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Effects of Zr Addition on Magnetic Susceptibility of Novel Biocompatible Ti-10Mo-(x)Zr Alloys for Biomedical Implants.

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Abstract

This study aims to evaluate the reduction of magnetic susceptibility depending on Zr element addition to the novel Ti-Mo-xZr alloy used for biomedical applications. Low magnetic susceptibility is essential for biomaterials to enable implant material to adapt inside the human body for a long time, prohibiting implant rejection and avoiding interference with the magnetic field through MRI examination. Zr addition to Ti-10Mo reduced magnetic susceptibility to a lower level than commercial Ti64 bio-implants (3.71×10^{-6} cm3/g), and TMZ6 alloy magnetic susceptibility (3.11×10^{-6} cm3/g) is lower than CP-Ti (3.38×10^{-6} cm3/g). Mo-equivalent and magnetic susceptibilities are claimed to be proportional inversely. The magnetization curves of entirely studied Ti-alloys are observed to maintain linearity, representing paramagnetic properties suitable for bio-implants and stable during MRI examinations. The results revealed that the addition of 6 wt.% Zr in Ti-Mo-xZr alloy reduces the magnetic susceptibilities from 3.088×10^{-6} to 2.967×10^{-6} cm3.g^{-1}. Measured and calculated magnetic susceptibility obtained the same behavior as Zr addition with different slopes.

Keywords: Magnetic Susceptibilities, Ti-10Mo-(x)Zr Alloys, Bio-implants, Mo equivalent, Paramagnetic.

1. Introduction

Metallic biomaterial selection undergoes medical applications, including orthopedic implants inside the human body, which should ensure stability for a long time without rejection. For that, metallic implants must obtain characteristics such as good mechanical properties, corrosion resistance, wear resistance, and Low magnetic susceptibility [1][2]. Ti alloys are great candidates for metallic biomaterials as they are widely used in orthopedic implants, ankle replacements, spinal fixtures, knee prostheses, finger plates, dental prostheses, and hip prostheses [3][4]. Other metallic elements, such as Magnesium and Molybdenum alloys, showed osteo-compatibility and biodegradability for orthopedic applications [5][6].

Ti64 alloy, one of the most extensive commercial Ti alloys, has an attractive low modulus of elasticity close to the human bone modulus range (~110 GPa). The low young modulus reduces the stress shielding effect between the metallic implant and bone[7]. Vanadium and aluminum elements have harmful effects on humans as they release ions through the bloodstream, which proved to increase health issues, including Alzheimer's plus metabolic bone diseases, so researchers went beyond new Ti-alloys approaching higher biocompatibility [8].

Molybdenum (Mo) element contributes as β-stabilizer when added to Ti-alloys; β phase is preferred in bio-implants because of the low Young’s modulus achieved. Mo improved solid solution strengthening, refined grain size, and enhanced corrosion resistance. Hence, biomaterials researchers are particularly interested in Ti-Mo seeking new vanadium-free Ti-alloys[1]. Zr element is a weak β-stabilizer in Ti-alloys, and inside the human body, it forms apatite surface layer bonelike that causes Zr to be suitable for implants [9]. Lin et al. [10] Investigated Ti-Mo-Zr and found that Zr addition to Ti-Mo increased yield strength. Recent studies investigated xMo and 6wt%Zr elements alloyed with Titanium and achieved favorable properties as bio-implant candidate materials[11][12].

MRI (magnetic resonance imaging) is a non-invasive medical diagnosis tool that generates high-resolution spatial images obtained with X-ray computed tomography (CT). This diagnosis tool has more advantages over standard tools, so MRI is sorted as one of the most vital techniques for human anatomy investigation [13]. Implant composition, as well as magnetic remanence, are two main factors that play a role in implant instability, heat disorder, and image quality degradation during MRI examinations of patients [14]. The effects of metallic implants on MRI take one of the following forms: geometric distortion, fat suppression failure, signal loss, or signal pile-up. The higher field strength, in addition to ferromagnetic alloys, maximizes previous effects during MRI examination, so titanium is considered a friendly element for MRI [15][16].

This work aims to study magnetization and the magnetic susceptibility of new novel alloys vanadium-free that incorporate non-allergenic and non-toxic elements while explicitly focusing on biomedical implant applications.

