Corrosion performance and mechanical properties of FeCrSiNb amorphous equiatomic HEA thin film

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Abstract

A quaternary amorphous equiatomic FeCrSiNb HEA thin film was synthesised and characterised with the view for applications in demanding environments. The film was produced on silica and silicon substrates by ion beam sputter deposition. Scanning Electron Microscopy (SEM) was used to analyse the film morphology, and Energy-dispersive X-ray spectroscopy (EDX) was used to investigate the atomic composition. The crystal structure of the sample was investigated using X-Ray Diffraction (XRD) and Selected Area Electron Diffraction (SAED). The film is amorphous and uniform at the atomic level. An electrochemical cell with a three-electrode arrangement was utilized to assess the corrosion behaviour of the sample in 0.6 M NaCl and H$_2$SO$_4$ solutions at room temperature under ambient pressure. In addition, the corrosion tests were conducted in a Libyan crude oil to simulate an oil field corrosion process. The corrosion results showed that the FeCrSiNb HEA thin film has an excellent corrosion resistance, and that the corrosion resistance is much better than that of 304 SS in 0.6 M NaCl, H$_2$SO$_4$ solutions, and in crude oil. The amorphous equiatomic FeCrSiNb HEA thin film has high hardness at around 15 ± 1.2 GPa, and reduced Young's modulus at around 229 ± 12 GPa.

Keywords:
FeCrSiNb equiatomic alloy, amorphous, high entropy alloy HEA, thin film, corrosion resistance, hardness and reduced Young's modulus.

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1. Introduction:

In a comparison with crystalline alloys, amorphous or metallic glasses alloys do not have grain boundaries with disordered atomic-scale structure. Therefore, amorphous alloys show a higher wear resistance, fatigue strength and better corrosion resistance than crystalline alloys in many cases according to certain compositions [1-3]. This high performance of amorphous alloys has attracted scientists and engineers to use them in applications in the shipbuilding and petroleum industries [4], and in biomedical devices [5]. However, amorphous alloys as conventional alloys comprise two, three or more elements based on one or two main elements such as Cu-based [6] and Zr-based [7]. They, also exhibit defects in some cases [8].

To break the classical alloy-design philosophy, a new class of materials have been discovered. High entropy alloys (HEAs) contain five or more elements in equiatomic or near equiatomic ratios to form a simple single-phase structure [9-11]. The entropy effect increases with the increase of the number of elements added to the composition, [12] as well as with the equiatomic ratio that ranged between 5 and 35 atomic percent of every single element [13, 14]. High entropy alloy studies usually seem to be motivated by the concept that high configurational entropy might favour a uniform single-phase structure with intermetallic phases [14]. However, many studies state that HEAs can have less than five elements with atomic concentration more than 35 and less than 5 in some case. This leads to the same or closer effect that can be found in the equiatomic high entropy alloys [15-23]. These type of alloys are known as compositionally concentrated alloys [24, 25], and/or complex concentrated alloys (CCAs) [26-28].

Generally, HEA alloys are crystalline and tend to form a single-phase structure comprising one of the following structures: face-centred cubic (FCC), body-centred cubic (BCC) or hexagonal close-packed (HCP), with homogenous structure in a few cases such as Fe20Cr20Mn20Ni20Co20 [11], and Fe20Cr20Mn20Ni20C20 which was investigated in earlier work [29]. However, the
majority have multi-phase structure with elemental separation for example; Fe$_{50}$Mn$_{30}$Co$_{10}$Cr$_{10}$ [30], FeCoNiAl$_{0.2}$Si$_{0.2}$ [31], and Ta$_{20}$Nb$_{20}$Hf$_{20}$Zr$_{20}$Ti$_{20}$ [32].

Furthermore, HEAs also can be amorphous where they are known as amorphous high entropy alloys or bulk metallic high entropy alloys BM-HEAs, which are defined as alloys composed four or more elements with equimolar concentration rapid quenched from the vapour or liquid state such as: Ti$_{20}$Zr$_{20}$Cu$_{20}$Ni$_{20}$Be$_{20}$ [33], Ca$_{20}$Mg$_{20}$Zn$_{20}$Sr$_{20}$Yb$_{20}$ [34], and Fe$_{25}$Co$_{25}$Ni$_{25}$(B, Si)$_{25}$ [35]. These types of alloys are found to satisfy the target properties in required applications, for instance to have high corrosion resistance where the absence of grain boundaries could lead to improve the corrosion resistance of the alloy [36]. More information can be found within the following citation [37]. This new type of alloys could help to avoid the defects (voids and element segregation) that found in the conventional amorphous alloys where the limited number of principle elements restricts material potential development [4]. This point was further confirmed and discussed in our previous study on an equiatomic FeCrMnNiC thin films [38].

