

ORIGINAL ARTICLE

The effects of Nd, La, and Ca addition on the corrosion properties of as-cast and as-rolled ZM21 Mg alloys

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Abstract. In this study, the effects of Nd, La, and Ca elements added to ZM21 alloy was investigated in terms of parameters such as microscopic, mechanical, and corrosion properties. The content of each of the elemental constituents was 0.5% by weight. The microstructural and mechanical behaviours of the investigated alloys were examined by XRD, EDX, SEM, OM, hardness surveys, tensile tests, and corrosion experiments. According to the XRD results, Ca_5Zn_3 , $\text{Ca}_2\text{Mg}_6\text{Zn}_3$, LaZn_2 , LaMg_3 , $\text{Mg}_{41}\text{Nd}_5$, and Mg_{12}Nd phases emerged on the investigated alloys. The grain sizes of the alloys were refined by element addition and rolling process, thus increasing their mechanical properties. Ca increased the hardness of the ZM21 alloys, but this had a negative effect on the rolled specimens. The tensile value of ZM21 alloy as cast decreased by 39.702%, 48.080%, 45.678% with the addition of (0.5% La+0.5% Nd), (0.5% La+0.5% Ca), (0.5% La+0.5% Nd+0.5% Ca), respectively. The tensile value of ZM21 alloy with (0.5% La+0.5% Nd) addition increased by 58.302% as rolled. Tensile test could not be performed because the rolled alloys with 0.5% Ca addition were fragmented during rolling. Ca contributed positively to the corrosion behaviour of the casting ZM21 alloy, but it worsened it in the rolled alloys. White oxide areas on the surface of the rolled alloys indicated an increased degree of corrosion formation.

Keywords: Mg alloys / ZM21 / microstructure / corrosion

1 Introduction

As light alloys, magnesium alloys are the choice of researchers owing to their desired properties such as strength, hardness, thermal conductivity, and damping performance. The automotive industry has increased the use of magnesium alloys [1,2]. The thermal characteristics of Mg alloys play an important role in high-temperature applications. While high thermal conductivity reduces thermally induced stresses, a uniform temperature distribution extends the working life of parts [3]. Recently, the addition of RE elements has been widely implemented to enhance the hot creep behaviour of magnesium alloys [4]. Among studies in the relevant literature, Peng et al. studied the microstructural and thermal behaviours of as-cast and as-extruded Mg-2Zn-1Mn-(x)Ce alloys with the addition of Ce at ratios of 0%, 0.2%, and 0.6% by weight. They reported that the gradual increase in the concentration of Ce increased the thermal conductivity coefficient of the Mg-2Zn-1Mn-(x)Ce alloy. The highest thermal conductivity value (133.29 W/(m K))

was obtained in the Mg-2Zn-1Mn-0.6Ce extruded alloy. Ce(cerium) refined the grain sizes of the as-cast and as-extruded Mg-2Zn-1Mn-(x)Ce alloys [5]. In another study [6], the effects of non-isothermal rolling on the micro morphology and mechanical features of ZM21 Mg alloys were examined. The rolling parameters in the study were 25–50%, and 75% thickness reduction at temperatures of 250 °C, 300 °C, 350 °C, and 400 °C, respectively. In the alloy matrix, the presence of shear bands, twins, and refined grains was reported. Coaxial grains were formed in the alloys subjected to the consecutive rolling and annealing processes, and as a result of these processes, the twins and shear bands dissipated and disappeared above the recrystallisation temperature. Alloys rolled at 250 °C with a thickness reduction of 75% were subjected to a short annealing process. As a result of this process, they showed good ductility (14%) and maximal ultimate strength (345 MPa) [6]. In another study [7], the effects of neodymium (Nd) addition on the properties of the cast ZM21 alloy were investigated. As a result of this process, a Mg–Zn–Nd ternary phase occurred, and larger grains were reported to occur [7]. A previous study [8] evaluated the corrosion characteristics of Mg (commercial pure) and ZM21 magnesium alloys. For this test, specimens were kept

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Table 1. Chemical analysis results of the investigated alloys.

Alloys	Zn	Mn	La	Ca	Nd	Mg
ZM21	2.05	0.8	–	–	–	Balance
ZM21+%0.5La+%0.5Nd	2.09	1.08	0.5	0.04	0.57	Balance
ZM21+%0.5La+%0.5Ca	2.04	1.21	0.52	0.65	–	Balance
ZM21+%0.5La+%0.5Ca+%0.5Nd	2.06	1.00	0.52	0.51	0.56	Balance

in “Ringer’s Solution” for a period of 92 h using the “Electrochemical Impedance Spectroscopy (EIS)” technique [8]. In the literature, it has been reported that the addition of La to cast ZM21 alloy causes a change in average grain size, grain shape and matrix. When SEM images are examined, it is reported that the phases formed in the matrix with the addition of La are elongated by rolling, the grain size becomes thinner and there are traces that are thought to be shear bands in the rolling direction. In addition, it is clearly seen that with the addition of Ca to ZM21 alloy, phases are formed at the matrix and grain boundaries, and these phases are broken by rolling. This is thought to be caused by the hardness and low yielding caused by the phases formed by the addition of Ca to the alloy [9].

In the study in the literature, it was reported that the amount of phase increased with increasing Zn content in XRD and SEM examinations of cast Mg–Zn–Mn–Ca alloys. The study also reported that the grain size decreased and the secondary phases were reported to be distributed in the form of strip-like grains at the grain boundary and grains in the matrix, these phases were reported to consist of Mg, Zn and Ca elements [10]. Some studies using the element Nd have shown that the element Nd can improve the biocompatibility and solid solution strength of Mg–Zn alloys [11].

There are studies on La, Ca and Nd added to cast ZM21 in the literature [9,12,13]. However, no studies on the inclusion of (La, Nd) or (La, Ca, Nd) together in testing the rolling process could be found. Therefore, this article presents a comparative study examining the effects of adding different rates of La, Ca, and Nd added to ZM21 alloys in as-cast and as-rolled conditions.

2 Experimental studies

In this study, the chemical contents of ZM21 Mg alloys with and without the addition of different elements (La, Ca, and Nd) were examined using the X-ray fluorescence (XRF) method with a Rigaku (ZSX Primus II) brand device. The elemental composition of the alloy is shown in Table 1 [12,13].

