at 450 °C and peak-aged at 200 °C for 24 h [89]
Mg-6Gd-2Nd-0.5Zr	275	375	17.5	extruded at 350 °C and peak-aged 200 °C for 24 h [89]
Mg-10Gd-3Y-0.5Zr	178	187	3.2	As-Cast [90]
Mg-10Gd-3Y-0.5Zr	210	312	19	Cast + Friction Stir Processed [90]
Mg-10Gd-3Y-0.5Zr	330	439	3.4	Cast + Friction Stir Processed+ Aged at 225 °C for 13 h [90]
Mg-3.99Y-3.81Nd-0.53Zr	-	167	7.4	As-cast [91]
Mg-3.99Y-3.81Nd-0.53Zr	-	260	8	As-Cast + Frictrion stir processed at 60 mm·min^{-1} and tool rotation rates of 400 r·min^{-1} [91]
Mg-3.99Y-3.81Nd-0.53Zr	-	290	17.2	As-Cast + Frictrion stir processed at 60 mm·min^{-1} and tool rotation rates of 800 r·min^{-1} [91]
Mg-3.99Y-3.81Nd-0.53Zr	-	280	11.4	As-Cast + Frictrion stir processed at 60 mm·min^{-1} and tool rotation rates of 1200 r·min^{-1} [91]
Mg-3.99Y-3.81Nd-0.53Zr	-	265	9.3	As-Cast + Frictrion stir processed at 60 mm·min^{-1} and tool rotation rates of 1500 r·min^{-1} [91]
Mg-0.56Zr-9Y-3.24MM	230	240	1.0	As-Cast [92]
Mg-0.56Zr-9Y-3.24MM	215	245	2.5	Cast + Homogenized at 535 °C for 18 h [92]
Mg-0.56Zr-9Y-3.24MM	245	305	12.5	Cast + Homogenized at 535 °C for 18 h + Extruded at 420 °C [92]

Table 19. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-0.56Zr-9Y-3.24MM	315	385	6.5	Cast + Homogenized at 535 °C for 18 h + Extruded at 420 °C + aged at 225 °C for 10 h in air [92]
Mg-12Gd-3Y-0.4Zr	187.3	282.5	6.3	Cast + Extruded at 400 °C [93]
Mg-12Gd-3Y-0.4Zr	309.6	381.8	4.4	Cast + Extruded at 400 °C and Hot rolled at 200 °C [93]
Mg-12Gd-3Y-0.4Zr	162.0	285.4	10.9	Cast + Extruded at 400 °C and Hot rolled at 200 °C + Annealed at 450 °C for 2 h [93]
Mg-12Gd-3Y-0.4Zr	141.8	252.8	8.1	Cast + Extruded at 400 °C and Hot rolled at 200 °C + Annealed at 500 °C for 2 h [93]
Mg-12Gd-3Y-0.4Zr	342.8	457.6	3.8	Cast + Extruded at 400 °C and Hot rolled at 200 °C + aged at 225 °C for 17 h (T5) [93]
Mg-8Gd-0.6Zr-1Er	96	190	5.6	As-Cast [53]
Mg-8Gd-0.6Zr-1Er	156	234	5.8	Cast + solution treated at 530 °C for 10 h + Aged at 230 °C [53]
Mg-8Gd-0.6Zr-3Er	101	210	5.3	As-Cast [53]
Mg-8Gd-0.6Zr-3Er	173	261	5.1	Cast + solution treated at 530 °C for 10 h + Aged at 230 °C [53]
Mg-8Gd-0.6Zr-5Er	99	205	4.9	As-Cast [53]
Mg-8Gd-0.6Zr-5Er	160	232	3.7	Cast + solution treated at 530 °C for 10 h + Aged at 230 °C [53]

* indicates the compressive properties of the same alloy.

4.5. Mg-Zn-RE Higher Alloy Systems

Xu *et al*. [94] reported that the as cast Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr alloy consisted of α-Mg grains surrounded by Mg_3(Gd,Y) eutectic compounds while the as-homogenized alloy consisted of 18R and 14 H type LPSO phases which was attributed to the higher strength of as-homogenized alloy. The same authors reported in [95] that the Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr alloy exhibited better properties when it is rolled with 96% reduction. Xu *et al*. [96] reported that upon ageing, the microstructure consisted of β' phase in the α-Mg grains and LPSO and Mg-Gd-Y containing phases at grain boundaries. Freeney *et al*. [97] reported the effects of Friction stir processing and ageing on the grain refinement and breakage and dissolution of second phase particles that resulted in the increase in the strength of the aged alloy. Yang *et al*. [98] attributed the high strength of the GWZ930 (Mg-9Gd-3Y-0.5Zn-0.5Zr) alloy mainly to precipitation strengthening and slightly to grain boundary strengthening. Al-Samman *et al*. [99] investigated sheet texture modification in ZEK100 alloys containing rare earths Ce, Nd, La, Gd and Ce rich Misch metal and reported that the Gd containing alloy has the highest tensile ductility of 30% and a very low tensile yield strength. This was because the Ce, La, Nd and Misch metal containing alloys were said to depict a common rare earth texture while Gd containing alloy revealed a different type of rare earth texture. In Mg-Zn-Mn based alloys, Stulikova *et al*. [100] reported that the as-cast MgY4Zn1Mn1 alloy contained 18R LPSO which were responsible for the high strength. For MgCe4Zn1Mn1 alloy, it was reported that $Mg_{12}Ce$ phase is present along with small particles of Zn and Mg which pins the dislocations thereby increasing the thermal stability of the alloy. Dobron *et al*. [101] investigated the effect of variation of extrusion speeds on the mechanical properties of ZEK100 alloys and reported that the increase in extrusion speed leads to the recrystallized and homogenized microstructure without much effect on the texture. Garcia *et al*. [102] investigated ZEK 100 alloys (with RE = Ce rich Misch metal) which are considered important biomaterials and reported the tensile and compressive properties with respect to the extrusion speeds. The addition of Ce rich misch metal led to the grain refinement leading to very high tensile and compressive properties and also inhibited grain growth due to the presence of intermetallic particles distributed in the matrix. With the addition of Ca to Mg-Zn-RE based alloys, Kamrani *et al*. [103] studied that the microstructure consists of Mg-Ca besides the Mg-RE precipitates that are responsible for the strength. The tension-compression asymmetry was studied and analyzed to be due to the grain size, texture, precipitates that are present at the grain boundaries and inside the grains. Zhang *et al*. [104] studied the effects of Er and reported that Er played a major role in enhancing the ductility as well as solid solution strengthening effects. Zhang *et al*. [105] also reported that the addition of Er has caused the interactions between dislocations and solute and thereby caused yield point phenomenon. Yu *et al*. [106] investigated Mg-Zn-Zr alloys and reported that with the addition of Gd to the alloys, quasicrystal I-phases (Mg-Zn-Gd ternary phase) are formed along the grain boundaries and increased with increasing the Gd content. In a similar study, Xiao *et al*. [107] reported that the Al_2REZn_2 phases are formed with increase in RE content. They also reported in [108] that after ageing, precipitates such as $Mg_{24}Y_5$, W-phase and I-phase were formed and affected the tensile properties of Mg-alloys as shown in Table 20. Langelier *et al*. [50] reported that the combined micro alloying of Ce and Ca results in the formation of $Mg_6Ca_2Zn_3$ particles and MgZnCe T-phase in annealed alloys that limit the texture effects due to their large size and coarse distribution. The improved properties of the alloys are due to the grain boundary pinning by $Mg_6Ca_2Zn_3$ precipitates. Li *et al*. [109] reported that the addition of Nd to Mg-5Zn-0.6Zr led to the change in the morphologies of the phases. The continuous intergranular phases in Mg-Zn-Nd-Zr led to the significant deterioration in the strength and ductility in the as-cast alloys. Yu *et al*. [110] studied the effect of extrusion speed on the mechanical properties and reported that the texture intensity decreased with the increase in extrusion speed thereby improving the tensile properties due to the increased fraction of unDRXed grains. Xu *et al*. [111] reported the properties of forged ZK60-Y alloys as shown in Table 20. Wang *et al*. [112] studied the effects of addition of RE to Mg-8Zn-4Al alloy and reported that a new quaternary Mg3Al4Zn2RE phase is formed and the microstructure is refined with increase in the RE due to the crystal multiplication mechanism and prevention of the grain growth by the quarternary phase that result in the tensile properties as shown in Table 20.