High Entropy Alloys in general possess enhanced structural stability as compared to majority of conventional alloys owing to the mixing of high entropy effect, lattice distortion effect, sluggish-diffusion effect which attributed to the limited rate of diffusion as Yeh has firstly described it [9]. Due to the presence of five or more principal elements in the solid solution phases with no dominant element in the compositions, the effective diffusion rate will be restricted because of the lattice distortion which provides additional energy barriers to atom movement. The diffusion kinetics of high entropy alloys is slower than in conventional alloys. Therefore, HEAs possess larger stability in the structure than conventional alloys [39-41]. The effect of stabilised mixing of few elements in equiatomic ratios leads to greater and unpredictable results. The combination of lattice distortion due to differences in elements atomic sizes, impeded diffusion, and high entropy all lead to new combined effects, so named “cocktail effects” [42].
Combination of unique structure and properties in HEAs have attracted significant attention and made HEAs to be key candidates for several engineering areas [43, 44]. For example, the alloys can be used in applications requiring high thermal stability [45-47], high hardness [48-51], high strength and ductility [30, 52, 53], excellent irradiation stability [54-56], good wear resistance [57, 58], good resistance to fatigue [59-61] and high oxidation resistance [62-64].

From a corrosion point of view, a considerable number of studies have been conducted to determine the corrosion behaviour of high entropy alloys in different solutions such as NaCl, H₂SO₄ and HCL at room temperature and under atmospheric pressure, and HEAs exhibited better corrosion resistance than stainless steel [65-68]. The first such experiment was done by Hsu et al in 2005. The study was conducted on varying the amount of copper on FeCoNiCrCu high entropy alloy in 3.5 % NaCl solution using a potentiodynamic polarization technique. The results showed that an increasing of the Cu content led to elemental segregation, thus decreasing the corrosion resistance. Also the uniform alloy exhibited the best corrosion resistance [69]. Moreover, the effect of Al amount on AlₓCoCrFeNi HEA showed the same result in which the resistance to corrosion reduced as the structure changed from a single phase to two phases in a 0.5 M H₂SO₄ solution. [70]. Similarly, an increase in the amount of Mn led to reduction in the corrosion resistance of Al₀.₃CoCrFeNiMnₓ in 3.5 % NaCl solution [71]. However, there are some exceptions, for instance the increase in Mo content was beneficial and enhancing the pitting corrosion on Co₁.₅CrFeNi₁₁.₅Ti₀.₅Moₓ in 1M NaCl solution [72]. It could therefore be inferred that a uniform and homogeneous alloy structure could lead to better corrosion resistance of HEA alloys [73].

Recently, surface coating techniques have been considered as an additional advantage to increase the corrosion resistance of HEAs. From the economic standpoint, the costs of high entropy bulk alloys prepared by vacuum arc melting furnace or casting are relatively high. However, coatings could solve this problem by making the overall cost lower [74]. Additionally, a HEA coating with the same composition as a bulk HEA displayed better
corrosion resistance, which could be referred to more homogeneous and uniform structure and also to the thickness of the coating [75]. As a consequence, HEA coatings, including thin films, have been successfully deposited on different substrates by several methods and demonstrated excellent corrosion resistance. This has been shown for thin film alloys synthesised by magnetron sputtering [76-80], laser cladding [66, 81], plasma spraying [82], plasma cladding [83] and mechanical alloying method [84].

In the oil and gas field, the most commonly used alloys are based on chromium and/or nickel content as they provide a good protective passive layer to protect the surface from corrosion. However, this passive layer is only effective up to a certain point and time in the presence of harsh environments such as CO₂ and H₂S. By breaking down the passive layer, the material surface becomes weak and susceptible to corrosion where pitting starts to occur. This leads to a failure of the material surface, which is a big problem for petroleum applications. [85-87]. In this paper we aim to provide a solution to this problem. A FeCrSiNb equiatomic amorphous HEA thin film was prepared by ion beam sputter deposition. The microstructure was investigated by set of techniques. Corrosion testing was performed using NaCl and H₂SO₄ solutions, and crude oil. Also, mechanical properties were examined.