The casting process parameters in this experiment were used in the casting of alloys in previous studies [14,15]. If briefly explained, the Mg alloys were melted in an atmosphere-controlled (argon and CO₂+SF₆ gases) induction furnace at 750 °C. They were then poured into permanent moulds under gas protection (99 vol% CO₂ + 1 vol% SF₆) at 250 °C. The homogenisation processes of the cast parts were carried out by keeping them at 400 °C for

16 h. After homogenisation, the specimens were prepared at dimensions of 10 × 30 × 60 mm. All specimens were rolled by applying the following parameters: 4.7 (m/min) rolling speed, 80% rolling ratio, and $\varphi = 0.2^\circ$ Constant deformation degree. Equation of deformation degree is given at equation (1).

$$\varphi = -\ln((h_{n+1})/h_n). \quad (1)$$

Among these terms, φ is the constant deformation degree, hn is the specimen thickness after the pass, and n is the number of passes. Before rolling, the specimens were kept at 350 °C in the furnace for 60 min. While rolling these specimens according to the parameters mentioned above, after each rolling pass, they were kept at 350 °C in the furnace for 15 min for the next pass [6]. To conduct a metallographic examination with a microscope, the surfaces of the specimens were sanded consecutively with 400, 600, 800, 1200, and 2000 grit sandpapers. Then, the surfaces of the specimens were polished using 1 μ m alumina. The specimens were flushed with distilled water and alcohol, followed by drying with hot air. Additionally, the specimens were etched with picric acid, the etched specimens were cleaned with alcohol and distilled water, and dried using hot air in this order. The microstructure specimens were examined under a Nikon brand optical microscope. Then, EDX analyses were performed, and SEM images were taken with a Carl Zeiss Ultra Plus Gemini brand Scanning Electron Microscope (SEM) device. After casting, XRD analyses of the specimens were performed using a “Rigaku Ultima IV” brand device at a scan speed of 3°/min and a range of 10°–90° for scanning angles.

The hardness values of the casting, homogeneous, and rolling specimens were measured by the Vickers hardness test. In the Vickers hardness test machine, the specimen was held for 15 s with a pyramid-shaped penetrating edge under a load of 0.3 kg. Thus, the dimensions of the tracks on the specimens were measured, and the results of the hardness tests were determined. Tensile tests were carried out at a ratio of $1.67 \times 10^{-3} \text{ s}^{-1}$ on both rolled and cast specimens by means of a ZWick/Roell Z600 tensile test device. The casting specimens were processed according to the EN ISO 6892-1 standard, and the rolled specimens were processed along the rolling direction according to the ASTM E8 M-04 standard. In this part of the study, 3 specimens were tested for each alloy, and the average of the results was used.

The corrosion tests in this study were carried out as immersion and potentiodynamic corrosion tests which are explained below. For the potentiodynamic polarisation test

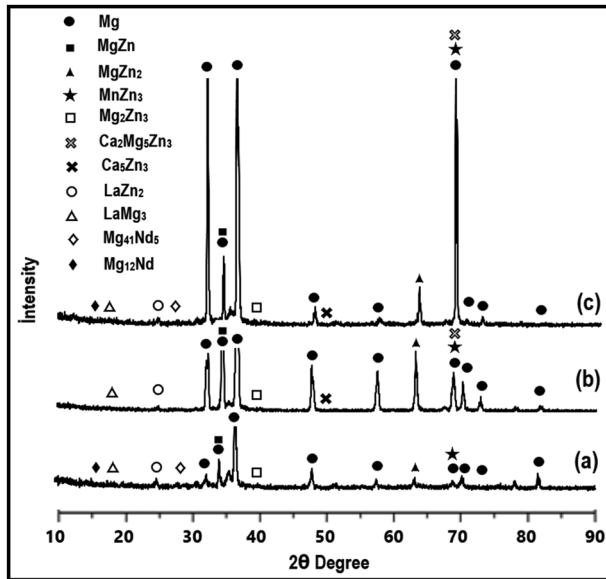


Fig. 1. XRD results of (a) ZM21+0.5La+0.5Nd, (b) ZM21+0.5La+0.5Ca, and (c) ZM21+0.5La+0.5Nd+0.5Ca [13].

processes, 0.25 cm² circular hole tapes were adhered the specimens sanded up to 1200 grit, and the experiments were ensured to be carried out in an equal area. The potentiodynamic polarisation testing processes were performed using a computer-aided (Gamry model PC4/300 mA potentiostat/galvanostat) DC105 corrosion experiment device in a 3.5% NaCl environment. In the experiments, graphite rods were used as the counter electrode, and SCE (Saturated Calomel Electrode) was used as the reference electrode. The experiments were carried out using a conventional 3-electrode cell, provided that the specimen surfaces were the working electrodes. Potentiodynamic polarisation curves were obtained by scanning in the range of -0.25 V (vs. open circuit potential, Eoc) to $+0.25$ V (vs. Eoc) at a scanning rate of 1 mV s^{-1} . In this experiment, for each alloy, three specimens were tested, and the average of the results was used. For the immersion corrosion tests, $2 \times 10 \leq 10$ mm rectangular prism-shaped specimens were prepared from the casting and rolling alloys, and their surfaces were cleaned by purified water in an ultrasonic cleaning device after sanding. The exterior surfaces of the specimens were measured, and their initial weights were taken using scales with a sensitivity of 0.0001 g before immersion. These specimens were suspended in 3.5% NaCl, they were placed in equal amounts in glass jars, with the help of plastic nets. These immersed specimens were taken out of the solution at 3, 6, 9, 12, 24, 48, and 72 h, their surfaces were cleaned, and their weights were measured and recorded. The corrosion products that formed on the surfaces of the specimens were cleaned by keeping them in an ultrasonic cleaner containing a chromic acid solution prepared in 180 g/L distilled water for 5 min after taking the specimens from the solution at the hourly intervals mentioned above. The specimens were then re-immersed in jars containing

3.5% NaCl. Afterwards, they were cleaned using an ultrasonic sterilisation device in purified water for 5 min and then alcohol for 5 more minutes to be immersed in 3.5% NaCl again. The weight loss values for each hour were calculated, and the average corrosion rates in total were determined. In the immersion corrosion test process, 3 specimens were tested for each alloy, and then, the average of the results was used. The immersion corrosion test was applied for 72 h. Afterwards, SEM and EDX analyses of the corroded surfaces were performed for each specimen, and the corrosion mechanisms of the specimens were examined.

3 Results and discussion

3.1 XRD patterns

The XRD analysis results of the alloys are shown in Figure 1 [13]. In the analysis, an α -Mg main matrix, as well as MgZn, MgZn₂, MgZn₃, Mg₂Zn₃, and MnZn₃ peaks and LaZn₂ and LaMg₃ phases were observed in the structure of the ZM21 alloy with La addition [12]. The presence of these phases has also been reported in previous studies [14,16–20]. It was also reported that Mg₄₁Zn₇ and MgZn₂, either each alone or both, can be found in precipitates [16]. It was stated in a study on the LaZn₂ phase that the La structure appeared as a superconductor [20]. While Mg₄₁Nd₅ and Mg₁₂Nd phases were detected in the alloys with Nd addition, Ca addition to the investigated alloys was found to lead to the formation of Ca₅Zn₃ and Ca₂Mg₆Zn₃ phases, compatible with the results of other studies in the literature [21–29]. It was shown that Mg₄₁Nd₅ phases precipitated at the grain boundaries after annealing at 350 °C [23]. In our study, the presence of this phase in these grain boundaries was also observed. Among the results of another study, the Ca₅Zn₃ phase was ductile, but some Ca-containing phases were brittle [27]. It was observed that the Ca₂Mg₆Zn₃ phase in our study was broken during rolling.