Table 20. Tensile properties of Mg-Zn-RE based higher alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiilty (%)	Remarks Processing Condition and Reference
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	119	187	2.1	As-Cast [94]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	130	206	5.5	Cast + homogenized at 520 °C for 12 h [94]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	186	297	7.3	Cast + hot rolled at 400 °C [94]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	313	373	6.4	Cast + homogenized at 520 °C for 12 h + hot rolled at 400 °C (Reduction 68%) [94]
Mg-8.2Gd-3.8Y-1Zn-0.4Zr	318	403	13.7	Cast + solution treated at 510 °C for 12 h + hot rolled at 400 °C (Reduction 96%) [95]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	455	469	1.3	Cast + Solution treated at 510 °C for 12 h + Rolled at 300 °C + Aged at 200 °C [96]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	393	423	1.5	Cast + Solution treated at 510 °C for 12 h + Rolled at 300 °C + Aged at 225 °C [96]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	372	473	10.2	Cast + Solution treated at 510 °C for 12 h + Rolled at 400°C + Aged at 200 °C [96]
Mg-8.2Gd-3.8Y-1.0Zn-0.4Zr	331	436	17.8	Cast + Solution treated at 510 °C for 12 h + Rolled at 400 °C + Aged at 225 °C [96]
Mg-0.5Zn-3,1Nd-1.7Gd-0.3Zr	188	290	7	Cast + Solutionized at 520 °C/8 h [97]
Mg-0.5Zn-3,1Nd-1.7Gd-0.3Zr	220	275	27	Cast + Friction Stir processed [97]
Mg-0.5Zn-3,1Nd-1.7Gd-0.3Zr	200	330	11.5	Cast + Friction stir processed + Solutionized at 520 °C /8 h (T6) [97]
Mg-0.5Zn-3,1Nd-1.7Gd-0.3Zr	180	320	14	Cast + Friction stir processed + SS + Aged at 200 °C/16 h [97]
Mg-0.5Zn-3,1Nd-1.7Gd-0.3Zr	270	305	14	Cast + Friction stir processed + Aged at 200 °C/16 h [97]
Mg-0.5Zn-0.4Zr-2.5Ce	-	139	-	As-Cast [113]
Mg-0.5Zn-0.4Zr-2.5Ce	-	251.3	-	Cast + homogenized at 320 °C for 18 h + extruded at 350 °C [113]
Mg-0.5Zn-0.4Zr-2.5Nd	-	212.9	-	As-Cast [113]
Mg-0.5Zn-0.4Zr-2.5Ce	-	276	-	Cast + homogenized at 320 °C for 18 h + extruded at 350 °C [113]
Mg-0.5Zn-0.4Zr-2.5Nd-2.5Y	-	244.8	-	As-Cast [113]
Mg-0.5Zn-0.4Zr-2.5Ce	-	258	-	Cast + homogenized at 320 °C for 18 h + extruded at 350 °C [113]
Mg-8.8Gd-3.1Y-0.6Zn-0.5Zr	170	230	7.0	As-Cast [98]
Mg-8.8Gd-3.1Y-0.6Zn-0.5Zr	208	297	17.6	Cast + Extruded at 250 °C [98]
Mg-8.8Gd-3.1Y-0.6Zn-0.5Zr	310	395	13.7	Cast + Extruded at 250 °C + Aged at 200 °C/40 h [98]

Table 20. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiilty (%)	Remarks
				Processing Condition and Reference
Mg-8.8Gd-3.1Y-0.6Zn-0.5Zr	375	430	9.5	Cast + Extruded at 250 °C + Aged at 200 °C/63 h [98]
Mg-8.8Gd-3.1Y-0.6Zn-0.5Zr	340	422	12.9	Cast + Extruded at 250 °C + Aged at 200 °C/100 h [98]
Mg-8.8Gd-3.1Y-0.6Zn-0.5Zr	320	407	14.3	Cast + Extruded at 250 °C + Aged at 200 °C/126 h [98]
Mg-0.7Zn-0.2Zr-0.8Ce	117	232	18.84	Cast + homogenized at 450 °C for 12 h + water quenched+ Rolled at 400 °C + Annealed at 400 °C for 1 h [99]
Mg-0.9Zn-0.2Zr-0.7La	109	241	24.41	
Mg-0.6Zn-0.3Zr-0.6Nd	99	237	28.02	
Mg-0.7Zn-0.2Zr-0.7Gd	78	229	30.34	
Mg-0.8Zn-0.3Zr-MM (MM = 0.6Ce + 0.2La + 0.06Nd)	112	242	23.58	
Mg-1Zn-1Mn-4Y	135	175	6	As-Cast [100]
Mg-1Zn-1Mn-4Y	123	165	10	Cast + Heat Treated at 250 °C/42 h (T5) [100]
Mg-1Zn-1Mn-4Ce	90	120	5	As-Cast [100]
Mg-1Zn-1Mn-4Ce	112	170	9	Cast + Heat Treated at 275 °C/36 h (T5) [100]
Mg-1Zn-0.6Zr-1Ce	199 ± 3.6	283 ± 1.6	6.3	Cast + hot rolled at 400 °C [25]
Mg-1Zn-0.6Zr-1Ce	192.5 ± 2.5	274 ± 2.5	7.9	Cast + hot rolled at 400 °C and annealed for 1 h at 250 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Ce	176 ± 2.7	276.4 ± 3.3	12.8	Cast + hot rolled at 400 °C and annealed for 1 h at 300 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Ce	169.6 ± 1.5	268 ± 2.4	29	Cast + hot rolled at 400 °C and annealed for 1 h at 350 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Ce	155 ± 1.7	263.6 ± 2.5	32.6	Cast + hot rolled at 400 °C and annealed for 1 h at 400 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Ce	135.7 ± 0.4	264 ± 2.9	31.8	Cast + hot rolled at 400 °C and annealed for 1 h at 450 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Gd	194.7 ± 3.8	236.4 ± 4.1	10	Cast + hot rolled at 400 °C
Mg-1Zn-0.6Zr-1Gd	193.8 ± 4.5	238.6 ± 5.9	4.3	Cast + hot rolled at 400 °C and annealed for 1 h at 250 °C+ Water Quenched [25]
Mg-1Zn-0.6Zr-1Gd	173.4 ± 2.7	236.4 ± 3.6	15.7	Cast + hot rolled at 400 °C and annealed for 1 h at 300 °C + Water Quenched [25]