2. Materials and methods:

Ion beam sputter deposition system was used to synthesise and deposit the thin film alloy on silicon (100 orientated wafers) and optically polished silica substrates. The overall deposition process was fully outlined in earlier work [88, 89]. Silicon wafers were cleaved into 1 square inch pieces and then carefully dusted with lint-free cloth and compressed air. The silica glass, 1 square inch pieces, was used as delivered from the manufacturer without additional cleaning.

The elements chosen for this work were Fe, Cr, Si and Nb in sheet shapes. The positions of the targets were adjusted several times towards the substrate to achieve the equiatomic
composition. The deposition was conducted under stable parameters of current, pressure and temperature. The base system pressure was 2.2 \times 10^{-4} \text{ Pa}, and the Argon partial pressure in the deposition chamber during the deposition system was about 3.3 \times 10^{-2} \text{ Pa}. The deposition was done at room temperature aiming to achieve the amorphous structure. In the deposition chamber, the targets were cleaning via the plasma for around 30 minutes before starting the deposition on the substrate. This is to avoid sputtering any contaminations might be left on the targets surface while substrate exchanges. The thickness of the thin film after around 120 minutes was measured by the FIB (focused ion beam) sectioning method to be approximately 1.5 microns.

For microstructural observation, a FEI Quanta FEG250 Scanning Electron Microscope (SEM) was used to study the thin film surface. Energy-dispersive X-ray spectroscopy (EDX) using an Oxford Instruments was employed to determine the chemical composition. The crystal structure of the film was investigated using X-Ray Diffraction (XRD) on a Bruker D2 Phaser instrument and Measurement Center 4.0 software. In addition, a Transmission Electron Microscope (TEM, Hitachi-9500.) sample was made by Focused Ion Beam (FIB), and Selected Area Diffraction (SAD) was utilised to examine the atomic structure in thoroughly. 300 keV electron beam was used for TEM analysis.

Corrosion tests were performed using potentiodynamic polarization technique in a three-electrode cell setup. The specimens, deposited on silicon, were set up as working electrodes (with an exposed area of 0.5 cm²), with a platinum counter electrode and using saturated calomel electrode as the reference. The tests were carried out in 0.6 M NaCl and H_2SO_4 solutions. Both solutions were purged with nitrogen in order to remove dissolved oxygen. In addition, the test was performed in a Libyan crude oil. The measurements were performed at room temperature and under atmospheric pressure. The potential and current were measured by means of an Autolab potentiostat fitted with Nova 1.10 software. According to ASTM International (American Society for Testing and Materials) standards, the scanning rate of each
test was set at 1 mV/s. Open Circuit Potential (OCP) measurements were performed for around half an hour (30 min) to achieve a stable potential. Polarization measurements were scanned between -0.1V and 1.2V. Corrosion parameters which are: corrosion potential ($E_{corr}$), corrosion current density ($i_{corr}$), and passivation regions were obtained by linear fit technique of polarization curves. For a comparison, stainless steel type 304 samples were used under same conditions.

For measuring mechanical properties of the amorphous equiatomic FeCrSiNb HEA thin film deposited on silicon, hardness and modulus were determined by a Nanoindentation system from Micro Materials Ltd, UK. A Berkovich nano-indenter was utilised to apply a ramped load up to maximum value of 50 mN.

3. Results and discussion:

3.1 Microstructure:

Figure 1 presents the data for a FeCrSiNb thin film synthesised by ion beam deposing system. A Backscatter Electron (BSE) image was taken at high magnification and is shown in fig.1 (a). The main purpose of BSE image is to clarify whether the elements are distributed uniformly or if there is any elemental and/or phase separation which will appear as contrast variation. In this case, the BSE image confirms that the microstructure of FeCrSiNb thin film is homogeneous and uniform. The Energy-dispersive X-ray spectroscopy (EDX) quantification showed that the alloy has an equiatomic composition as evident on Fig.1 (b).
Figure 1: SEM analysis of the amorphous equiatomic FeCrSiNb high entropy alloy thin film.