3.2 Microstructure

In the microstructure images taken after casting, which are shown in Figure 2, it was observed that fine-structured phases were formed at the grain boundaries and in the matrix of the entire alloy. It was seen that these fine-structured phases in the ZM21+0.5La+0.5Nd alloy were dispersed as large and small formations along the grain boundaries [13]. The microstructure pictures shown as rolled in Figure 2 were taken from the rolling contact surface. In the microstructure pictures taken from the rolling contact surfaces, grain elongation and shear bands are observed along the rolling direction. As seen in the EDX and SEM analysis results of the cast alloys in Figure 3, the distribution of Ca₅Zn₃, Ca₂Mg₆Zn₃, LaZn₂, LaMg₃, Mg₄₁Nd₅, and Mg₁₂Nd phases in the structure was observed to agree with the XRD results. Mg–xZn–Mn–Ca alloys in cast form with different Zn contents were investigated [10]. The study revealed that the secondary phase was as strip-like formation distributed at the grain boundaries; however, some coarse-grained phases were reported to contain internal

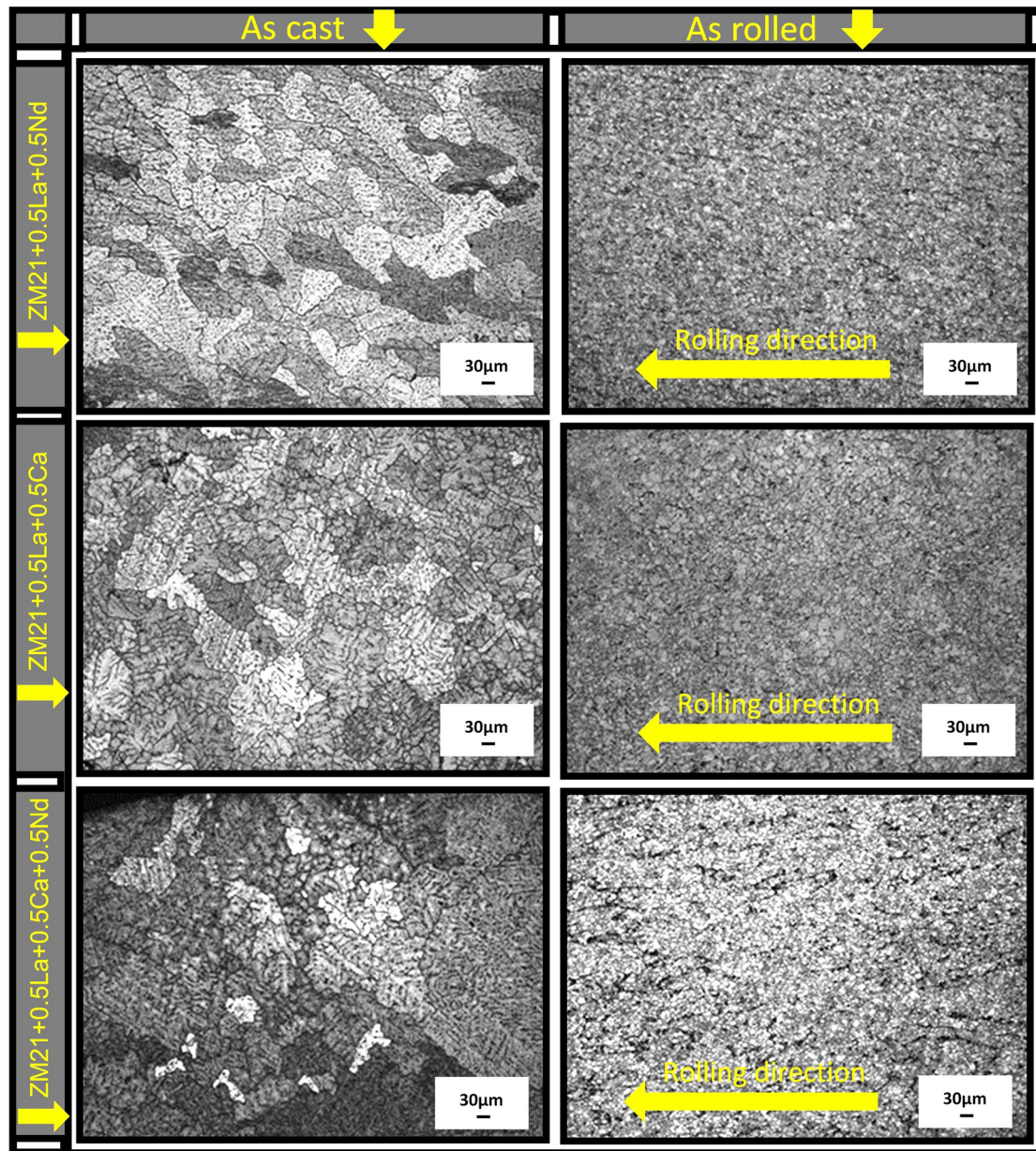


Fig. 2. Optical microscope images of the investigated alloys [13].

grains. Additionally, in the EDX results, secondary phases formed by Mg, Zn, and Ca were obtained both at the grain boundaries and in the grains [10]. There are studies on similar alloys related to these phases in the literature [21–29].

Looking at the optical microscope images of the rolled alloys in Figure 2, a significant change occurred in all alloys due to dynamic recrystallisation (DRX) in hot rolling. It was also observed that the intermetallic phases were aligned in the rolling direction. As seen in the EDX and SEM test results of the rolled alloys shown in Figure 3, the intermetallic particles along the grain boundary were broken and dispersed. In a similar study, Gao et al. [30] reported that the temperature and thickness reduction in the rolling process applied to the ZME200 Mg alloy had a significant effect on the deformation of the alloy. In this alloy, twinning formation increased, and the grain size

decreased with the decrease in rolling temperature and the increase in the amount of rolling thickness. The authors stated that annealing formed static recrystallisation in the ZME200 alloy [30]. The Mg_2Ca compound was determined at the grain boundaries of the Mg–0.5Ca alloy in the study conducted by Bünyamin et al. [31]. Wu et al. reported that CaO and $CaCO_3$ were formed with increasing Ca content in Mg–3.5Gd– x Ca alloys. Ca was added at ratios of $x = (0), (0.5), (1.0), (3.0)$ wt.% [32]. We determined the formation of intermetallic compounds in the matrix and at the grain boundaries with the addition of 0.5% La, 0.5% Nd, and 0.5% Ca in the cast alloys. We found that the phases at the grain boundaries and in the matrix became coarse and broad with the effect of Ca. We saw that the rolling process had a thinning effect on the grains, and the intermetallic phases changed shape. Additionally, the intermetallic phases of the