Table 20. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiilty (%)	Remarks Processing Condition and Reference
Mg-1Zn-0.6Zr-1Gd	153.7 ± 4.4	277.8 ± 3.2	37.2	Cast + hot rolled at 400 °C and annealed for 1 h at 350 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Gd	124.7 ± 7	276.5 ± 5	38.8	Cast + hot rolled at 400 °C and annealed for 1 h at 400 °C + Water Quenched [25]
Mg-1Zn-0.6Zr-1Gd	101.9 ± 1.7	249.5 ± 2.6	30	Cast + hot rolled at 400 °C and annealed for 1 h at 450 °C + Water Quenched [25]
Mg-1.3Zn-0.2Ce-0.5Zr	305 ± 3	313 ± 3	7.5 ± 0.1	Cast + Extruded at 300 °C at a speed of 1 m/min[101]
Mg-1.3Zn-0.2Ce-0.5Zr	204 ± 1	257 ± 1	9.3 ± 0.1	Cast + Extruded at 300 °C at a speed of 10 m/min [101]
Mg-1.3Zn-0.2Ce-0.5Zr	209 ± 2	259 ± 2	9.2 ± 0.1	Cast + Extruded at 300 °C at a speed of 20 m/min [101]
Mg-1Zn-0.8RE-0.4Zr	296 184 *	299 434 *	18 9 *	Cast + Extruded at 300 °C at 1 m/min + Annealed at 400 °C/1 h [102]
Mg-1Zn-0.8RE-0.4Zr	221 156 *	260 381 *	21 10 *	Cast + Extruded at 300 °C at 5 m/min + Annealed at 400 °C/1 h [102]
Mg-1Zn-0.8RE-0.4Zr	201 142 *	251 369 *	19 11*	Cast + Extruded at 300 °C at 10 m/min + Annealed at 400 °C/1 h [102]
Mg-2Zn-0.8RE-0.6Zr	308 201 *	311 462 *	19 9 *	Cast + Extruded at 300 °C at 1 m/min + Annealed at 400 °C/1 h [102]
Mg-2Zn-0.8RE-0.6Zr	246 162 *	275 435 *	20 10 *	Cast + Extruded at 300 °C at 5 m/min + Annealed at 400 °C/1 h [102]
Mg-2Zn-0.8RE-0.6Zr	225 154 *	264 412 *	19 10 *	Cast + Extruded at 300 °C at 10 m/min + Annealed at 400 °C/1 h [102]
Mg-2.8Zn-0.8RE-0.6Zr	260 185 *	290 450 *	19 9.5 *	Cast + Extruded at 300 °C at 1m/min + Annealed at 400 °C/1 h [102]
Mg-2.8Zn-0.8RE-0.6Zr	243 169 *	279 447 *	21 10 *	Cast + Extruded at 300 °C at 5 m/min + Annealed at 400 °C/1 h [102]
Mg-2.8Zn-0.8RE-0.6Zr	218 156 *	267 420 *	20 10 *	Cast + Extruded at 300 °C at 10 m/min + Annealed at 400 °C/1 h [102]
Mg-1.4Zn-0.1Zr-0.1RE (RE: 49.1 Ce, 35.9 La, 11.0 Nd, 4.0 Pr)	200 ± 7 **150 ± 6 ***	250 ± 5 **441 ± 3 ***	15.3 ± 0.3 **12.0 ± 0.2 ***	Die Cast + Extruded at 300 °C + Annealed at 300 °C for 30 min [103]
Mg-1.4Zn-0.1Zr-0.1RE-0.4Ca (RE: 49.1 Ce, 35.9 La, 11.0 Nd, 4.0 Pr)	171 ± 2 **148 ± 1 ***	243 ± 1 **432 ± 6 ***	14.6 ± 0.0 **11.7 ± 0.2 ***	
Mg-1.4Zn-0.1Zr-0.1RE-0.8Ca (RE: 49.1 Ce, 35.9 La, 11.0 Nd, 4.0 Pr)	174 ± 1 **149 ± 2 ***	243 ± 1 **410 ± 4 ***	15.1 ± 1.1 **22.0 ± 5.0 ***	

Table 20. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiilty (%)	Remarks Processing Condition and Reference
Mg-1.5Zn-0.6Zr-0.5Er	261	300	27	Cast + homogenized for 12 h at 410 °C + Extruded at 350 °C [104]
Mg-1.5Zn-0.6Zr-0.5Er	261	290	27	Cast + homogenized for 12 h at 410 °C + Extruded at 420 °C [105]
Mg-1.5Zn-0.6Zr-1Er	205	385	25	Cast + homogenized for 12 h at 410 °C + Extruded at 350 °C [104]
Mg-1.5Zn-0.6Zr-1Er	285	305	24	Cast + homogenized for 12 h at 410 °C + Extruded at 420 °C [105]
Mg-1.5Zn-0.6Zr-2Er	195	340	31	Cast + homogenized for 12 h at 410 °C + Extruded at 350 °C [104]
Mg-1.5Zn-0.6Zr-2Er	255	275	30	Cast + homogenized for 12 h at 410 °C + Extruded at 420 °C [105]
Mg-1.5Zn-0.6Zr-4Er	230	270	37	Cast + homogenized for 12 h at 410 °C + Extruded at 350 °C [104]
Mg-1.5Zn-0.6Zr-4Er	230	260	37	Cast + homogenized for 12 h at 410 °C + Extruded at 420 °C [105]
Mg-9Gd-1Er-1.6Zn-0.6Zr	220	302	19	Cast + annealed at 400 °C for 24 h + Extruded at 400 °C [114]
Mg-9Gd-1Er-1.6Zn-0.6Zr	269	344	10	Cast + annealed at 525 °C for 4 h + Extruded at 400 °C [114]
Mg-9Gd-2Er-1.6Zn-0.6Zr	221	306	17.8	Cast + annealed at 400 °C for 24 h + Extruded at 400 °C [114]
Mg-9Gd-2Er-1.6Zn-0.6Zr	262	342	11.7	Cast + annealed at 525 °C for 4 h + Extruded at 400 °C [114]
Mg-9Gd-3Er-1.6Zn-0.6Zr	223	308	14.6	Cast + annealed at 400 °C for 24 h + Extruded at 400 °C [114]
Mg-9Gd-3Er-1.6Zn-0.6Zr	263	339	10.4	Cast + annealed at 525 °C for 4 h + Extruded at 400 °C [114]
Mg-9Gd-4Er-1.6Zn-0.6Zr	235	321	14.2	Cast + annealed at 400 °C for 24 h + Extruded at 400 °C [114]
Mg-9Gd-4Er-1.6Zn-0.6Zr	261	333	8.4	Cast + annealed at 525 °C for 4 h + Extruded at 400 °C [114]
Mg-2Zn-0.3Ca-0.1Ce	131 ± 12.3	222 ± 7.0	23.9 ± 0.27	Cast + homogenized for 3 h at 300 °C + 24 h at 400 °C + hot rolled at 400 °C + annealed at 400 °C for 30 min [50]
Mg-4Zn-0.3Ca-0.1Ce	119 ± 2.1	240 ± 1.5	18.3 ± 1.30	
Mg-5Zn-1Nd-0.6Zr	100	200	7.5	As-Cast [109]
Mg-5Zn-2Nd-0.6Zr	90	135	3	
Mg-5Zn-2Nd-0.5Y-0.6Zr	95	205	9.5	
Mg-5Zn-2Nd-1Y-0.6Zr	105	220	12	
Mg-5.5Zn-0.6Zr-0.2Gd	227	307	25.3	Cast + homogenized at 300 °C for 20 h and 400 °C for 12 h + high strain rate rolled at 400 °C [106]
Mg-5.5Zn-0.6Zr-0.5Gd	235	318	23.2	
Mg-5.5Zn-0.6Zr-0.8Gd	242	327	22	