(a): BSE image microstructure image. (b): chemical composition of HEA thin film.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si K</td>
<td>12.50</td>
<td>24.56</td>
</tr>
<tr>
<td>Cr K</td>
<td>24.67</td>
<td>26.18</td>
</tr>
<tr>
<td>Fe K</td>
<td>25.47</td>
<td>25.17</td>
</tr>
<tr>
<td>Nb L</td>
<td>40.56</td>
<td>24.09</td>
</tr>
<tr>
<td>Totals</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

Element mapping of the FeCrSiNb thin film is presented on Fig.2. As it can be seen from the mapping, all the elements are distributed uniformly and homogeneously.

Figure 2: EDX mapping of the amorphous equiatomic FeCrSiNb HEA thin film.
In order to confirm the absence of element segregation, EFTEM (Energy filtered TEM) imaging of FeCrSiNb thin film was performed. The elemental maps prove a uniform distribution for all elements (iron, chromium, silicon and niobium) without any element segregation or precipitation as presented as on Fig. 3.

Figure 3: EFTEM images of the amorphous equiatomic FeCrSiNb HEA thin film.

In order to assess the film crystalline structure, the film was deposited on silica glass. The X-Ray diffraction pattern (XRD) demonstrates that the FeCrSiNb HEA thin film possesses no crystalline structure. The XRD pattern is characteristic to an amorphous material as displayed in Fig.4. The main film diffraction peak at around 44° is very broad and has low intensity which a typical amorphous material XRD. The second peak at 21° is related to the silica substrate as confirmed on Fig.5.
Figure 4: XRD pattern of the FeCrSiNb thin film on silica substrate.

Figure 5: XRD pattern of the silica glass substrate.
For further examination of the amorphous structure of the amorphous equiatomic FeCrSiNb high entropy alloy thin film, a FIB (Focused Ion Beam) sample was studied in a Transmission Electron Microscope (TEM). Fig. 6 (a) shows a bright field image (BFTEM) high-resolution TEM image of a high entropy thin film synthesised by ion beam sputtering. Fig. 6 (b) is the selected area diffraction (SAED) of the thin film which was taken from the marked area, and confirms the formation of a fully amorphous structure by the presence of only diffraction rings without any crystallinity patterns.

![Fig. 6 (a): BFTEM images of the amorphous equiatomic FeCrSiNb high entropy alloy thin film synthesised by ion beam sputtering.](image)

![Fig. 6 (b): SAED images of amorphous film taken from marked area.](image)

All the aforementioned results from the SEM-BSE, EDX mapping show that the amorphous equiatomic FeCrSiNb high entropy alloy thin film synthesised by ion beam sputter deposition
is a single phase and uniform alloy. This is mainly attributed to the layer-by-layer deposition which has been carried out under stable conditions of temperature and pressure [88, 89]. The formation of a dense and amorphous alloy has been confirmed by XRD and TEM results. The main reason for this is due to the transformation from ionic state to solid state which led to significantly high cooling rate at deposition chamber, and the condensation energy is released [90]. The amorphization of high entropy thin films could be attributed to the high mixing entropy and large atomic size difference. The high mixing entropy increases the mutual solubility of different elements in thin films and impedes the formation of phase separation [91]. Also, the presence of Niobium has played a vital role in improving amorphization process of the alloy. A study of the phase evolution in NbCoCrCuFeNi thin film deposited by magnetron sputtering has demonstrated that the film structure changed from a crystalline to an amorphous structure with a higher Nb content [92].

3.2 Corrosion tests:

Figure 7 shows a potentiodynamic polarisation curve of the amorphous equiatomic FeCrSiNb high entropy alloy thin film which was carried out in the three-electrode electrochemical cell in 0.6 M NaCl (3.5 % sodium chloride) solution under conditions of atmospheric pressure and room temperature. Table 1 presents corrosion parameters for FeCrSiNb HEA thin film which were obtained by a linear fit technique. Figure 8 is a potentiodynamic polarisation curve of the amorphous equiatomic FeCrSiNb HEA thin film which was conducted in in 0.6 M H2SO4 (sulphuric acid) solution under the same conditions. The obtained corrosion parameters are listed in table 2.
Figure 7: polarisation curves of the amorphous equiatomic FeCrSiNb high entropy alloy thin film and 304 SS in 0.6 M NaCl solution.

