APPLICATION OF HIGH-ENTROPY ALLOYS IN STRAIN SENSORS

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Abstract. This article investigates the physicochemical properties of the high-entropy alloy MoNbTaVW and its potential application in strain gauge sensors for structural health monitoring of composite constructions, particularly wind turbines. The material's suitability for accurate mechanical tension measurements is analyzed, taking into account its high thermal stability, resistance to corrosion, and tolerance to radiation exposure. It is demonstrated that MoNbTaVW maintains structural integrity at elevated temperatures, outperforming conventional metals commonly used in sensing systems. Special attention is given to the alloy's compatibility with composite materials such as carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP), aiming to prevent delamination and minimize residual tensions. The mechanisms are analyzed, by which the alloy's defect structure influences its electrical resistance, which are critical for the stability of strain gauge sensor performance. The unique crystalline structure of the high-entropy alloy is shown to reduce vacancy migration, ensuring long-term stability of electrical properties. Methods for applying MoNbTaVW as thin-film covering are discussed, with emphasis on their impact on sensor sensitivity. A detailed analysis of magnetron sputtering processes is presented, highlighting the importance of preserving film uniformity and minimizing residual tensions. It is shown that controlling deposition parameters, including working pressure and substrate temperature, significantly affects the electromechanical characteristics of the material. The article also explores calibration techniques for strain gauge sensors, particularly accounting for distortion effects under biaxial loading. It is demonstrated that mathematical models based on the Euler-Bernoulli beam theory can reduce measurement error by providing more accurate tension estimations within the structure. The findings confirm that integrating the MoNbTaVW high-entropy alloy into sensor systems enhances their durability, sensitivity, and operational stability in wind energy applications.

Key words: electrical resistance, composite materials, biaxial loading, magnetron sputtering, sensor calibration, wind turbines.

1. Introduction

High-entropy alloys (HEAs) have attracted considerable attention due to their unique combination of mechanical, thermal, and chemical properties, which make them promising candidates for applications under extreme conditions. Their thermal stability, high melting points, exceptional mechanical strength, high impact toughness, and resistance to oxidation and corrosion have positioned HEAs at the forefront of ongoing research and development. These properties are highly dependent on the specific chemical composition and the synthesis method employed. One of the important application areas for HEAs is in strain gauge sensors, where materials must exhibit high stability of characteristics across a wide temperature range, withstand mechanical loading, and resist corrosive environments.

2. Problem Statement

The integration of strain gauge sensors into composite systems presents a range of challenges, including the need to match coefficients of thermal expansion, minimize structural defects, and maintain long-term measurement accuracy. Addressing these factors is critical for the development of reliable strain gauge sensors capable of operating effectively under demanding service conditions.

3. Research Objective

The objective of this article is to investigate the physicochemical properties of the high-entropy alloy MoNbTaVW and to explore its potential use in the structure of strain gauge sensors designed for structural health monitoring of wind turbine blades manufactured from carbon fiber reinforced polymers (CFRPs).

4. Main Body of the Research

HEAs have increasingly emerged as a class of materials with significant potential for use in deformation sensors (strain gauge sensors), particularly in systems incorporating complex composite materials prone to deformation under certain conditions. This article focuses on the MoNbTaVW alloy, which exhibits a unique combination of properties that render it potentially effective in environments characterized by extreme temperatures, high mechanical loads, and corrosive exposure.

MoNbTaVW demonstrates the ability to maintain structural integrity at temperatures up to 1500 °C, exceeding the crystallization threshold of pure tungsten by approximately 400 °C. This thermal stability is primarily supported by its high vacancy formation energy around 3.48 eV, which results in reduced atomic diffusion, because lower vacancy concentration at higher temperatures minimizes microstructural drift [1]. Generally, this property goes in parallel reliability of strain gauge sensor measurements.

Moreover, an important advantage is the alloy's compatibility in terms of coefficient of thermal expansion (CTE) with ceramic composites such as silicon carbide (SiC) and boron carbide (B C). Close matching of CTE values helps to prevent delamination between layers within the composite material and between the sensor and the substrate, promoting strong adhesion. In this context, the behavior of thermal expansion can be described using the linear relationship:

$$\Delta l/l^0 = \alpha\Delta T, \quad (1)$$

where $\Delta l/l_0$ represents the relative change in length, α denotes the coefficient of thermal expansion (CTE), and ΔT corresponds to temperature variation. As previously mentioned, in applications involving composite materials, it is critically important to ensure that the strain sensor exhibits a CTE value compatible with the ceramic matrix, in order to avoid thermomechanical stress.