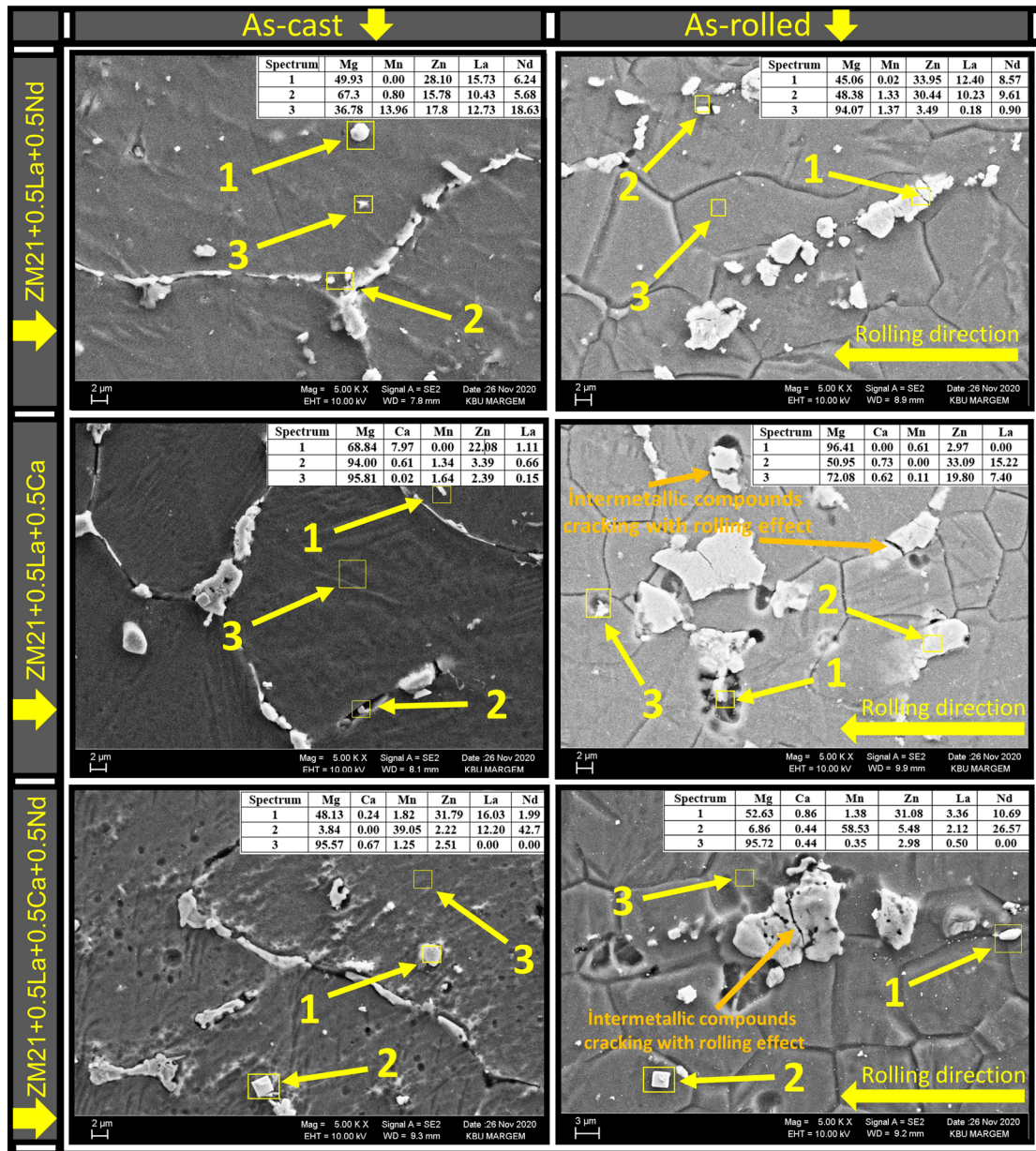


Fig. 3. SEM and EDX images of the investigated alloys [13].

rolled Ca-doped alloys were broken by rolling. These cracks may have occurred due to the CaO that emerged with the addition of Ca, as stated in the study conducted by Wu et al. [32], who showed that Ca had a high affinity for oxygen (O) by means of the Ellingham diagram [32].

3.3 Mechanical tests

3.3.1 Hardness

The hardness values (Fig. 4) increased with the addition of the tested elements (La, Nd, and Ca) to the ZM21 Mg alloy [12]. As an effect of theirs, these elements contributed to the formation of LaZn_2 and LaMg_3 phases with La addition and $\text{Mg}_{41}\text{Nd}_5$ and Mg_{12}Nd phases with Nd addition. The higher increase in the hardness value with the Ca content in the alloys can be attributed to the presence of binary Ca_5Zn_3

and triple $\text{Ca}_2\text{Mg}_6\text{Zn}_3$ phases along with the grain boundaries [13]. We determined that the hardness measurements of the rolling alloys increased significantly compared to the casting alloys. Chen et al. reported that the phases formed in the structure strengthened solid solution hardening and dispersive strength [29]. Ümit et al. used a rolling thermomechanical process to improve the mechanical properties of ZM21 magnesium alloy and reported a 40% reduction in grain size in rolled samples [33].

3.3.2 Tensile properties

The tensile and elongation (%) values of the cast ZM21 alloys diminished remarkably by the addition of the elements La, Ca, and Nd (Figs. 5 and 6) [12]. In particular, the elongation behaviour of the cast alloys with the