2. Experimental work

The current study focuses on the effect of Zr addition to Ti-10Mo-xZr alloy; Zr=x (0,3,6) wt%; these alloys were produced and investigated, named after TMZ0, TMZ3, and TMZ6, respectively. Sponge titanium, molybdenum, and zirconium with high purity above 99.9% were melted in an electric arc melting furnace within an argon atmosphere after cleaning inside an ultrasonic device with distilled water and ethanol. To ensure high homogeneity during melting, the ingots were flipped upside down inside the furnace and remelted twice. A muffle furnace was used for the homogenization treatment of produced samples at 900° C for 1.8 Ks, followed by hot forging, then quenched in water at room temperature. The wire-cutting machine cut the ingots into smaller pieces.

In preparation for SEM, samples were cut with dimensions (10mm*10mm*8mm), followed by grinding with sandpaper up to 4000 grits, then polishing with Colloidal silica suspension, and kroll etchant was used. The scanning electron microscopy type (TESCAN MIRA) is attached to the electron backscatter detector Volt. Energy dispersive X-ray spectroscopy (EDX) type (OXFORD XPLORE) was used for spectrum elemental analysis.

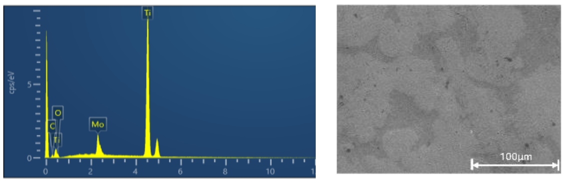
Also, thin films with dimensions (5mm*10mm) were cut and then polished with sandpaper up to 4000 grit. The thin films were used to measure the magnetization of all samples with the device type (Lake Shore VSM 7410), and films were placed in the center between pick-up coils. The operated field range is -20000 to +20000 Oe, and measuring was applied at room temperature. The relation between magnetization and magnetic field was obtained, and then magnetic susceptibility was derived by calculating slope values of the linear fitting between magnetization and magnetic field.

3. Results and discussion

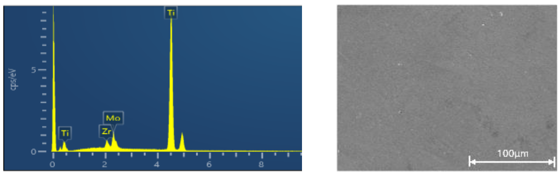
Elemental composition investigation is essential when applying for a magnetization test because any contamination during production would affect the accuracy of the results. The elemental composition of TMZ0, TMZ3, and TMZ6 alloys are plotted in Figure 1, obtained by OXFORD XPLORE EDX. The spectrum for TMZ0 alloy showed Ti and Mo peaks, although TMZ3 and TMZ6 alloys showed Ti, Mo, and Zr peaks. Ti, Mo, and Zr elements have no magnetic properties, so all studied samples are not exposed to be affected by any applied external magnetic field. From the literature study [17], titanium alloys have a non-magnetic nature, making them a safe choice for MRI without any metallic artifacts or distorting images. Element addition may slightly affect magnetic susceptibility, but Ti-alloys still achieve relatively weak magnetic susceptibility compared to ferromagnetic materials. Also, Molybdenum addition proved to have no significant effect on titanium magnetic properties, so the alloys currently studied are expected to show a slight attraction to the external magnetic field.

Figure 2 displays the magnetic moment (M) variation of the Ti-10Mo-xZr alloys caused by the magnetic field (H) of the Zr=x (0,3,6) wt.% at room temperature. While changing the magnetic field, the magnetization curve of all alloys is observed to maintain linearity, indicating that the paramagnetic property of Mo is unchanged when adding alloying elements Zr and Ti. As can be seen, the Zr-addition to Ti-10Mo alloys exhibits lower magnetic susceptibility. The slope of the magnetization curve determines the magnetic susceptibility of the Ti-10Mo-xZr alloy via linear data fitting.

(a)TMZO



(b)TMZ3



(c)TMZ6

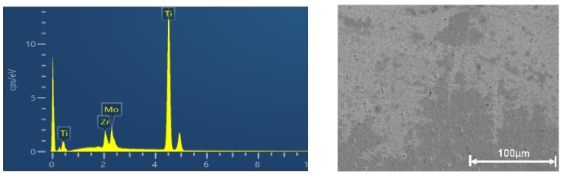


Fig. 1 EDX spectrum elemental analysis for hot forged TMZ0, TMZ3, and TMZ6 alloys.

