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Editorial

Relationships between Processing and Properties of Magnesium-Based Alloys

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1. Introduction and Scope

Magnesium alloys can be used in a wide range of applications, from lightweight structural and transport applications to biomaterials. The first step in designing a material is to identify a possible application and to derive the property profile for it. This is used to tailor the material and the processes for the production of a component. Different manufacturing processes have certain advantages and disadvantages in order to obtain the desired property profile of the material. Therefore, it is essential to know how the processing parameters affect the property profile of magnesium alloys. This understanding is important during the development and optimization of new materials on different process routes, as well as in the transfer to industrial processes and quality control. Therefore, the focus of this issue is on the relationship between processes and properties of magnesium-based alloys. Contributions are intended to show the influence of the manufacturing process, e.g., extrusion, rolling, heat treatment, Equal-Channel Angular Pressing (ECAP), and processing parameters, e.g., temperature, time, and cooling, on the property profile. This encompasses microstructural developments such as changes in grain size or texture, as well as mechanical properties, but also corrosion properties for mechanical engineering applications or degradation properties for medical applications.

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2. Contributions

Eight research articles have been published in this Special Issue of *Crystals*. The different alloy systems, Mg-Ca-Zn [1–3], Mg-Zn [4], Mg-Al-Zn-Mn [5,6], Mg-Dy-Nd-Zn-Zr [7], and Mg-Gd-Mn [8], were investigated, and the following production processes were used: extrusion [1,3,5,6,8], ECAP [2], turn-induced deformation (TID) [3], rolling [4,5], and heat treatment [5–7].

The first contribution in this issue was from Zhang et al. [1]. This work investigated the Mg-1.3Zn-0.5Ca (wt.%, ZX10) alloy processed via hot indirect extrusion using three different temperatures after T4 treatment. The amount of Mg_2Ca as well as dynamically recrystallized grain fraction gradually increased with the extrusion temperature. They were able to adjust the microstructure and texture through temperature variation to increase the room temperature mechanical properties of Ultimate Tensile Strength (UTS) from ~274 to ~355 MPa, True Yield Strength (TYS) from ~220 to ~284, and for Elongation at Fracture (EF) from ~5.7 to ~15.1%. This work has shown, as the first publication in this issue, that by controlling the processing temperature, mechanical properties can be enhanced.

In the study by Martynenko et al. [2], the comparable alloy Mg-1.0Zn-0.3Ca (wt.%, ZX10) was investigated, but it was produced using the ECAP process. In a previous study, they were able to improve the homogenized extruded material using ECAP and improved TYS from ~92 to ~106 MPa, UTS from ~194 to ~215 MPa, fatigue limit from ~100 to ~110 MPa, and EF was doubled to ~23.9%. In this contribution, they considered the effect of ECAP processing on the in vivo and in vitro corrosion rates. The corrosion rate did not change significantly either under in vitro conditions with ~1 mm/year or under in vivo conditions with 20% mass loss. ECAP can therefore improve the mechanical properties without affecting the corrosion behaviour.

Wang et al. [3] investigated the effect of extrusion temperature on the properties of Mg-4Zn-1Ca (wt.%, ZX41) billets produced from turn-induced deformation (TID) of turnings. By varying the extrusion temperature, the microstructure and texture could be adjusted to achieve 0.2% Compression Yield Strength (CYS) from ~123 to ~191 MPa, Ultimate Compression Strength (UCS) from ~360 to ~463 MPa, Compressive Strain at Fracture (CF) from ~18 to ~23%, an attenuation capacity of ~0.43 to ~0.59 Ns/mm, and a corrosion rate of ~0.38 to ~2.86 mm/y over 3 days in Hank's Balanced Salt Solution at 37 °C. This TID technology offers a high-performance Mg material using turnings, scrap recycling energy-efficient method, which is of great economic and environmental significance.

The overall objective of Wilkes et al. [4] was to determine the interactions between the microstructural parameters and the media buffer on the degradation behaviour of rolled Mg-1Zn (wt%, Z1) alloy. They varied the percentage reductions per pass between 30, 40, and 50% and achieved an average recrystallized grain size of ~10.6, ~12.0, and ~6.6 µm with a distinct texture, respectively. Despite the grain refinement, rolling resulted in more severe corrosion in the various corrosion tests than in the initial condition, regardless of the buffer system. This shows that the microstructure determines the overall corrosion rate in corrosion tests, but in contrast to other studies, the smaller grain size did not lead to a significant reduction in the corrosion rate. For the buffer systems HEPES (4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid) and $NaHCO_3/CO_2$, an influence on corrosion kinetics and pitting morphology was found. The authors of the study point out that the texture and the resulting corrosion profile can lead to misleading conclusions about the corrosion resistance of real orthopaedic implants as they come into contact with body fluids.