Table 1: corrosion parameters of FeCrSiNb HEA thin film and 304 SS in 0.6 M NaCl solution.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$i_{corr}$, A/Cm$^2$</th>
<th>$E_{corr}$, V SCE</th>
</tr>
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<tbody>
<tr>
<td>FeCrSiNb</td>
<td>$8.66 \times 10^{-10}$</td>
<td>0.06</td>
</tr>
<tr>
<td>304 SS</td>
<td>$1.10 \times 10^{-7}$</td>
<td>-0.29</td>
</tr>
</tbody>
</table>
Figure 8: polarisation curves of amorphous equiatomic FeCrSiNb high entropy alloy thin film and 304 SS in 0.6 M H$_2$SO$_4$ solution.

Table 2: corrosion parameters of FeCrSiNb HEA thin film and 304 SS in 0.6 M H$_2$SO$_4$ solution.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$i_{corr}$, A/Cm$^2$</th>
<th>$E_{corr}$, V SCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCrSiNb</td>
<td>1.22*E$^{-8}$</td>
<td>0.36</td>
</tr>
<tr>
<td>304 SS</td>
<td>4.86*E$^{-6}$</td>
<td>-0.46</td>
</tr>
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</table>

Figure 9 displays a potentiodynamic polarisation curve of the amorphous equiatomic FeCrSiNb high entropy alloy thin film which was carried out in crude oil under conditions of atmospheric pressure and room temperature. The obtained corrosion parameters are listed in table 3.
Figure 9: polarisation curves of FeCrSiNb HEA thin film & 304 SS in crude oil.

Table 3: corrosion parameters of FeCrSiNb HEA thin film and 304 SS in crude oil

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$i_{\text{corr}}, \text{A/Cm}^2$</th>
<th>$E_{\text{corr}}, \text{V SCE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCrSiNb</td>
<td>$8.56 \times 10^{-12}$</td>
<td>0.27</td>
</tr>
<tr>
<td>304 SS</td>
<td>$9.91 \times 10^{-12}$</td>
<td>0.12</td>
</tr>
</tbody>
</table>

It is well known in electrochemistry when analysing the corrosion performance of a material, that when there is a smaller current density and a higher corrosion potential, the resistance to corrosion is better. In addition, the passivation layer occurs when the corrosion potential shifts to the positive site with continuing the corrosion current density at the same value or a gradually increasing [70, 93, 94].
As it can be seen from the polarisation curve in fig. 7 and corrosion parameters of the FeCrSiNb HEA thin film and 304 SS in 0.6 M NaCl solution in table 1, the FeCrSiNb HEA thin film has a corrosion potential of 0.06 V and corrosion current density of $8.66 \times 10^{-10} \text{A/cm}^2$, comparing to -0.29 V and $1.1 \times 10^{-7} \text{A/cm}^2$ for 304 SS. From fig. 8 and table 2 the corrosion potential of the HEA thin film is 0.36 V and corrosion current density is $1.22 \times 10^{-8} \text{A/cm}^2$ in 0.6 M H$_2$SO$_4$ solution, whereas 304 SS has -0.46 V and $4.86 \times 10^{-6} \text{A/cm}^2$.

In addition, 304 SS shows a presence of passive layers, then protective oxide failure happens and pitting occurs suddenly in both solutions. In the case of amorphous equiatomic FeCrSiNb HEA thin film, the corrosion current density is increasing slowly, non-exponentially, (where the obvious pitting occurs) and reach to a stable area at around $E - 5 \text{A/cm}^2$ of corrosion current density which still a small value at around 1.2 V of corrosion potential in both solutions. Whereas 304 SS at the same value $E - 5 \text{A/cm}^2$ is clearly in pitting state at around 0.38 V in NaCl and at 0.76 V in H$_2$SO$_4$ solutions. This reflects that the corrosion resistance of FeCrSiNb HEA thin film to the corrosion is much higher than 304 SS.

In the case of crude oil test, the FeCrSiNb HEA thin film exhibited a corrosion potential of 0.27 V, higher than that for 304 SS of 0.12 V. The corrosion current density of the amorphous equiatomic FeCrSiNb HEA thin film and 304 SS showed close values with a small advantage for the thin film alloy ($8.56 \times 10^{-12}, 9.91 \times 10^{-12} \text{A/cm}^2$) respectively. As a result, the amorphous equiatomic FeCrSiNb high entropy alloy thin film has an excellent corrosion resistance nobler than 304 SS in in NaCl, H$_2$SO$_4$ solutions and in crude oil.