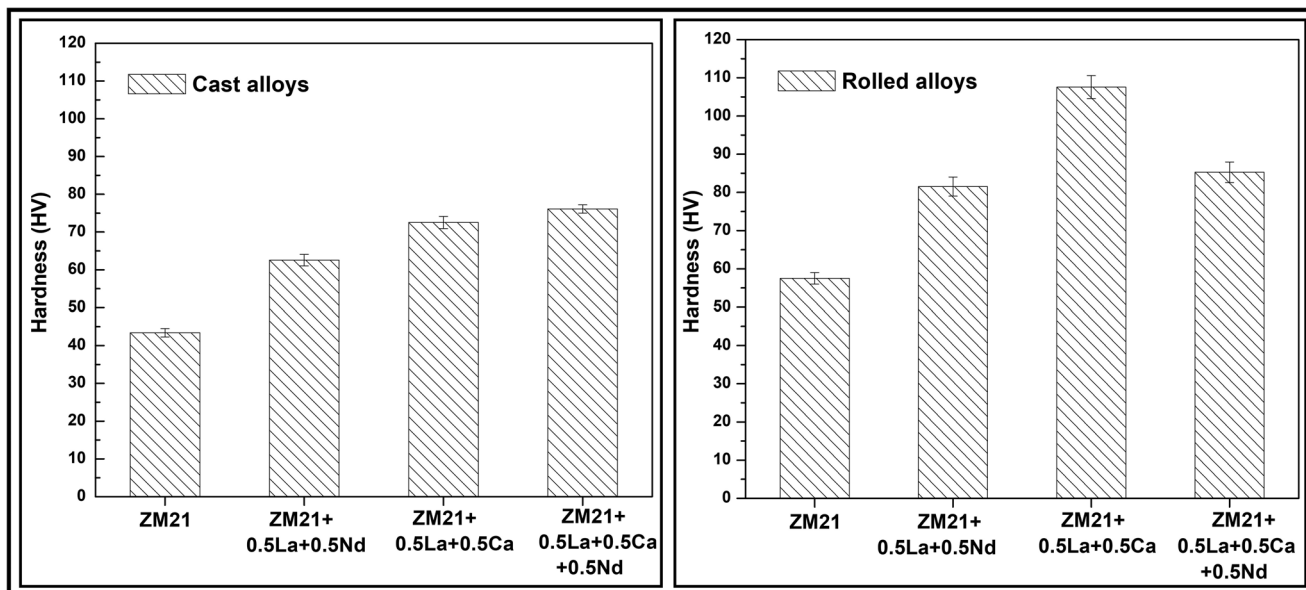


Fig. 4. Hardness results of the investigated alloys as cast and rolled.

individual or combined addition of Ca and Nd showed a remarkable decrease due to the brittle secondary phases with Ca content. In the tensile test results shown in Figure 5 and 6, tensile test specimens could not be obtained from the rolled ZM21+0.5La+0.5Ca and ZM21+0.5La+0.5Ca+0.5Nd alloys. The reason for this was the long brittle secondary phases containing Ca in the matrix and grain boundaries as seen in Figure 3. Wu et al. reported that CaO and CaCO₃ were formed along with increasing Ca content. These phases have been reported to cause the oxidation of Ca, which has a high affinity for oxygen (O). This is known based on the Ellingham diagram for oxides. The researchers reported increased oxide film formation and surface roughness values with an increase in Ca content [32].

Considering the cast specimens demonstrated in Figure 4, it is thought that hardness values increased with the effect of the intermetallic compounds that formed in the grain boundaries and in the matrix in reaction to the addition of the element. It was observed that hard brittle intermetallic compounds and oxides were formed with the addition of Ca. As demonstrated in Figure 5, the % elongation of the specimens decreased due to the compounds that were formed in the microstructure with the addition of Ca in the casting process. Also, as shown in Figure 6, the cast (ZM21+La+Nd) alloy was found to have 30% lower yield stress than cast ZM21 alloy [13,14]. Since the alloys containing Ca were broken during rolling, their % elongation could not be shown in Figure 5, and their tensile and yield values could not be shown in Figure 6. The hardness results of the alloys containing Ca were taken from the broken rolled parts and determined to be 107.56 HV. Because of high hardness values, tensile specimens could not be taken from the alloys containing Ca. The alloys containing La and Nd also had increased hardness, but these alloys were suitable for rolling.

3.4 Corrosion behaviour

3.4.1 Potentiodynamic polarisation test

Tafel curves were obtained as a result of the potentiodynamic polarisation corrosion experiments, and then, the potential values and corrosion current density results were obtained as a consequence of the analyses of these curves. The results are given in Figures 7 and 8. The corrosion potentials (Fig. 8) of the studied alloys were negative, that is, active. The potentials of the cast specimens were also less negative and better than those of the rolled specimens [13]. The corrosion potential of the rolled alloys (−1.4 V) was similar to that of the rolled ZM21 alloy [14]. Compared to the corrosion potential of the cast ZM21 alloy (−1.3 V) [14], a decrease (approximately −0.7 V) was observed in the corrosion potential values of the cast alloys to which La, Ca, and Nd were added [13]. Compared to the I_{corr} values of the cast and rolled ZM21 alloys [14], a decrease in those of the ZM21+0.5La+0.5Nd and ZM21+0.5La+0.5Ca alloys, and in contrast, an increase in that of the ZM21+0.5La+0.5Ca+0.5Nd alloy were observed (Fig. 8). The addition of La+Nd to the alloys significantly affected their corrosion resistance values. The reason for the deterioration of the corrosion resistance of the cast and rolled ZM21+0.5La+0.5Ca+0.5Nd alloys could be the cathodic action of multiple Ca₂Mg₅Zn₃, Ca₅Zn₃, Mg₄₁Nd₅, and Mg₁₂Nd intermetallic phases in the structure.

Yang et al. [34] reported that the Ca₂Mg₆Zn₃ phase, which prevents the corrosion of the α-Mg matrix of extruded ZM21 alloys, and the addition of 0.7 wt.% Ca contributes to the formation of this phase. The addition of 1.6 wt.% Ca caused the formation of Mg₂Ca phases, which deteriorated corrosion resistance values [34].