In this context, a model based on the Grüneisen parameter (γ_G) and the third-order Birch – Murnaghan equation of state allows for the correlation of the Debye temperature (Θ_D) with lattice compression. This relationship is expressed as follows:

$$\Theta_D(V) = \Theta_{D_0}\left(\frac{V}{V_0}\right)^{\gamma_G} \quad (2)$$

where the pressure – volume relationship is given by:

$$P(V) = \left(\frac{3}{2}\right)B\left[\left(\frac{V}{V^0}\right)^{-7/3} - \left(\frac{V}{V^0}\right)^{-5/3}\right] \left\{1 + \frac{3}{4}(B' - 4)\left[\left(\frac{V}{V_0}\right)^{-2/3} - 1\right]\right\} \quad (3)$$

where B denotes the bulk modulus, B' is its pressure derivative, and V_0 is the reference volume of the material. These formulations provide a basis for predicting the behavior of HEAs, ensuring stable performance even under conditions of significant thermal loading, which is essential for advanced sensing applications, for example, in the monitoring of turbine blades and components of hypersonic vehicles [2, 3].

MoNbTaVW combines the high-temperature strength of tungsten with the characteristic lattice distortion effects induced by vanadium, whose large atomic size mismatch disrupts regular atomic alignment, thereby enhancing the alloy's resistance to cracking and fracture under high stress. These properties make the material particularly suitable for use in composite systems based on carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP). The overall effectiveness in terms of mechanical load resistance can be attributed to the inherent strength of tungsten, supplemented by a strengthening effect arising from lattice distortions. The mechanical response can be modeled by taking into account the critical stress σ_c, which increases with the lattice mismatch parameter δ, itself a function of vanadium content. The effective yield strength ($\sigma_{y,eff}$) is then approximated by the following expression:

$$\sigma_{y,eff} \approx \sigma_{y,W} + k\delta, \quad (4)$$

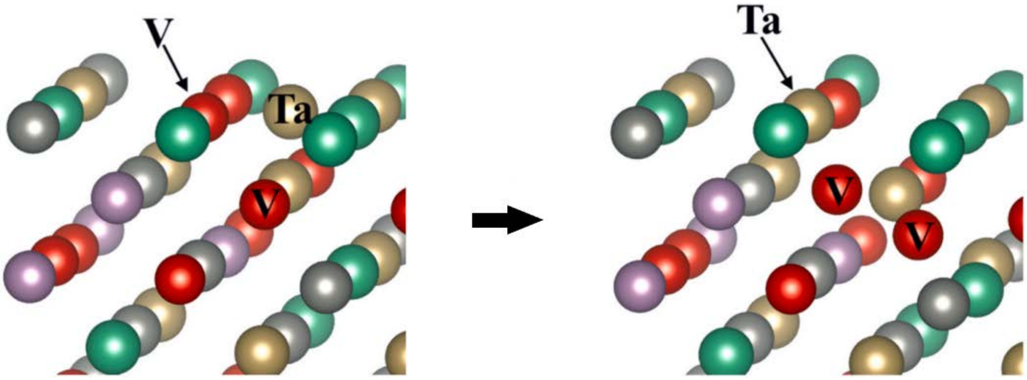
where $\sigma_{y,W}$ denotes the yield strength of pure tungsten, and k is a proportionality constant.

Due to its body-centered cubic (BCC) lattice structure, MoNbTaVW serves as an effective protective material against intense neutron and ionizing radiation. In materials with alternative lattice structures, such irradiation tends to result in defect accumulation over time, reducing material performance. In contrast, MoNbTaVW exhibits high formation energies for both vacancies and Frenkel pairs estimated at approximately 7.34 eV. The presence of vanadium promotes the formation of interatomic "vanadium – vanadium" splitting events, as illustrated in Figure.