This can be attributed to several reasons. Generally, the behaviour of high entropy alloys as they have uniform single-phase microstructure with no element separation leads to a good corrosion resistance [74, 95]. Moreover, the cocktail effect of existing elements such as Cr, Si and Nb have the ability to create a passive layer to protect the material from corrosion [43, 82, 96]. The higher corrosion potential ($E_{corr}$) of amorphous equiatomic FeCrSiNb HEA thin film could be attributed to that high entropy alloys undergo self-passivation at OCP, and forms a
passive protective film as Shi et al. has stated in AlCoCrFeNi HEA [19, 97]. The amorphous structure with the absence of grain boundaries where the corrosion is more likely to happen could enhance the surface resistance to corrosion of the thin film alloy [98]. This has been discussed and proved in earlier work, where the amorphous equiatomic FeCrMnNiC HEA thin film displayed excellent corrosion resistance ($E_{corr}=0.07$ V, $i_{corr}=2.5E^{-10}$ A/cm$^2$) in NaCl solution under same conditions [38].

3.3 Mechanical properties:

The hardness measurement of the thin film was carried out by means of nanoindentation. The load was slowly increased from 10 to 50 mN. Loading and unloading was done at fixed time – 20 sec/loading/unloading, dwell period at maximum load was 60 sec, thermal drift correction was done post-indentation for 60 sec.

Hardness measurement with the range of loads allows to account in principle for various effects. At low loads the surface effect, oxide layers for instance, can be identified. It can be seen on Fig. 10 that the penetration curves at low loads are continuously smooth which indicates negligent surface oxide development. The hardness is then can be averaged over measured data. The result showed that amorphous equiatomic HEA thin film has hardness of $15 \pm 1.2$ GPa. The penetration depth is higher than usually used 1/10$^{th}$ of film thickness but it is rightful as silicon substrate has not so dissimilar to the thin film mechanical values. Fig.11 displays the value of reduced Young’s modulus over plastic depth. Smooth decay with plastic penetration depth, as expected, also enforces rightfulness of negligible substrate influence on measured values.
Figure 10. Nanoindentation data set for amorphous equiatomic FeCrSiNb HEA thin film.

Figure 11. Reduced Young's modulus of amorphous equiatomic FeCrSiNb HEA thin film.
In terms of reduced Young’s modulus, the true value should be determined at zero load. This is done by linear extrapolation in accordance with the international standard. In our case the Young’s modulus value is at around 229 ± 12 GPa as can be seen on Fig.10.

The obtained mechanical properties in this work were superior to other high entropy thin film alloys. For example, the amorphous equiatomic FeCrSiNb HEA thin film are harder than CoCrFeNi [99] NbTiAlSiZrNx [100] crystalline, and FeCoNiCuVZrAl [101] amorphous high entropy alloy films. The crystalline HETF alloys [99, 100] showed hardness of 8.5 & 12.4 GPa and Young’s modulus of 161.9 & 169 GPa respectively. While the hardness and Young’s modulus of amorphous equiatomic HEA thin film were 12 GPa and 166 GPa [101].

These superior properties of high hardness and reduced modulus in this work, are produced due to the effect of the uniform and single-phase structure which led to strengthening of the bonding structure [95]. Furthermore, it could be possible to suggest that the presence of Niobium played a significant role in improving hardness as it was examined in AlCoCrFeNiNb, High entropy thin film alloy [102].

4. Conclusion:

In conclusion, an amorphous equiatomic FeCrSiNb high entropy alloy thin film was prepared by ion beam sputter deposition. The alloy was confirmed to be equiatomic and amorphous. Corrosion tests were carried out in 0.6 M sodium chloride, sulphuric acid solutions and crude oil using an electrochemical cell. The corrosion parameters proved that the FeCrSiNb HEA thin film is nobler than the 304 SS, as it displayed a higher corrosion potential in NaCl, H2SO4 and in crude oil. The amorphous equiatomic FeCrSiNb HEA thin film exhibited a high hardness at 15 ± 1.2 GPa. The Young’s modulus value was observed at about 229 ± 12 GPa.
**CRediT authorship contribution statement:**

Waleed Muftah: conceptualization, methodology, data curation, investigation, formal analysis, writing - original draft, preparation. John Allport: review and editing. Vladimir Vishnyakov: supervision, review & editing.

**Declaration of interests:**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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