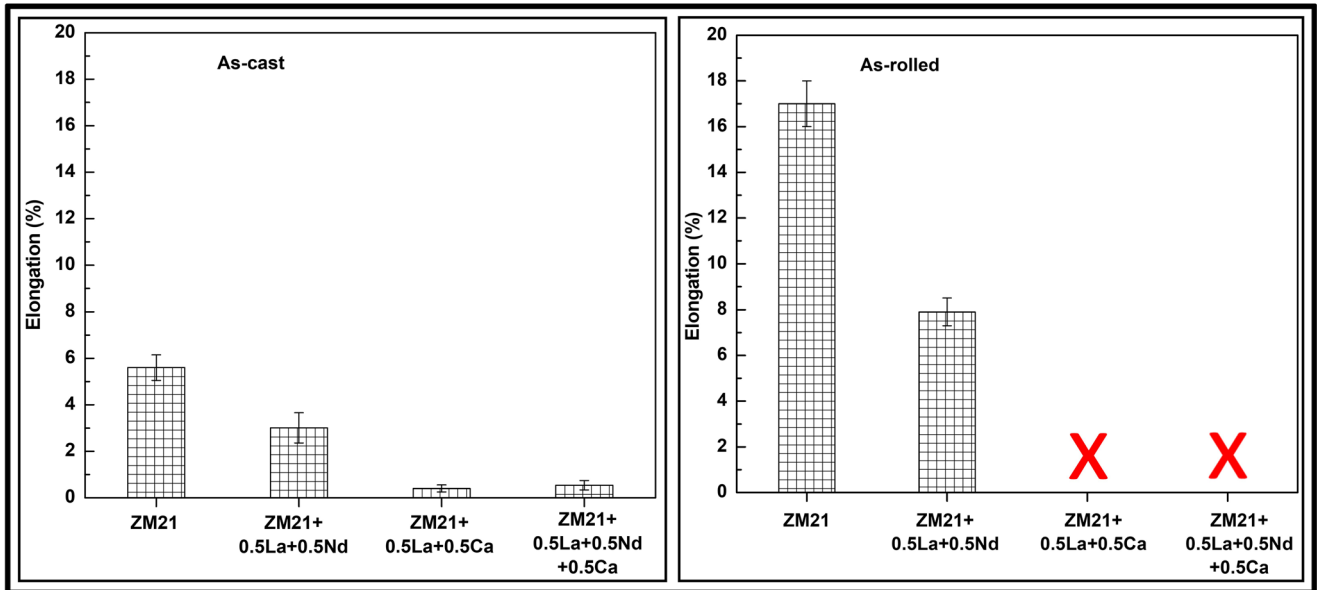


Fig. 5. % Elongation test results of the alloys as cast and rolled.

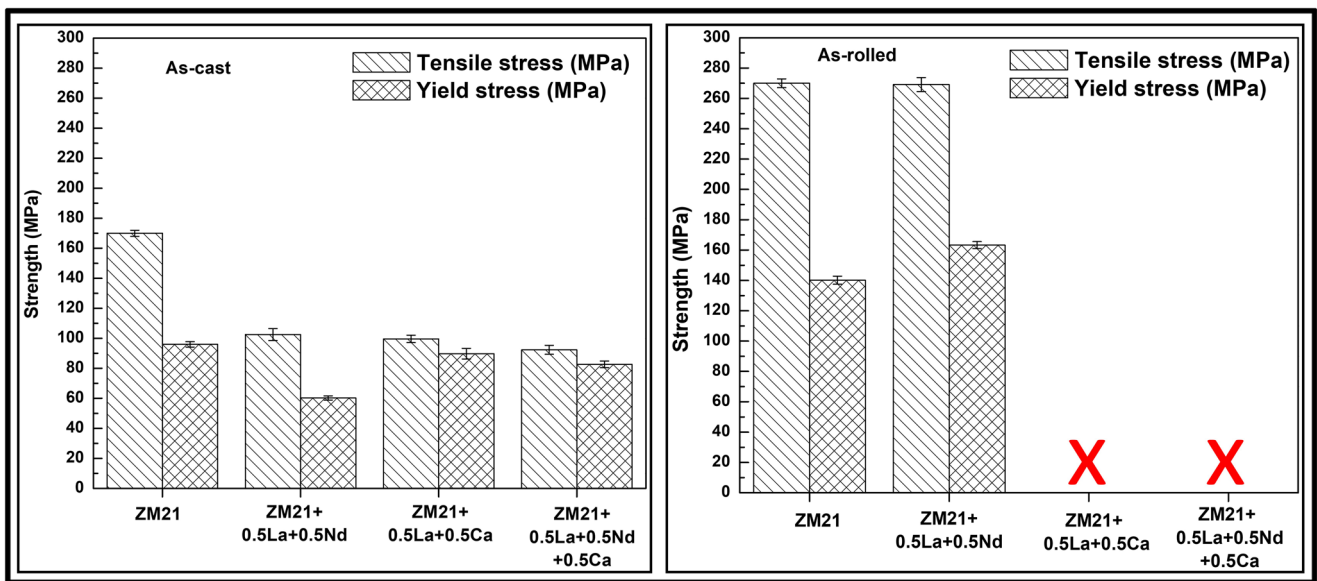


Fig. 6. Tensile and yield test results of the alloys as cast and rolled.

3.4.2 Immersion test

Candan et al. reported that corrosion resistance can be increased by adding elements to Mg alloys [35]. Elen et al. showed that the amount of weight loss in cast alloys was almost the same in the initial 12 h of immersion, and the difference in loss between alloys increased in further hours [36]. The mass losses and corrosion rates of the alloys that were examined in this study are given in Figure 9 as cast specimen results [13]. Figure 10 shows the mass losses and corrosion rates of the rolled specimens. In the cast alloys, mass loss and corrosion rate values were lower than those of the rolled alloys. The corrosion rates of the studied alloys decreased parabolically up to 1.5 days, but they reached a steady state after 1.5 days. The steady state corrosion rates of

the cast and rolled alloys were $150 \text{ mg}/(\text{dm}^2 \text{ day})$ and $300 \text{ mg}/(\text{dm}^2 \text{ day})$, respectively.

As the number of elements added to Mg-based alloys increases, the secondary phases and precipitates formed in the structure of the alloy increase. Thereby, both the amount and distribution of precipitates in Mg alloys can affect the pitting and micro-galvanic corrosion behaviours of the alloys. The SEM images in Figure 11 show that the degradation in the rolled alloys was higher than that in the cast alloys. The corroded surfaces of the rolled alloys had wider and deeper cavities than the cast alloys. According to the EDS results obtained from the corroded surfaces of the cast alloys, especially like the dendritic structures, the high amount of Zn reduced the corrosion current value and prevented the formation of deep pits in comparison to the

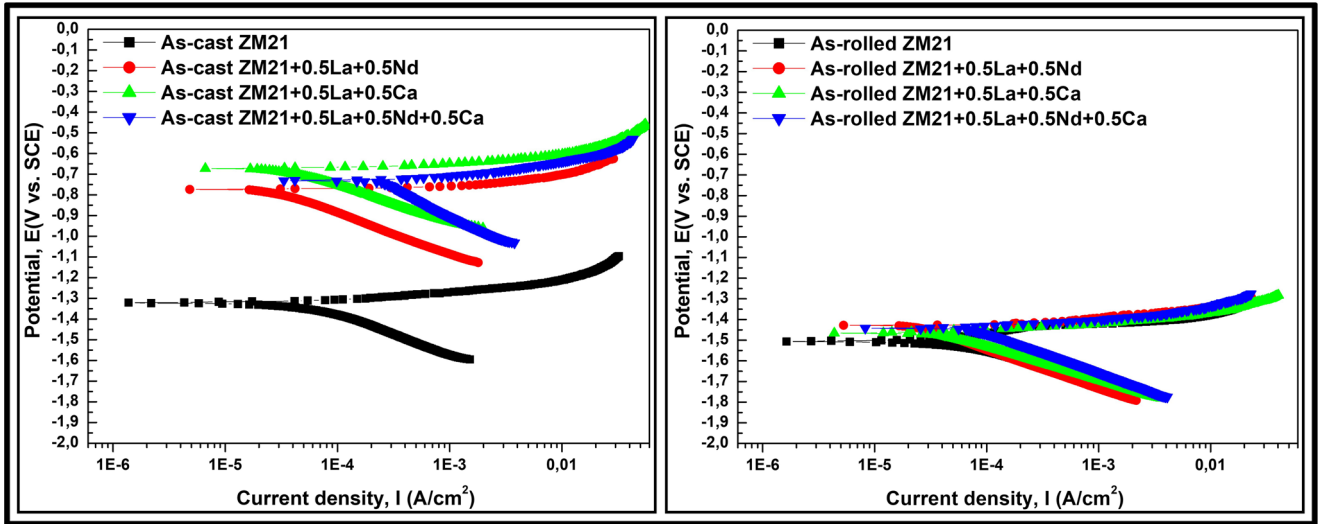


Fig. 7. Tafel curves of the alloys as cast and rolled.