The production of rolled, rolled + heat-treated (HT), and extruded Mg-3Al-1Zn-0.4Mn (wt.%, AZ31) flat products was studied by Nienaber et al. [5]. The determining factors for textures, microstructure, deformation, and recrystallization were compared between processing routes covering different ranges of mechanical properties, as summarized in Table 1. The most significant changes were seen in EF and Erichsen value (EV), which could be attributed to the primary influence of the different textures. This work provides the basis for the selection of the production process for flat products in order to adjust the property profile more precisely and to enable a wider industrial application.

Table 1. Summary of mechanical properties from Nienaber et al. [5].

Condition	TYS [MPa]	UTS [MPa]	EF [%]	EV [mm]
Rolled	~188 to ~249	~248 to ~302	~0.5 to ~4.7	~2.0 to ~3.0
Rolled + HT	~116 to ~178	~216 to ~255	~6.4 to ~17.2	~3.0 to ~6.1
Extruded	~86 to ~203	~238 to ~279	~13.2 to ~24.6	~2.8 to ~3.4

The next contribution considered the possibilities of developing Mg metal matrix composites. In order to recycle Carbon Fibres (rCF) into Mg hybrid material, Mg-9Al-1Zn-0.2 Mn (wt%, AZ91) with 5 wt.% and without rCF was cast, heat treated, and extruded + heat treatments (T4 and T6) by Mance et al. [6]. The reinforcements with 100 µm and 500 µm long rCF achieved a 32 and 41 MPa increase in UCS, respectively, compared to AZ91. The maximum values were obtained for the extruded material with 500 µm long rCF with UCS 428 MPa and YCS 219 MPa, and the lowest for pure AZ91 in T4 with UCS 349 MPa and YCS 135 MPa. In situ synchrotron radiation diffraction studies of the deformation were carried out to investigate the changes in the properties in detail. The deformation mechanisms in the heat-treated alloys and composites were similar, but the expansion twinning was significantly increased in both reinforced cases. These findings can be used to develop high-performance composites with sustainability in mind.

The changes to the mechanical properties of extruded Mg-12.6Dy-1.1Nd-0.9Zn-0.1Zr (wt.%) through heat treatment was investigated by Maier et al. [7]. For this, the heat treatment process was varied between 0.5 and 120 h at 500 °C with cooling in air (fast) and in water (slow). In this study, the microstructure was changed so that the phase morphology of the long-period stacked phases (LPSO) transforms from 18R-LPSO to blocky 14H-LPSO phases into lamellar form. Cooling in air and quenching in water slightly affects the microstructure and resulted in slight changes in solid solution strengthening, which could be detected by nanoindentation. After 24 h, the highest total nano-hardness was achieved, and after 72 h, the highest grain size. The decrease in nano-hardness over longer durations could be attributed to the increased proportion of LPSO lamellae. It was possible to show how local mechanical properties and microstructure could be changed to better understand and control the mechanical properties at a macro level.

The final contribution looks at a less complex Mg-Rare Earth Elements (REE) alloy system Mg-xGd-yMn (x = 2/4/9 wt.%, y = 0.5/1.0 wt.%) and was investigated by Wiese et al. [8] during extrusion processing by varying the temperature and the extrusion speed. The results show similar behaviour to the binary Mg-Gd system in terms of processing and material properties such as recrystallization, texture, and grain size. The Mn content of 0.5 to 1.0 wt.% reduces grain growth by suppressing grain boundary movement, improves recrystallization of extruded alloys without grain growth, acts as a strengthening alloying element, and reduces the degradation rate. This allows the mechanical properties to be in the range of TYS ~104 to ~233 MPa, UTS ~189 to ~297 MPa, EF ~9.9 to ~31.5%, CYS ~76 to ~253 MPa, UCS ~309 to ~475 MPa, CF ~12.4 to ~25.7 MPa, and hardness ~43.4 to ~90.8 HV. It may be assumed that these conclusions may be indicative of the behaviour of other Mg-REE systems and thermomechanical manufacturing processes.

3. Concluding Remarks/Conclusions and Outlook

Various alloying systems and processes have been studied and shown to influence a range of different material properties. In many cases, several properties are linked, e.g., more precipitates often lead to increased corrosion or higher strengths reduce ductility. This coupling of properties is important for some applications but is not always the case. This has been shown in some papers, as well as the classical more general relationships, which in combination show further possibilities for process optimization for certain Mg alloys. In addition to classic empirical research and development methods, modelling and simulation approaches are becoming more and more important, but these require good experimental data. Expanding the understanding of relationships between process and properties show clues for accelerated, sustainable materials development and process design. This Special Issue contributes to a deeper understanding of composition–microstructure–property relations for Mg alloys through new experimental results.

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