Table 20. *Cont.*

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductiilty (%)	Remarks Processing Condition and Reference
Mg-6Zn-0.5Zr-1Ce	293	337	26.9	Cast + homogenized at 440 °C for 8 h + water quenched+ extruded at 250 °C at 0.3 mm/s [110]
Mg-6Zn-0.5Zr-1Ce	286	333	25.4	Cast + homogenized at 440 °C for 8 h + water quenched+ extruded at 250 °C at 1.0 mm/s [110]
Mg-6Zn-0.5Zr-1Ce	247	311	22.6	Cast + homogenized at 440 °C for 8 h + water quenched+ extruded at 250 °C at 3 mm/s [110]
Mg-6.3Zn-2Zr-1Y	127	267	12.1	Cast + Forged [111]
Mg-6.3Zn-2Zr-1Y	84	244	13.2	Cast + Forged +Solid solution for 2.5 h at 500 °C (T_4) [111]
Mg-6.3Zn-2Zr-1Y	124	259	10.8	Cast + Forged + Solid solution for 2.5 h at 500 °C + aged for 15 h at 180 °C (T6) [111]
Mg-6.3Zn-2Zr-1Y	129	309	18.7	Cast + Forged + aged for15 h at 180 °C (T5) [111]
Mg-7.5Zn-5Al-0.123RE	100	175	2.2	As-Cast [107]
Mg-7.5Zn-5Al-0.123RE	100	160	1.5	Cast + heat treated at 350 °C for 96 h + water quenched + aged at 175 °C for 16 h [107]
Mg-7.6Zn-5Al-0.763RE	104	198	2.8	As-Cast [107]
Mg-7.6Zn-5Al-0.763RE	120	232	3.4	Cast + heat treated at 350 °C for 96 h + water quenched + aged at 175 °C for 16 h [107]
Mg-7Zn-5Al-1.753RE	100	186	1.9	As-Cast [107]
Mg-7Zn-5Al-1.753RE	120	240	5.2	Cast + heat treated at 350 °C for 96 h + water quenched + aged at 175 °C for 16 h [107]
Mg-8Zn-4Al-0.5RE	110	145	4.5	
Mg-8Zn-4Al-1.0RE	118	158	4.2	As-Cast [112]
Mg-8Zn-4Al-1.5RE	123	165	4	
Mg-12.3Zn-5.8Y-1.4Al	191	100	6.9	As-Cast [108]
Mg-12.3Zn-5.8Y-1.4Al	203	106	4.9	Cast + Solution treated at 335 °C for 12 h + quenched in water + Aged at 200 °C [108]

* indicates the compressive properties of the same alloy.

4.6. Mg-Sn-RE Higher Alloy System

Cheng *et al*. [115] reported that peak ageing occurred faster with the addition of Ce to the Mg-5Sn-4Zn alloy. They showed that the microstructure consisted of Sn-Ce precipitates in the aged alloy in addition to the α-Mg phase and Mg_2Sn phase. It was also reported that with the addition of Ce, the Sn-Ce phase predominates reducing the Mg_2Sn phase thereby affecting the properties as shown in Table 21.

Table 21. Tensile properties of Mg-Sn-RE based higher alloys.

Alloy (wt.%)	TensileYield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-4Zn-5Sn-1Ce	155	275	27.5	Cast + homogenized at 420 °C for 24 h + Extruded at 250 °C [115]
Mg-4Zn-5Sn-1Ce	190	200	30	Cast + homogenized at 420 °C for 24 h+ Extruded at 250 °C + solutionized at 450 °C for 1 h + aged at 200 °C (T6) [115]

4.7. Other Higher Alloy Systems

The combined addition of Er/Al by microalloying has led to improved mechanical properties due to the reduced grain size and homogenous microstructure after particle-stimulated nucleation assisted dynamic recrystallization [56]. Du *et al.* [57] reported that the addition of V resulted in improvement in morphology of 18R LPSO thereby resulting in improved properties as compared to Mg-10Er-2Cu stated in Table 15. The properties are as shown in Table 22.

Table 22. Tensile properties of other higher alloys.

Alloy (wt.%)	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Ductility (%)	Remarks Processing condition and Reference
Mg-1.8Mn-0.1Er-0.05Al	224	244	4	Cast + homogenized at 450 °C for 4 h +
Mg-1.8Mn-0.4Er-0.2Al	224	245	8	Extruded at 450 °C + Annealed at 390 °C
Mg-1.8Mn-0.7Er-0.34Al	226	250	19	for 1 h [56]
Mg-10Er-2Cu-V	370	430	11	Cast + homogenized at 450 °C for 24 h + Extruded at 430 °C [57]

Hence, the rare earths have an immense effect on the properties of the Mg alloys but the cost of most of the rare earths is higher compared to the conventional alloying elements due to the scarcity in their availability.

5. Conclusions

In this review, the mechanical properties of various magnesium-rare earth alloys processed under different conditions, investigated by various researchers, are reviewed, and the reasons for their mechanical behavior are studied. The tensile properties of the investigated binary alloys which include Mg-Y, Mg-Ce, Mg-Gd, Mg-La, Mg-Er, Mg-Nd, and Mg-Dy systems are reported. The report also includes the tensile and compressive properties of Mg-RE ternary system containing two different rare earths as alloying elements and Mg-Zn-RE, Mg-Zr-RE, Mg-Sn-RE, and other ternary systems are reported. Finally, the properties of Mg-Al-RE, Mg-Li-RE, Mg-Zr-RE, Mg-Zn-RE, Mg-Sn-RE and other higher alloy systems containing three or more alloying elements are also briefly studied.

Rare earths are widely added to Mg in the form of Misch Metals which are unspecified blends of RE due to the low cost of Misch metals. However, considering the microstructure and mechanical properties of different Mg-RE systems, each one behaves differently from the others. So, it would be necessary to indicate the actual type and composition of RE addition in order to attribute the effect of RE addition to the properties. Further, in biodegradable Mg-RE alloys, each RE element has unique toxicity level and self-degradation period and therefore the use of Misch metals would make the alloy design complex.

Of all the rare earth elements, Y and Ce are being researched widely in combination with other alloying elements due to their significant influence on mechanical properties and texture effects. Besides having good tensile properties, some of the alloys like Mg-Y, Mg-Gd, Mg-Dy, Mg-Nd, WE43, LAE442, ZEK100, JDBM, *etc*., have good biodegradability and the properties of these biodegradable materials are also presented.

The research on Mg-RE systems conducted so far revealed that with regard to specific Mg-RE binary alloy systems, Mg-Y alloys exhibited the best strength while the Mg-Er alloys exhibited the best ductility. In ternary alloys, Mg-Zn-RE system exhibited the highest strength and ductility. Similarly among the higher alloy systems, Mg-Zn-RE based higher alloy system containing three or more alloying elements exhibited best tensile strength and ductility levels.

Overall, the best combination of both strength and ductility was observed in Mg-Y alloys in binary systems, Mg-Zn-RE alloys in ternary systems and Mg-Zn-RE based alloys in higher alloy systems.

Owing to the high cost of rare earths, it is not economical to use rare earths in high concentrations. Hence, it is suggested that further research be done by micro alloying (<1%) to offset the cost of the rare earths without compromising the properties.