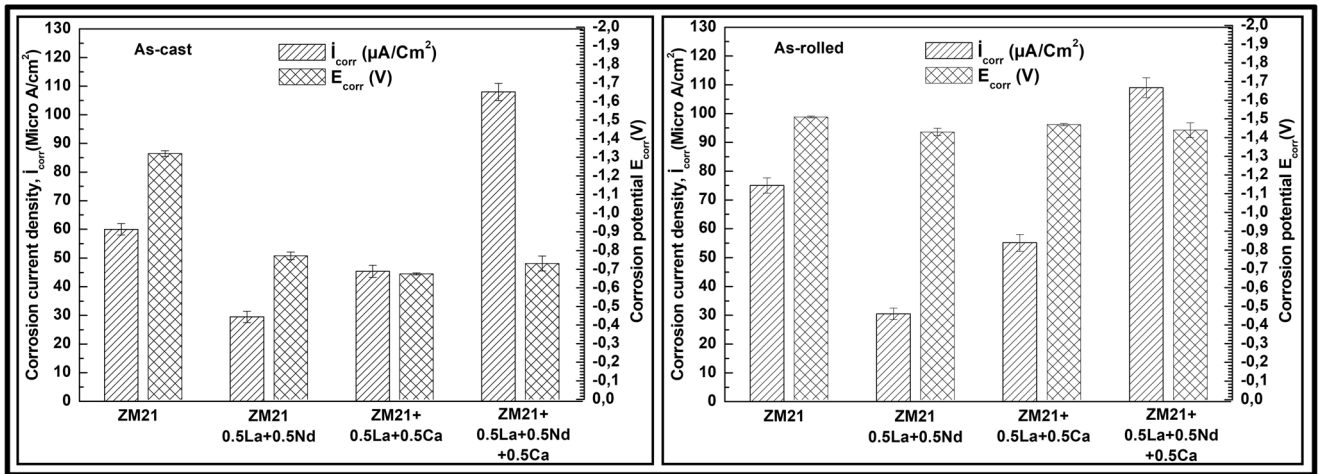
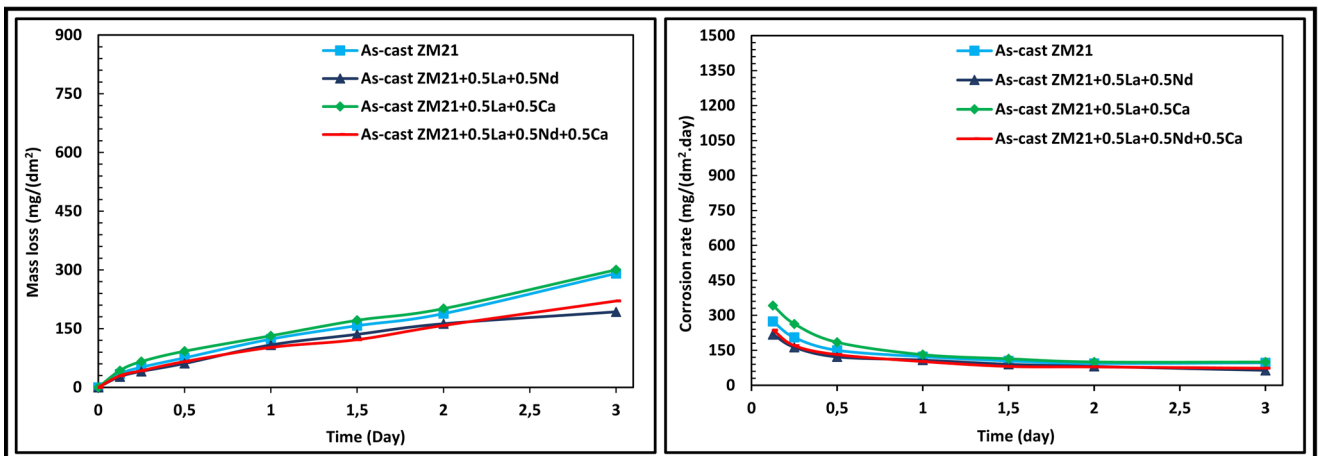
Fig. 8. I_{corr} and E_{corr} values of the alloys as cast and rolled.

Fig. 9. As-cast: mass losses and corrosion rates.

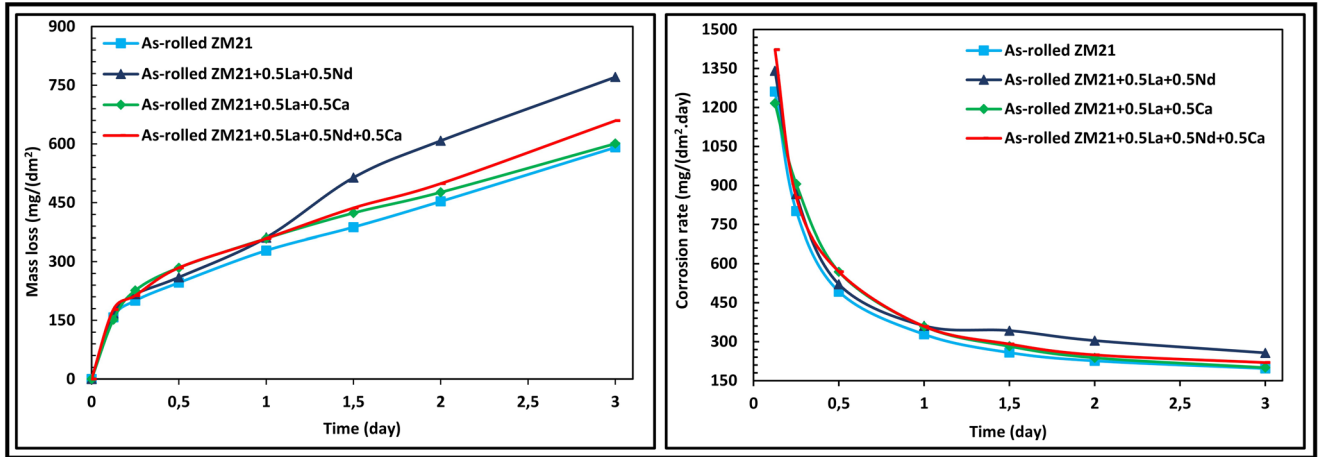


Fig. 10. As-rolled: mass losses and corrosion rates.