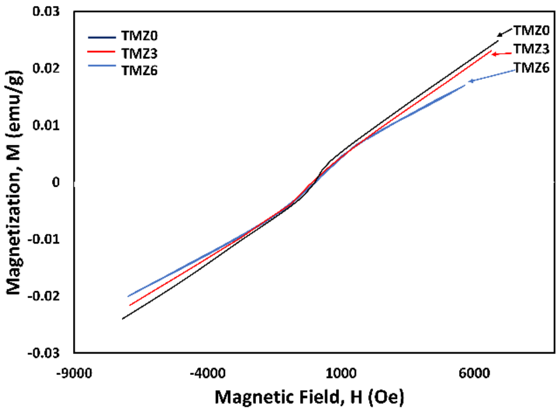


Fig. 2 The magnetization as a function of the magnetic field of hot forged Ti–10Mo–(x)Zr alloys at room temperature.

Figure 3 compares the magnetic susceptibilities between CP-Ti and Ti-64 alloys with the magnetic susceptibilities of the Ti-10Mo-xZr alloys as the Zr=x (0,3,6) wt% at room temperature. the magnetic susceptibilities of CP-Ti and Ti-64 are 3.38×10^{-6} and 3.71×10^{-6} cm^3/g, respectively. Values obtained from the literature study [18]. The Zr displays enhanced magnetic susceptibility with increasing Zr content, with the highest magnetic susceptibility of 3.61223×10^{-6} cm^3/g observed for the TMZ0 alloy. The effect of Zr-addition to Ti-10Mo alloys reduced the magnetic susceptibility value, as presented in Figure 3. These results agree with the literature done by Anderson Kiyoshi et al. [19], who proved that Zr-based materials obtained lower magnetic susceptibilities and that Zr addition significantly reduced the occurrence of MRI artifacts. All the studied alloys exhibit lower magnetic susceptibility values than the Ti-64 alloy. TMZ0 alloy exhibits a slightly higher magnetic susceptibility value than CP-Ti alloy (3.61223×10^{-6} and 3.38×10^{-6} cm^3/g), respectively; in contrast to the TMZ6 alloy. The CP-Ti and TMZ3 alloys have almost the same magnetic susceptibility value with a very slight difference ≈ 0.01 $\times10^{-6}$ cm^3/g.

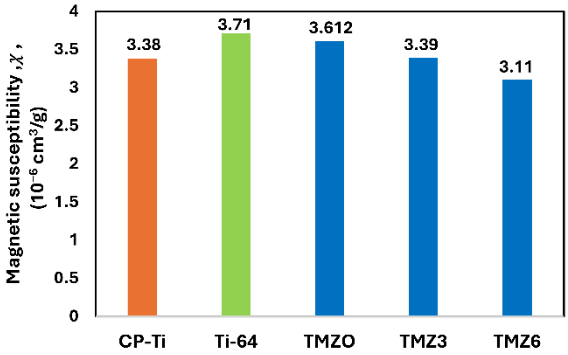


Fig. 3 Magnetic susceptibilities for hot forged TMZ0, TMZ3, and TMZ6 alloys compared with CP-Ti and Ti-64 from literature studies.

Vegard's rule authenticates magnetic susceptibilities of mixtures using the equation $\chi mix=\Sigma cixi$ where χmix (theoretical magnetic susceptibility of alloy), xi (constituent elements magnetic susceptibility). The magnetic susceptibility values of pure constituent elements Ti, Mo, and Zr are 3.35×10^{-6}, 7.3×10^{-7}, and 1.33×10^{-6} cm3.g-1, respectively [20][21][22]. The deviation of magnetic susceptibilities between measured and calculated values can be calculated by the formula $\Delta\chi/\chi mix=(\chi mes-\chi mix)/\chi mix$ as illustrated in Table 1. The deviation between measured and calculated decreases by adding Zr; the highest deviation is 0.1698 for TMZ0 alloy.

Figure 4 shows the difference between calculated and measured magnetic susceptibility for TMZ0, TMZ3, and TMZ6 alloys. Zr addition lowered the magnetic susceptibility values for both calculated and measured trends. For measured values, the line inclination is more significant than the calculated one, representing that Zr addition has a more considerable effect on magnetic susceptibility in practical experiments.