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Author Contributions

All authors contributed to the paper. Sravya Tekumalla acquired and interpreted the data. Sravya Tekumalla and Sankaranarayanan Seetharaman provided the analysis in the paper and prepared the manuscript. Manoj Gupta designed the scope of the paper and Manoj Gupta and Abdulhakim Almajid revised the paper. All authors discussed the conclusions and reviewed the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Mordike, B.L.; Ebert, T. Magnesium: Properties—Applications—Potential. *Mater. Sci. Eng. A* **2001**, *302*, 37–45.
2. Somekawa, H.; Mukai, T. Effect of texture on fracture toughness in extruded AZ31 magnesium alloy. *Scripta Mater.* **2005**, *53*, 541–545.
3. Yang, Z.; Li, J.P.; Zhang, J.X.; Lorimer, G.W.; Robson, J. Review on research and development of magnesium alloys. *Acta Metall. Sinica (Engl. Lett.)* **2008**, *21*, 313–328.
4. Huang, Y.; Gan, W.; Kainer, K.U.; Hort, N. Role of multi-microalloying by rare earth elements in ductilization of magnesium alloys. *J. Magnes. Alloys* **2014**, *2*, 1–7.
5. Stanford, N.; Atwell, D.; Beer, A.; Davies, C.; Barnett, M.R. Effect of microalloying with rare-earth elements on the texture of extruded magnesium-based alloys. *Scripta Mater.* **2008**, *59*, 772–775.
6. Chia, T.L.; Easton, M.A.; Zhu, S.M.; Gibson, M.A.; Birbilis, N.; Nie, J.F. The effect of alloy composition on the microstructure and tensile properties of binary Mg-rare earth alloys. *Intermetallics* **2009**, *17*, 481–490.
7. Gao, L.; Chen, R.S.; Han, E.H. Solid solution strengthening behaviors in binary Mg–Y single phase alloys. *J. Alloy. Compd.* **2009**, *472*, 234–240.
8. Hirsch, J.; Al-Samman, T. Superior light metals by texture engineering: Optimized aluminum and magnesium alloys for automotive applications. *Acta Mater.* **2013**, *61*, 818–843.
9. Luo, A.A.; Sachdev, A.K. 12—Applications of magnesium alloys in automotive engineering. In *Advances in Wrought Magnesium Alloys*; Bettles, C., Barnett, M., Eds.; Woodhead Publishing: Cambridge, UK, 2012; pp. 393–426.
10. Witte, F. The history of biodegradable magnesium implants: A review. *Acta Biomater.* **2010**, *6*, 1680–1692.
11. Zheng, Y.F.; Gu, X.N.; Witte, F. Biodegradable metals. *Mater. Sci. Eng. R. Rep.* **2014**, *77*, 1–34.
12. Hort, N.; Huang, Y.; Fechner, D.; Störmer, M.; Blawert, C.; Witte, F.; Vogt, C.; Drücker, H.; Willumeit, R.; Kainer, K.U.; *et al.* Magnesium alloys as implant materials—Principles of property design for Mg–RE alloys. *Acta Biomater.* **2010**, *6*, 1714–1725.
13. Rokhlin, L.L. Structure and properties of alloys of the Mg-RE system. *Met. Sci. Heat Treat.* **2006**, *48*, 487–490.
14. Zhao, H.D.; Qin, G.W.; Ren, Y.P.; Pei, W.L.; Chen, D.; Guo, Y. The maximum solubility of Y in α-Mg and composition ranges of $Mg_{24}Y_{5-x}$ and Mg_2Y_{1-x} intermetallic phases in Mg–Y binary system. *J. Alloy. Compd.* **2011**, *509*, 627–631.
15. Gu, X.; Zheng, Y.; Cheng, Y.; Zhong, S.; Xi, T. *In vitro* corrosion and biocompatibility of binary magnesium alloys. *Biomaterials* **2009**, *30*, 484–498.
16. Zhou, N.; Zhang, Z.; Jin, L.; Dong, J.; Chen, B.; Ding, W. Ductility improvement by twinning and twin–slip interaction in a Mg-Y alloy. *Mater. Des.* **2014**, *56*, 966–974.
17. Essadiqi, E.; Shehata, M.T.; Javaid, A.; Shen, G.; Aljarrah, M.; Verma, R.; Mishra, R. In *Alloying and Process Design of Mg Sheet*; CANMET Materials: Ottawa, ON, Canada, 2011.
18. Sandlöbes, S.; Zaefferer, S.; Schestakow, I.; Yi, S.; Gonzalez-Martinez, R. On the role of non-basal deformation mechanisms for the ductility of mg and Mg–Y alloys. *Acta Mater.* **2011**, *59*, 429–439.

19. Wu, B.L.; Zhao, Y.H.; Du, X.H.; Zhang, Y.D.; Wagner, F.; Esling, C. Ductility enhancement of extruded magnesium via yttrium addition. *Mater. Sci. Eng. A* **2010**, *527*, 4334–4340.
20. Sugamata, M.; Hanawa, S.; Kaneko, J. Structures and mechanical properties of rapidly solidified Mg-Y based alloys. *Mater. Sci. Eng. A* **1997**, *226–228*, 861–866.
21. Zhang, B.; Nagasekhar, A.V.; Tao, X.; Ouyang, Y.; Cáceres, C.H.; Easton, M. Strengthening by the percolating intergranular eutectic in an hpdc Mg–Ce alloy. *Mater. Sci. Eng. A* **2014**, *599*, 204–211.
22. Mishra, R.K.; Gupta, A.K.; Rao, P.R.; Sachdev, A.K.; Kumar, A.M.; Luo, A.A. Influence of cerium on the texture and ductility of magnesium extrusions. *Scripta Mater.* **2008**, *59*, 562–565.
23. Chino, Y.; Kado, M.; Mabuchi, M. Enhancement of tensile ductility and stretch formability of magnesium by addition of 0.2 wt%(0.035 at%)Ce. *Mater. Sci. Eng. A* **2008**, *494*, 343–349.
24. Luo, A.A.; Wu, W.; Mishra, R.K.; Jin, L.; Sachdev, A.K.; Ding, W. Microstructure and mechanical properties of extruded magnesium-aluminum-cerium alloy tubes. *Metall. Mater. Trans. A* **2010**, *41*, 2662–2674.
25. Basu, I.; Al-Samman, T. Triggering rare earth texture modification in magnesium alloys by addition of zinc and zirconium. *Acta Mater.* **2014**, *67*, 116–133.
26. Nayeb-Hashemi, A.A. *Phase Diagrams of Binary Magnesium Alloys*; ASM International: Metals Park, OH, USA, 1998.
27. Gao, L.; Chen, R.S.; Han, E.H. Effects of rare-earth elements Gd and Y on the solid solution strengthening of mg alloys. *J. Alloy. Compd.* **2009**, *481*, 379–384.
28. Peng, Q.; Wu, Y.; Fang, D.; Meng, J.; Wang, L. Microstructures and properties of melt-spun and as-cast Mg-20Gd binary alloy. *J. Rare Earths* **2006**, *24*, 466–470.
29. Stanford, N.; Atwell, D.; Barnett, M.R. The effect of gd on the recrystallisation, texture and deformation behaviour of magnesium-based alloys. *Acta Mater.* **2010**, *58*, 6773–6783.
30. Stanford, N.; Barnett, M.R. The origin of "rare earth" texture development in extruded Mg-based alloys and its effect on tensile ductility. *Mater. Sci. Eng. A* **2008**, *496*, 399–408.
31. Rokhlin, L.L. *Magnesium Alloys Containing Rare Earth Metals*; Taylor & Francis: New York, NY, USA, 2003.
32. Wu, B.L.; Wan, G.; Du, X.H.; Zhang, Y.D.; Wagner, F.; Esling, C. The quasi-static mechanical properties of extruded binary Mg–Er alloys. *Mater. Sci. Eng. A* **2013**, *573*, 205–214.
33. Wang, Z.; Jia, W.; Cui, J. Study on the deformation behavior of Mg-3.6%Er magnesium alloy. *J. Rare Earths* **2007**, *25*, 744–748.
34. Yan, J.; Sun, Y.; Xue, F.; Xue, S.; Tao, W. Microstructure and mechanical properties in cast magnesium–neodymium binary alloys. *Mater. Sci. Eng. A* **2008**, *476*, 366–371.
35. Seitz, J.M.; Eifler, R.; Stahl, J.; Kietzmann, M.; Bach, F.W. Characterization of $MgNd_2$ alloy for potential applications in bioresorbable implantable devices. *Acta Biomater.* **2012**, *8*, 3852–3864.
36. Bi, G.; Li, Y.; Zang, S.; Zhang, J.; Ma, Y.; Hao, Y. Microstructure, mechanical and corrosion properties of Mg–2Dy–*x*Zn (x = 0, 0.1, 0.5 and 1 at.%) alloys. *J. Magnes. Alloy.* **2014**, *2*, 64–71.
37. Yang, L.; Huang, Y.; Peng, Q.; Feyerabend, F.; Kainer, K.U.; Willumeit, R.; Hort, N. Mechanical and corrosion properties of binary Mg–Dy alloys for medical applications. *Mater. Sci. Eng. B* **2011**, *176*, 1827–1834.