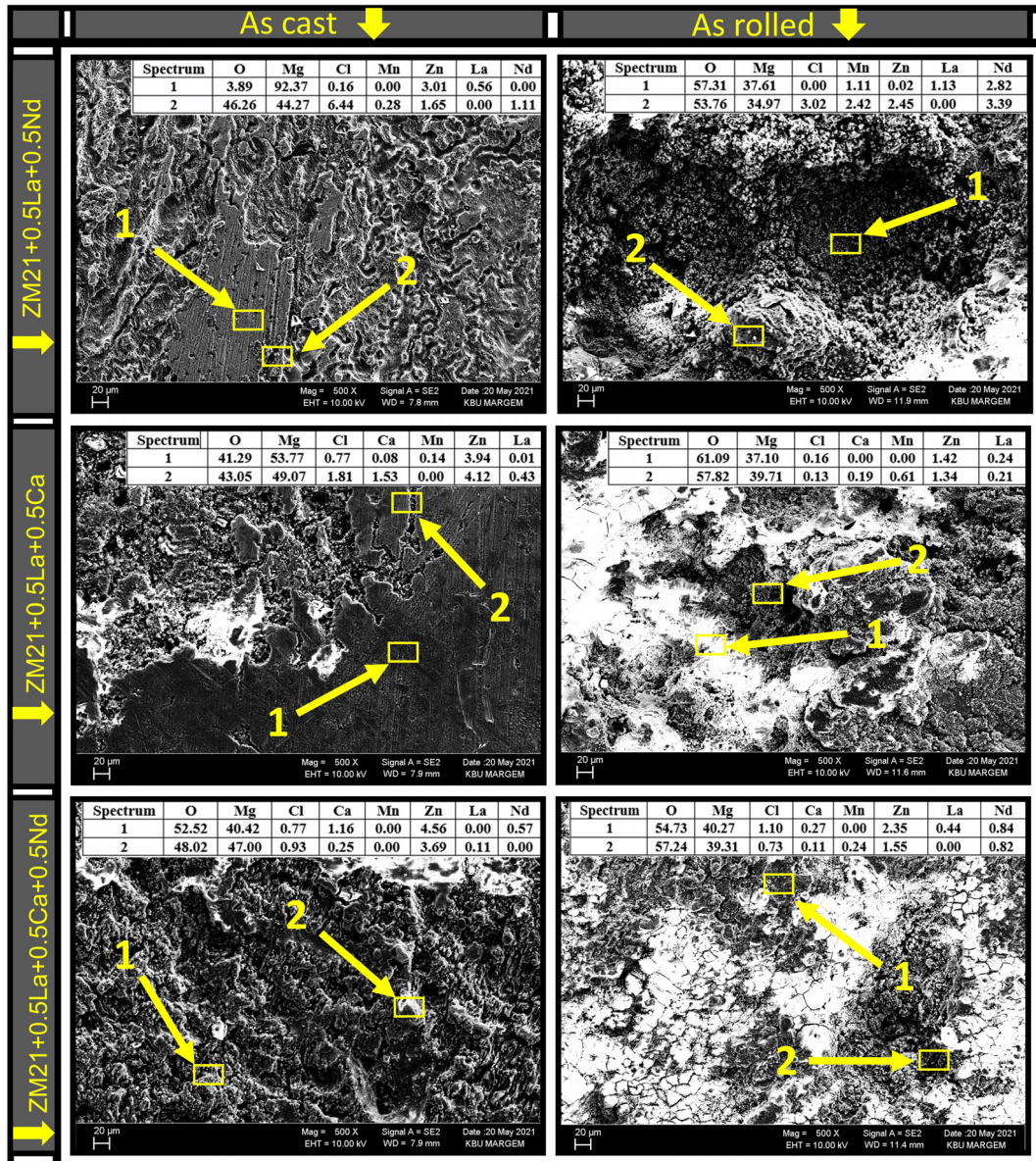


Fig. 11. EDX and SEM results of the investigated alloys after immersion corrosion tests.

corrosion behaviour of the as-rolled alloys. However, according to the EDS results obtained from the surfaces of the alloys in which dendritic structures were eliminated by the homogenisation and rolling processes, the low amount of Zn increased the corrosion current value; thus, corrosion failures progressed homogeneously in a wide area. In the EDS results, the formation of $\text{Mg}(\text{OH})_2$ in the rolled alloys was a sign showing that large surface pits and corrosion rates were higher in the alloys that were homogenised and corroded.

4 Conclusions

The effects of casting and rolling processes on the microstructural, corrosion, and mechanical behaviours of ZM21+0.5La+0.5Nd, ZM21+0.5La+0.5Ca and ZM21+0.5La+0.5Ca+0.5Nd alloys are explained below.

- The XRD, EDX, and SEM analyses of the alloys showed MnZn_3 , MgZn_2 , MgZn , LaMg_3 , LaZn_2 , $\text{Mg}_{41}\text{Nd}_5$, Mg_{12}Nd , Ca_5Zn_3 , and $\text{Ca}_2\text{Mg}_6\text{Zn}_3$ phases in their microstructures. These phases were coarsened intermittently at the grain boundaries and dispersed in the matrix of the ZM21+0.5La+0.5Nd alloy.
- The addition of different elements (La, Nd and Ca) to the ZM21 alloy increased its hardness. The rolled ZM21 and ZM21+0.5La+0.5Nd alloys showed better yield strength, elongation, tensile, and hardness values than the other alloys due to dispersion strengthening.
- In the results of the potentiodynamic polarisation corrosion and immersion corrosion experiments, it was determined that the degree of corrosion in the cast alloys was lower than that in the rolled alloys.
- The corrosion resistance of the ZM21+0.5La+0.5Nd and ZM21+0.5La+0.5Ca alloys improved along with a decreasing corrosion current density. Corrosion resistance decreased in the cast and rolled ZM21+0.5La+0.5Ca+0.5Nd alloys in which $\text{Ca}_2\text{Mg}_5\text{Zn}_3$, Ca_5Zn_3 , $\text{Mg}_{41}\text{Nd}_5$, and Mg_{12}Nd intermetallic phases were formed. It is known that intermetallic multiple phases can develop a cathodic degradation effect in casting processes. It was observed that rolling had a negative effect on corrosion resistance.
- In the SEM images, it was determined that the degree of corrosion increased with an increase in white oxide regions.

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Conflicts of Interest

There is no conflict of interest between the authors.

Data availability statement

The authors contributed equally to the study.

Author contribution statement

The authors have read and approved the final version of the manuscript.

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