Table. 1 Different values of magnetic susceptibility for TMZ0, TMZ3, and TMZ6 alloys.

Magnetic susceptibility ($cm^3.g^{-1}$)	**TMZ0**	**TMZ3**	**TMZ6**
Calculated	3.088×10^{-6}	3.027×10^{-6}	2.967×10^{-6}
Measured	3.612×10^{-6}	3.389×10^{-6}	3.110×10^{-6}
Deviation	0.1698	0.1199	0.0482

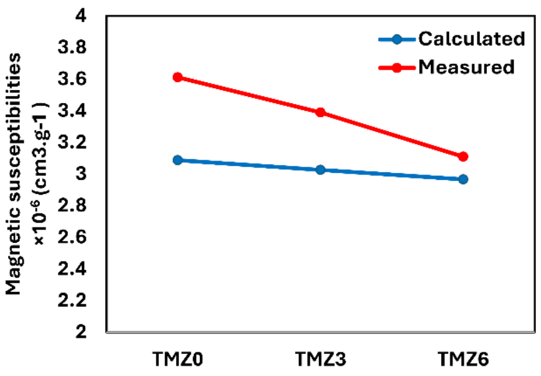


Fig. 4 Comparison between calculated and measured magnetic susceptibility for TMZ0, TMZ3, and TMZ6 alloys.

According to Fermi energy, the phase-stabilized affects the magnetic susceptibility values as the β phase is expected to have higher values compared to the α phase and *ω* phase as ($\chi_\beta > \chi_\alpha > \chi_\omega$) [23][24]. The phase stability due to the impact of alloying elements on α and β phases can be described by equivalent Mo ([Mo]eq) concentrations. The following equation provided by [Mo]eq gives the specific contribution of the entire element.

$$(Mo_{eq})_Q = 1.0\ Mo + 1.25\ V + 0.59\ W + 0.28\ Nb + 0.22\ Ta + 1.93\ Fe + 1.84\ Cr + 1.51\ Cu + 2.46\ Ni + 2.67\ Co + 2.26\ Mn + 0.30\ Sn + 0.47\ Zr + 3.01\ Si - 1.47\ Al$$

(wt. pct) [25].

This remark provides that equivalent Mo implies that alloy composition affects magnetic susceptibilities. Figure 5 Discussed the relationship between Mo equivalent and measured magnetic susceptibilities of the Ti-10Mo-xZr alloys as the Zr=x (0,3,6) wt% at room temperature. Mo equivalent is inversely proportional to measured magnetic susceptibilities as Zr addition percentages increase the [Mo]eq value.

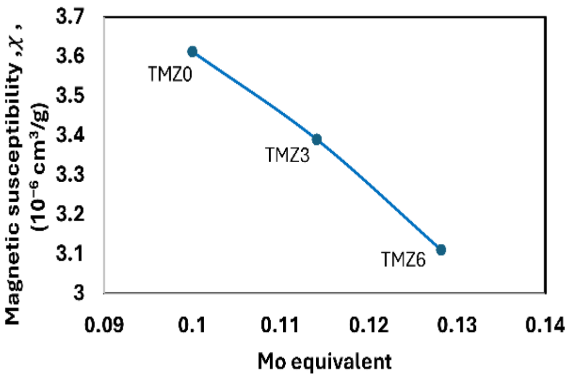


Fig. 5 Relation between Mo equivalent and Magnetic Susceptibilities of hot forged TMZ0, TMZ3, and TMZ6 alloys.

4. Conclusions

In this current study, the following remarks are concluded.

- Zr addition to Ti-10Mo-xZr exhibits a paramagnetic property that is unchanged when adding alloying elements as the maximum measured magnetic susceptibilities achieved 3.61223×10^{-6} $cm3.g^{-1}$, so Zr addition significantly reduced the occurrence of MRI artifacts.
- Magnetic susceptibilities for hot-forged TMZ0, TMZ3, and TMZ6 alloys achieved lower values than commercial bio-implant Ti-64 alloy with a slight difference.
- Both measured and calculated magnetic susceptibility values decreased with Zr addition with the lowest values of TMZ6 alloy 3.11012×10^{-6} and 2.967×10^{-6} $cm3.g^{-1}$, respectively.
- Mo equivalent values are inversely proportional to measured magnetic susceptibilities and could be used to predict material magnetic behavior.

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