38. Yang, L.; Huang, Y.; Feyerabend, F.; Willumeit, R.; Kainer, K.U.; Hort, N. Influence of ageing treatment on microstructure, mechanical and bio-corrosion properties of Mg–Dy alloys. *J. Mech. Behav. Biomed. Mater.* **2012**, *13*, 36–44.
39. Zhang, Q.; Li, Q.; Jing, X.; Zhang, X. Microstructure and mechanical properties of Mg-10Y-2.5Sm alloy. *J. Rare Earths* **2010**, *28* (Suppl. 1), 375–377.
40. Gavras, S.; Easton, M.A.; Gibson, M.A.; Zhu, S.; Nie, J.-F. Microstructure and property evaluation of high-pressure die-cast Mg–La–rare earth (Nd, Y or Gd) alloys. *J. Alloy. Compd.* **2014**, *597*, 21–29.
41. Wang, X.; Wang, Z.; Du, W.; Liu, K.; Li, S. Microstructure evolutions of Mg-8Gd-2Er (wt.%) alloy during isothermal ageing at 200 °C. *J. Rare Earths* **2012**, *30*, 1168–1171.
42. Luo, A.A.; Mishra, R.K.; Sachdev, A.K. Development of high ductility magnesium-zinc-cerium extrusion alloys. In Proceedings of the 2010 TMS Annual Meeting & Exhibition, Seattle, WA, USA, 14–18 February 2010; pp. 313–318.
43. Le, Q.-C.; Zhang, Z.-Q.; Shao, Z.-W.; Cui, J.-Z.; Xie, Y. Microstructures and mechanical properties of Mg-2%Zn-0.4%Re alloys. *Trans. Nonferrous Metals Soc. China* **2010**, *20*, s352–s356.
44. Wu, D.; Chen, R.S.; Han, E.H. Excellent room-temperature ductility and formability of rolled Mg–Gd–Zn alloy sheets. *J. Alloy. Compd.* **2011**, *509*, 2856–2863.
45. Wang, Z.-H.; Wang, X.-D.; Wang, Q.-F.; Du, W.-B. Effects of ultrasonic treatment on microstructure and mechanical properties of Mg-5Zn-2Er alloy. *Trans. Nonferrous Metals Soc. China* **2011**, *21*, 773–777.
46. Zhao, X.-F.; Li, S.-B.; Wang, Q.-F.; Du, W.-B.; Liu, K. Effects of heat treatment on microstructure and mechanical properties of Mg–5Zn–0.63Er alloy. *Trans. Nonferrous Metals Soc. China* **2013**, *23*, 59–65.
47. Wang, Q.; Liu, K.; Wang, Z.; Li, S.; Du, W. Microstructure, texture and mechanical properties of as-extruded Mg–Zn–Er alloys containing W-phase. *J. Alloy. Compd.* **2014**, *602*, 32–39.
48. Srinivasan, A.; Huang, Y.; Mendis, C.L.; Blawert, C.; Kainer, K.U.; Hort, N. Investigations on microstructures, mechanical and corrosion properties of Mg–Gd–Zn alloys. *Mater. Sci. Eng. A* **2014**, *595*, 224–234.
49. Singh, A.; Somekawa, H.; Mukai, T. High temperature processing of Mg–Zn–Y alloys containing quasicrystal phase for high strength. *Mater. Sci. Eng. A* **2011**, *528*, 6647–6651.
50. Langelier, B.; Nasiri, A.M.; Lee, S.Y.; Gharghouri, M.A.; Esmaeili, S. Improving microstructure and ductility in the Mg–Zn alloy system by combinational Ce–Ca microalloying. *Mater. Sci. Eng. A* **2015**, *620*, 76–84.
51. Li, H.; Du, W.; Li, S.; Wang, Z. Effect of Zn/Er weight ratio on phase formation and mechanical properties of as-cast Mg–Zn–Er alloys. *Mater. Des.* **2012**, *35*, 259–265.
52. Liu, K.; Wang, Q.-F.; Du, W.-B.; Wang, Z.-H.; Li, S.-B. Microstructure and mechanical properties of extruded Mg–6Zn–*x*Er alloys. *Trans. Nonferrous Metals Soc. China* **2013**, *23*, 2863–2873.
53. Peng, Q.; Dong, H.; Wu, Y.; Wang, L. Age hardening and mechanical properties of Mg–Gd–Er alloy. *J. Alloy. Compd.* **2008**, *456*, 395–399.
54. Zhao, H.-D.; Qin, G.-W.; Ren, Y.-P.; Pei, W.-L.; Chen, D.; Guo, Y. Microstructure and tensile properties of as-extruded Mg-Sn-Y alloys. *Trans. Nonferrous Metals Soc. China* **2010**, *20*, s493–s497.