These vanadium – vanadium splittings act as recombination centers, reducing the steady-state defect concentration and suppressing void swelling [5]. The recombination dynamics can be expressed using a simplified rate equation, in which the defect concentration D evolves according to:

$$\frac{dD}{dt} = G - R(D), \quad (5)$$

where G represents the defect generation rate under irradiation conditions, and $R(D)$ denotes the recombination rate, which is enhanced by the presence of atomic splitting. A high recombination rate implies that the electrical and mechanical properties remain largely unaffected.



Relaxation forming a split interstitial made of two vanadium atoms after a tantalum atom was placed as an interstitial defect [4]

Regarding chemical stability, MoNbTaVW possesses the ability to form protective oxide layers, primarily due to the presence of niobium, tantalum, and tungsten (Nb_2O_5, Ta_2O_5, WO_2), which makes the alloy relatively chemically stable in marine environments–particularly in the foundations of offshore wind turbines. Oxidative resistance is dictated by thermodynamic stability, which is characterized by the low Gibbs free energy of oxide formation for the individual alloy components (ΔG_{ox}) [6]. This aspect can be summarized as follows:

$$\Delta x^2 = k_p t. \tag{6}$$

In this expression, Δx represents the thickness of the oxide layer, and k_p is the parabolic rate constant, where a low value indicates slow formation of the oxide film on MoNbTaVW.

A key requirement for high-performance strain sensors is their ability to detect small changes in the stress state of structural components, based on variations in electrical resistance. In the HEA under consideration, this requirement is met through the combined effect of high configurational entropy and defect-dependent electron scattering mechanisms. The total electrical resistivity (ρ_{total}) of the alloy can be expressed as the sum of residual resistivity (ρ_{res}) and the contribution from s–d scattering (ρ_{sd}):

$$p(X_1, X_2, \ldots, X_n / X) = \prod_{i=1}^{n} \left[\frac{1}{\sqrt{2\pi\sigma_i}} exp\left\{ -\frac{(X_i - X)^2}{2 \cdot \sigma_i^2} \right\} \right] \tag{7}$$

where $N(E_F)$ denotes the density of electronic states at the Fermi level, and α and β are coefficients representing the relative contributions of residual resistivity and temperature-dependent scattering processes, respectively. The low mobility of vacancies in the alloy further ensures minimal resistivity drift over time.

A final, yet equally important aspect of the high-entropy alloy MoNbTaVW considered in this study is its self-healing capability [7]. This property arises from the same defect dynamics responsible for the alloy's resilience to ionizing radiation. As previously mentioned, vanadium–characterized by its strong tendency to form interatomic splitting within the lattice–facilitates the recombination of microdefects without the need for an external activation energy barrier [8]. This mechanism can be generalized by considering the maintenance of a low equilibrium defect concentration, thereby preserving the functional performance of the sensor. The microdefect dynamics are expressed as follows:

$$D_{eq} \sim \frac{G}{(R_0 + \delta R)}, \tag{8}$$

where R_0 denotes the intrinsic recombination rate, while δR represents the contribution from interatomic splitting. The absence of a significant energy barrier for defect migration implies the potential for continuous "self-healing" of the material.

High-entropy alloys (HEAs) integrated into strain sensor structures are typically applied in the form of thin films. Critical film parameters influencing material performance include thickness, deposition method, adhesion strength, residual stress, specific electrical resistivity, surface morphology, and microstructural stability. For MoNbTaVW-based strain sensors, the optimal film thickness falls within the range of 200 to 500 nm [9]. Thinner films, approximately 100 nm, may enhance the sensor's gauge factor (strain sensitivity), though they tend to suffer from poor adhesion or mechanical brittleness. Conversely, thicker films exceeding 1 μm reduce sensitivity and may introduce stress-induced deformation.

The deposition method determines film density, uniformity, and defect concentration. Among available technologies, RF/DC magnetron sputtering is the most effective for achieving low porosity and high adhesion to substrates. During deposition, the working pressure is typically maintained between 1 and 5 mTorr, while the substrate temperature ranges from room temperature to 600 °C, depending on the desired microstructural properties. Higher temperatures promote grain growth, which reduces specific electrical resistivity but may simultaneously increase material brittleness.

Adhesion enhancement is typically achieved by applying a 5–10 nm adhesion layer of titanium or chromium prior to the deposition of the high-entropy film. The residual stress generally ranges around ±100 MPa, depending on the sputtering power and deposition conditions. The specific electrical resistivity typically ranges from 40 to 80 μΩ·cm. The strain sensitivity, quantitatively expressed by the gauge factor, generally falls within the range of 2 to 4.