55. Wang, Q.; Chen, Y.; Xiao, S.; Zhang, X.; Tang, Y.; Wei, S.; Zhao, Y. Study on microstructure and mechanical properties of as-cast Mg-Sn-Nd alloys. *J. Rare Earths* **2010**, *28*, 790–793.
56. Zhang, J.; Yuan, F.; Liu, M.; Pan, F. Microstructure and mechanical properties of Mg–1.8%Mn alloy modified by single Er and composite Er/Al microalloying. *Mater. Sci. Eng. A* **2013**, *576*, 185–191.
57. Du, X.H.; Duan, G.S.; Hong, M.; Wang, D.P.; Wu, B.L.; Zhang, Y.D.; Esling, C. Effect of V on the microstructure and mechanical properties of Mg–10Er–2Cu alloy with a long period stacking ordered structure. *Mater. Lett.* **2014**, *122*, 312–314.
58. Zhang, X.; Yuan, G.; Mao, L.; Niu, J.; Ding, W. Biocorrosion properties of as-extruded Mg–Nd–Zn–Zr alloy compared with commercial AZ31 and WE43 alloys. *Mater. Lett.* **2012**, *66*, 209–211.
59. Mabuchi, M.; Chino, Y.; Iwasaki, H. Tensile properties at room temperature to 823 K of Mg-4Y-3RE alloy. *Mater. Trans.* **2002**, *43*, 2063–2068.
60. Su, Z.; Liu, C.; Wan, Y. Microstructures and mechanical properties of high performance Mg–4Y–2.4Nd–0.2Zn–0.4Zr alloy. *Mater. Des.* **2013**, *45*, 466–472.
61. Mukai, T.; Mohri, T.; Mabuchi, M.; Nakamura, M.; Ishikawa, K.; Higashi, K. Experimental study of a structural magnesium alloy with high absorption energy under dynamic loading. *Scripta Mater.* **1998**, *39*, 1249–1253.
62. Panigrahi, S.K.; Yuan, W.; Mishra, R.S.; DeLorme, R.; Davis, B.; Howell, R.A.; Cho, K. A study on the combined effect of forging and aging in Mg–Y–RE alloy. *Mater. Sci. Eng. A* **2011**, *530*, 28–35.
63. Rzychoń, T.; Kiełbus, A.; Cwajna, J.; Mizera, J. Microstructural stability and creep properties of die casting Mg–4Al–4RE magnesium alloy. *Mater. Charact.* **2009**, *60*, 1107–1113.
64. Dai, J.; Zhu, S.; Easton, M.A.; Zhang, M.; Qiu, D.; Wu, G.; Liu, W.; Ding, W. Heat treatment, microstructure and mechanical properties of a Mg–Gd–Y alloy grain-refined by Al additions. *Mater. Sci. Eng. A* **2013**, *576*, 298–305.
65. Zhang, J.-J.; Liu, S.-J.; Leng, Z.; Zhang, M.-L.; Meng, J.; Wu, R.-Z. Structure stability and mechanical properties of high-pressure die-cast Mg–Al–Ce–Y-based alloy. *Trans. Nonferrous Metals Soc. China* **2012**, *22*, 262–267.
66. Zhang, J.; Leng, Z.; Liu, S.; Zhang, M.; Meng, J.; Wu, R. Structure stability and mechanical properties of Mg–Al-based alloy modified with Y-rich and Ce-rich misch metals. *J. Alloys Compd.* **2011**, *509*, L187-L193.
67. Rzychoń, T.; Kiełbus, A.; Lityńska-Dobrzyńska, L. Microstructure, microstructural stability and mechanical properties of sand-cast Mg–4Al–4RE alloy. *Mater. Charact.* **2013**, *83*, 21–34.
68. Zhang, J.; Yu, P.; Liu, K.; Fang, D.; Tang, D.; Meng, J. Effect of substituting cerium-rich mischmetal with lanthanum on microstructure and mechanical properties of die-cast Mg–Al–RE alloys. *Mater. Des.* **2009**, *30*, 2372–2378.
69. Zhang, J.; Leng, Z.; Zhang, M.; Meng, J.; Wu, R. Effect of ce on microstructure, mechanical properties and corrosion behavior of high-pressure die-cast Mg–4Al-based alloy. *J. Alloy. Compd.* **2011**, *509*, 1069–1078.
70. Zhang, J.; Zhang, M.; Meng, J.; Wu, R.; Tang, D. Microstructures and mechanical properties of heat-resistant high-pressure die-cast Mg–4Al–*x*La–0.3Mn (x = 1, 2, 4, 6) alloys. *Mater. Sci. Eng. A* **2010**, *527*, 2527–2537.

71. Zhang, J.; Liu, K.; Fang, D.; Qiu, X.; Yu, P.; Tang, D.; Meng, J. Microstructures, mechanical properties and corrosion behavior of high-pressure die-cast Mg–4Al–0.4Mn–*x*Pr (*x* = 1, 2, 4, 6) alloys. *J. Alloy. Compd.* **2009**, *480*, 810–819.
72. Zhang, J.; Wang, J.; Qiu, X.; Zhang, D.; Tian, Z.; Niu, X.; Tang, D.; Meng, J. Effect of Nd on the microstructure, mechanical properties and corrosion behavior of die-cast Mg–4Al-based alloy. *J. Alloy. Compd.* **2008**, *464*, 556–564.
73. Wang, J.; Liao, R.; Wang, L.; Wu, Y.; Cao, Z.; Wang, L. Investigations of the properties of Mg–5Al–0.3Mn–*x*Ce (*x* = 0–3 wt.%) alloys. *J. Alloy. Compd.* **2009**, *477*, 341–345.
74. Chen, Y.; Hao, L.; Ruiyu, Y.; Liu, G.; Xia, T. Effects of Nd on microstructure and mechanical properties of Mg–Al–Ca alloy. *Mater. Sci. Technol.* **2013**, *30*, 495–500.
75. Wu, G.; Fan, Y.; Gao, H.; Zhai, C.; Zhu, Y.P. The effect of Ca and rare earth elements on the microstructure, mechanical properties and corrosion behavior of AZ91D. *Mater. Sci. Eng. A* **2005**, *408*, 255–263.
76. Krause, A.; von der Höh, N.; Bormann, D.; Krause, C.; Bach, F.-W.; Windhagen, H.; Meyer-Lindenberg, A. Degradation behaviour and mechanical properties of magnesium implants in rabbit tibiae. *J. Mater. Sci.* **2010**, *45*, 624–632.
77. Zeng, R.; Qi, W.; Zhang, F.; Cui, H.; Zheng, Y. *In vitro* corrosion of Mg–1.21Li–1.12Ca–1Y alloy. *Prog. Nat. Sci. Mater. Int.* **2014**, *24*, 492–499.
78. Tao, W.; Zhang, M.; Niu, Z.; Liu, B. Influence of rare earth elements on microstructure and mechanical properties of Mg-Li alloys. *J. Rare Earths* **2006**, *24*, 797–800.
79. Zhou, W.R.; Zheng, Y.F.; Leeflang, M.A.; Zhou, J. Mechanical property, biocorrosion and *in vitro* biocompatibility evaluations of Mg–Li–(Al)–(RE) alloys for future cardiovascular stent application. *Acta Biomater.* **2013**, *9*, 8488–8498.
80. Wang, T.; Zhang, M.; Wu, R. Microstructure and properties of Mg–8Li–1Al–1Ce alloy. *Mater. Lett.* **2008**, *62*, 1846–1848.
81. Wu, R.Z.; Qu, Z.K.; Zhang, M.L. Reviews on the influences of alloying elements on the microstructure and mechanical properties of Mg-Li based alloys. *Rev. Adv. Mater. Sci.* **2010**, *24*, 14–34.
82. Wang, J.; Nie, J.-J.; Wang, R.; Xu, Y.-D.; Zhu, X.-R.; Ling, G.-P. Effect of Y on age hardening response and mechanical properties of Mg-*x*Y–1.5LPC−0.4Zr alloys. *Trans. Nonferrous Metals Soc. China* **2012**, *22*, 1549–1555.
83. Mohri, T.; Mabuchi, M.; Saito, N.; Nakamura, M. Microstructure and mechanical properties of a Mg-4Y-3RE alloy processed by thermo-mechanical treatment. *Mater. Sci. Eng. A* **1998**, *257*, 287–294.
84. Zhang, X.-B.; Xue, Y.-J.; Wang, Z.-Z. Effect of heat treatment on microstructure, mechanical properties and *in vitro* degradation behavior of as-extruded Mg-2.7Nd-0.2Zn-0.4Zr alloy. *Trans. Nonferrous Metals Soc. China* **2012**, *22*, 2343–2350.
85. Zhang, X.; Yuan, G.; Wang, Z. Mechanical properties and biocorrosion resistance of Mg-Nd-Zn-Zr alloy improved by cyclic extrusion and compression. *Mater. Lett.* **2012**, *74*, 128–131.
86. Zhang, X.; Yuan, G.; Niu, J.; Fu, P.; Ding, W. Microstructure, mechanical properties, biocorrosion behavior, and cytotoxicity of as-extruded Mg–Nd–Zn–Zr alloy with different extrusion ratios. *J. Mech. Behav. Biomed. Mater.* **2012**, *9*, 153–162.

87. Zhang, X.; Wang, Z.; Yuan, G.; Xue, Y. Improvement of mechanical properties and corrosion resistance of biodegradable Mg–Nd–Zn–Zr alloys by double extrusion. *Mater. Sci. Eng. B* **2012**, *177*, 1113–1119.
88. Kielbus, A.; Rzychon, T. Mechanical and creep properties of Mg-4Y-3RE and Mg-3Nd-1Gd magnesium alloy. *Procedia Eng.* **2011**, *10*, 1835–1840.
89. Zheng, K.Y.; Dong, J.; Zeng, X.Q.; Ding, W.J. Effect of thermo-mechanical treatment on the microstructure and mechanical properties of a Mg–6Gd–2Nd–0.5Zr alloy. *Mater. Sci. Eng. A* **2007**, *454–455*, 314–321.
90. Xiao, B.L.; Yang, Q.; Yang, J.; Wang, W.G.; Xie, G.M.; Ma, Z.Y. Enhanced mechanical properties of Mg–Gd–Y–Zr casting via friction stir processing. *J. Alloy. Compd.* **2011**, *509*, 2879–2884.
91. Li, J.; Zhang, D.-T.; Chai, F.; Zhang, W. Microstructures and mechanical properties of WE43 magnesium alloy prepared by friction stir processing. *Rare Met.* **2014**, 1–6.
92. He, L.-Q.; Li, Y.-J.; Li, X.-G.; Ma, M.-L.; Zhang, K.; Wang, X.-W.; Yan, J.-M.; Lin, H.-T. Microstructure and properties of WE93 alloy. *Trans. Nonferrous Metals Soc. China* **2011**, *21*, 790–794.
93. Wang, R.; Dong, J.; Fan, L.-K.; Zhang, P.; Ding, W.-J. Microstructure and mechanical properties of rolled Mg-12Gd-3Y-0.4Zr alloy sheets. *Trans. Nonferrous Metals Soc. China* **2008**, *18*, s189–s193.
94. Xu, C.; Zheng, M.Y.; Xu, S.W.; Wu, K.; Wang, E.D.; Kamado, S.; Wang, G.J.; Lv, X.Y. Microstructure and mechanical properties of rolled sheets of Mg–Gd–Y–Zn–Zr alloy: As-cast *versus* as-homogenized. *J. Alloy. Compd.* **2012**, *528*, 40–44.
95. Xu, C.; Xu, S.W.; Zheng, M.Y.; Wu, K.; Wang, E.D.; Kamado, S.; Wang, G.J.; Lv, X.Y. Microstructures and mechanical properties of high-strength Mg–Gd–Y–Zn–Zr alloy sheets processed by severe hot rolling. *J. Alloy. Compd.* **2012**, *524*, 46–52.
96. Xu, C.; Zheng, M.Y.; Xu, S.W.; Wu, K.; Wang, E.D.; Fan, G.H.; Kamado, S.; Liu, X.D.; Wang, G.J.; Lv, X.Y. Microstructure and mechanical properties of Mg–Gd–Y–Zn–Zr alloy sheets processed by combined processes of extrusion, hot rolling and ageing. *Mater. Sci. Eng. A* **2013**, *559*, 844–851.
97. Freeney, T.A.; Mishra, R.S. Effect of friction stir processing on microstructure and mechanical properties of a cast-magnesium–rare earth alloy. *Metall. Mat. Trans. A* **2010**, *41*, 73–84.
98. Yang, Z.; Li, J.P.; Guo, Y.C.; Liu, T.; Xia, F.; Zeng, Z.W.; Liang, M.X. Precipitation process and effect on mechanical properties of Mg–9Gd–3Y–0.6Zn–0.5Zr alloy. *Mater. Sci. Eng. A* **2007**, *454–455*, 274–280.
99. Al-Samman, T.; Li, X. Sheet texture modification in magnesium-based alloys by selective rare earth alloying. *Mater. Sci. Eng. A* **2011**, *528*, 3809–3822.
100. Stulikova, I.; Smola, B. Mechanical properties and phase composition of potential biodegradable Mg–Zn–Mn–base alloys with addition of rare earth elements. *Mater. Charact.* **2010**, *61*, 952–958.
101. Dobroň, P.; Chmelik, F.; Parfenenko, K.; Letzig, D.; Bohlen, J. On the effect of the extrusion speed on microstructure and plastic deformation of ZE10 and ZEK100 magnesium alloys—An acoustic emission study. *Acta Phys. Polonica A* **2012**, *122*, 593.

102. García, E.M. Influence of alloying elements on the microstructure and mechanical properties of extruded Mg-Zn based alloys. Technischen Universität, Berlin, Germany, 2010. Available online: opus4.kobv.de/opus4-tuberlin/files/2653/mezagarcia_enrique.pdf (accessed on 17 December 2014).
103. Kamrani, S.; Fleck, C. Effects of calcium and rare-earth elements on the microstructure and tension–compression yield asymmetry of ZEK100 alloy. *Mater. Sci. Eng. A* **2014**, *618*, 238–243.
104. Zhang, J.; Li, W.; Zhang, B.; Dou, Y. Influence of Er addition and extrusion temperature on the microstructure and mechanical properties of a Mg–Zn–Zr magnesium alloy. *Mater. Sci. Eng. A* **2011**, *528*, 4740–4746.
105. Zhang, J.; Zhang, X.; Li, W.; Pan, F.; Guo, Z. Partition of Er among the constituent phases and the yield phenomenon in a semi-continuously cast Mg–Zn–Zr alloy. *Scripta Mater.* **2010**, *63*, 367–370.
106. Yu, H.; Yan, H.; Chen, J.; Su, B.; Zheng, Y.; Shen, Y.; Ma, Z. Effects of minor gd addition on microstructures and mechanical properties of the high strain-rate rolled Mg–Zn–Zr alloys. *J. Alloy. Compd.* **2014**, *586*, 757–765.
107. Xiao, W.; Shen, Y.; Wang, L.; Wu, Y.; Cao, Z.; Jia, S.; Wang, L. The influences of rare earth content on the microstructure and mechanical properties of Mg–7Zn–5Al alloy. *Mater. Des.* **2010**, *31*, 3542–3549.
108. Xiao, W.; Wang, J.; Yang, J.; Jia, S.; Wang, L. Microstructure and mechanical properties of Mg–12.3Zn–5.8Y–1.4Al alloy. *Mater. Sci. Eng. A* **2008**, *485*, 55–60.
109. Li, Q.; Wang, Q.; Wang, Y.; Zeng, X.; Ding, W. Effect of nd and y addition on microstructure and mechanical properties of as-cast Mg–Zn–Zr alloy. *J. Alloy. Compd.* **2007**, *427*, 115–123.
110. Yu, H.; Park, S.H.; You, B.S.; Kim, Y.M.; Yu, H.S.; Park, S.S. Effects of extrusion speed on the microstructure and mechanical properties of ZK60 alloys with and without 1 wt% cerium addition. *Mater. Sci. Eng. A* **2013**, *583*, 25–35.
111. Xu, D.K.; Liu, L.; Xu, Y.B.; Han, E.H. The effect of precipitates on the mechanical properties of ZK60-Y alloy. *Mater. Sci. Eng. A* **2006**, *420*, 322–332.
112. Wang, Y.; Guan, S.; Zeng, X.; Ding, W. Effects of Re on the microstructure and mechanical properties of Mg–8Zn–4Al magnesium alloy. *Mater. Sci. Eng. A* **2006**, *416*, 109–118.
113. Wu, A.-R.; Xia, C.-Q. Study of the microstructure and mechanical properties of Mg-rare earth alloys. *Mater. Des.* **2007**, *28*, 1963–1967.
114. Wang, J.; Song, P.; Huang, S.; Pan, F. Effects of heat treatment on the morphology of long-period stacking ordered phase and the corresponding mechanical properties of Mg–9Gd–*x*Er–1.6Zn–0.6Zr magnesium alloys. *Mater. Sci. Eng. A* **2013**, *563*, 36–45.
115. Cheng, W.; Park, S.S.; Tang, W.; You, B.S.; Koo, B.H. Influence of rare earth on the microstructure and age hardening response of indirect-extruded Mg-5Sn-4Zn alloy. *J. Rare Earths* **2010**, *28*, 785–789.