Considering interfacial shear stress, it is assumed that the effective stress transferred from the composite material to the HEA film is a function of the film thickness (t_f), its Young's modulus (E_f) and the characteristic length (L) over which the strain is applied. In this case, the shear stress (τ) is expressed as follows:

$$\tau = \left(\frac{E_f \cdot t_f}{L}\right) \cdot \varepsilon, \tag{9}$$

where ε represents the strain applied to the composite. According to this formulation, if τ exceeds the critical adhesion strength, the structural integrity of the sensor is maintained [10].

More specifically, when considering the gauge factor (GF), which reflects the electromechanical response of the system by quantifying the relative change in resistance ($\frac{\Delta R}{R_0}$) per unit strain (ε), the effective strain applied to the film (ε_{eff}), must be directly proportional to the strain applied to the composite (ε_{comp}), mediated by the effective coupling coefficient (C_{eff}):

$$\varepsilon_{eff} = C_{eff} \cdot \varepsilon_{comp} \tag{10}$$

Thus, the sensor response can be expressed as:

$$\frac{\Delta R}{R_0} = GF \cdot \varepsilon_{eff}. \quad (11)$$

Within this formulation, the coupling coefficient depends on the degree of interfacial adhesion and the mechanical compliance between the film and the composite material [11].

In the context of the present study, HEAs are considered for use in damage detection in wind turbine blades, which are primarily manufactured from GFRP and CFRP. Due to the complex structure and composition of the blades, each type of damage may result from multiple causes. Typical damage types include:

– Trailing edge cracks – these are common and typically occur along the bonding region between the two halves of the blade shell, manifesting as either longitudinal or transverse defects.

– Lightning damage – remains a significant threat despite the implementation of IEC 61400-24 standards. CFRP is highly susceptible to lightning strikes, particularly in high-altitude wind farm environments. Strikes occurring within one meter of the blade tip often result in complete loss of structural integrity. Surface contaminants such as dirt and salt can act as current receptors, exacerbating damage severity.

– Leading edge erosion and contamination – increase aerodynamic drag and can reduce annual energy production by up to 25 %. Rain droplets, hail, and airborne particles contribute to the surface degradation of the blade, while environmental factors like humidity and insect accumulation further accelerate deterioration. Over time, the repeated impact of these factors results in pitting and groove formation.

– Blade icing – even minor ice accumulation alters the blade profile, increasing drag and turbulence. Ice buildup can also lead to mass imbalance in the structure, resulting in irregular vibrations that accelerate wear in other components [12].

To accurately capture strain distribution, the strain sensor is configured based on the Wheatstone bridge principle [13], allowing compensation for temperature variations and enabling differential measurement of mechanical loads. The loads are applied via a controlled biaxial fatigue test that simulates realistic operational stresses experienced by wind turbine blades [14]. The strain gauge sensor is subjected to both in-plane bending and transverse loading, affecting individual components that must be decoupled for precise measurement. This is achieved through a calibration approach that accounts for curvature, based on the Euler – Bernoulli beam theory [15]. The strain responses at various sensor positions along the blades are compared to bending moments using a generalized inverse strain-curvature transformation matrix:

$$\begin{bmatrix} \kappa_x \\ \kappa_y \end{bmatrix} = B \begin{bmatrix} \varepsilon_1 - \varepsilon_{10} \\ \varepsilon_2 - \varepsilon_{20} \\ \vdots \\ \varepsilon_n - \varepsilon_{n0} \end{bmatrix} \quad (12)$$

where κ_x and κ_y represent the principal curvatures of the composite structure, and B is the transformation matrix derived from calibration loading conditions.

5. Conclusions

High-entropy alloys (HEAs) represent a promising class of materials that combine unique physico-mechanical properties such as high thermal stability, strength, and resistance to oxidation and corrosion. Their composition and synthesis methods play a key role in determining their final characteristics, making HEAs as a subject of intensive research. Owing to their exceptional properties, these alloys are increasingly being applied in aerospace engineering, industrial equipment, and energy generation systems, which open new frontiers for advanced engineering and technological development.

Conflict of Interest

The authors declare re no financial or other potential conflicts of interest regarding this work.

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