Electrical resistivity and oxidation behavior of Cu and Ti doped laser deposited high entropy alloys

Modupeola Dada and Patricia Popoola
Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa

Ntombi Mathe
Department of the National Laser Centre, Council for Scientific and Industrial Research, Pretoria, South Africa

Sisa Pityana
Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa and Council for Scientific and Industrial Research, Pretoria, South Africa, and

Samson Adeosun
Metallurgical and Materials Engineering, University of Lagos, Lagos, Nigeria and Department of Industrial Engineering, Durban University of Technology, Durban, South Africa

Abstract
Purpose – In this study, AlCoCrFeNi–Cu (Cu-based) and AlCoCrFeNi–Ti (Ti-based) high entropy alloys (HEAs) were fabricated using a direct blown powder technique via laser additive manufacturing on an A301 steel baseplate for aerospace applications. The purpose of this research is to investigate the electrical resistivity and oxidation behavior of the as-built copper (Cu)- and titanium (Ti)-based alloys and to understand the alloying effect, the HEAs core effects and the influence of laser parameters on the physical properties of the alloys.

Design/methodology/approach – The as-received AlCoCrFeNiCu and AlCoCrFeNiTi powders were used to fabricate HEA clads on an A301 steel baseplate preheated at 400°C using a 3 kW Rofin Sinar d’Y044 continuous-wave laser-deposition system fitted with a KUKA robotic arm. The deposits were sectioned using an electric cutting machine and prepared by standard metallographic methods to investigate the electrical and oxidation properties of the alloys.

Findings – The results showed that the laser power had the most influence on the physical properties of the alloys. The Ti-based alloy had better resistivity than the Cu-based alloy, whereas the Cu-based alloy had better oxidation residence than the Ti-based alloy which attributed to the compositional alloying effect (Cu, aluminum and nickel) and the orderliness of the lattice, which is significantly associated with the electron transportation; consequently, the more distorted the lattice, the easier the transportation of electrons and the better the properties of the HEAs.

Originality/value – It is evident from the studies that the composition of HEAs and the laser processing parameters are two significant factors that influence the physical properties of laser deposited HEAs for aerospace applications.

Keywords Laser deposition, Electrical resistivity, Oxidation, High entropy alloys

Paper type Research paper

Introduction

For over a decade, high entropy alloys (HEAs) have been extensively studied for aerospace applications attributed to their distinct design concept and properties. Conventional alloy designs were based on only one principal element called the base metal, with the addition of several alloying elements to improve the properties of the base metal, thus forming binary, tertiary and quaternary alloys. However, the innovative HEAs concept is based on at least five principal elements, with each element having a concentration between 35 and 5 at.%
HEAs are potential materials for several applications and properties (Kao et al., 2004; He et al., 2017). The HEA concept is very different from the traditional principal elemental approach of alloy development. HEAs can be made from minor elements with <5 at.% attributed to their solid solution phases and their higher mixing entropies (Tsai and Yeh, 2014). These characteristic solid solution phases give HEAs attractive properties such as excellent elevated temperature strength (Hsu et al., 2011), hardness (Zhou et al., 2007; Xin et al., 2021), wear resistance (Chuang et al., 2011; Jin et al., 2018), corrosion resistance (Kao et al., 2010), thermal stability (Tsai et al., 2011; Chen et al., 2019) and electrical and magnetic properties (Kao et al., 2011). According to Arif et al. (2021), HEAs are potential materials for several applications and industries such as petrochemical, caming and bottling industries, nuclear fusion and fission reactors, energy storage, automobile, biomedical, marine equipment and aerospace turbine blades application (Arif et al., 2022; Maulik et al., 2018). AlCoCrFeNi HEA is one of the most studied compositions, which acts as an excellent binder owing to its high entropy mixing effect (Zhu et al., 2013). Properties of this alloying system can be improved with the inclusion of other alloying elements. The influence of adding Nb to the AlCoCrFeNi HEA composition was investigated (Ma and Zhang, 2012). The authors mentioned that the alloy’s microhardness and yield strength increased linearly with an increase in Nb content. In another study, the effect of vanadium on the properties of AlCoCrFeNi HEA composition was examined; the authors recorded an increase in the plastic strain, microhardness and compressive strength of the alloy with an increase in the vanadium content (Dong et al., 2014). The minor addition of Zr to the AlCoCrFeNi HEA composition was reported to have significantly increased the mechanical properties of the alloy (Chen et al., 2016). The influence of copper (Cu) on the mechanical and microstructural properties of the AlCoCrFeNi HEA composition was examined. The results showed that Cu influenced the face centred cubic (FCC) phase formation, with an increase in the yield strength and reduction in the plastic strain as the Cu content increased (Zhu et al., 2016). The effect of titanium (Ti) on the mechanical properties of the AlCoCrFeNi HEA was tested. The results showed that the alloy had a dendritic phase with a body centred cubic (BCC) structure. The hardness and yield strength increased as the Ti content increased and the authors attributed the increment to the solid solution strengthening mechanism of the Ti addition to the HEA (Wang et al., 2013).

Nonetheless, most studies in the literature on the AlCoCrFeNi HEAs compositional system with Cu and Ti additions are focused on the mechanical properties with limited reports on the electrical and thermal properties (Qiao et al., 2021; Kang et al., 2018). The physical properties of HEAs are still in their preliminary stages, with the mechanism of the composition and properties of the alloys being unclear, thus causing difficulties in controlling these properties which makes the reports on the phonon and electronic band structure of HEAs limited in the literature and should be explored (Tsai, 2013). Few studies investigated the relative contribution of the phonon and electron to the thermal conductivity and electrical resistivity of arc melted AlCoCrFeNi (Chou et al., 2009). The authors argued that the phonon and electron components in the HEA are comparable with some conventional metals but need further studies. Furthermore, the authors reported a new class of soft magnetic material using HEAs (Zhang et al., 2013). The electrical properties of FeCoNi(AlSi), with the molar ratio of x from 0 to 0.8 via arc melting was investigated. The results showed that the HEAs had an optimum balance of properties at x = 0.2 with electrical resistivity of 69.5 μΩ·cm. The electrical properties of as-cast AlCoCrFeNi were also analyzed and the results showed that the residual electrical resistivity of the HEAs varied between 100 and 200 μΩ·cm (Kao et al., 2011).

The improvement of the thermal properties of HEAs is essential for nuclear power plants vehicle and aero engines. These improvements can be attributed to the addition of alloying elements (Waseem and Ryu, 2020). Alloying elements such as Si, aluminum (Al) and chromium (Cr) form protective oxides like Cr2O3, SiO2 and Al2O3 which improve the oxidation properties of HEA compositions (Zelenitsas and Tsakiroopoulos, 2006; Cai et al., 2019). Hence, the influence of Al on the oxidation behavior of FeCoCrNiMnAlx (0 ≤ x ≤ 0.75) HEA via laser-deposition method, was examined in air at 600°C. It was observed that the weight gain decreased with an increase in the volume fraction of Al attributed to the α-Al2O3 oxide formed at FeCoCrNiMnAl0.5 and FeCoCrNiMnAl0.75, respectively (Cui et al., 2020a). However, the α-Al2O3 oxide scale formed had poor adhesion to the surface of the alloy. Furthermore, the oxidation properties of Al–Co–Cr–Ni–(Fe, Si) HEAs at elevated temperatures were studied. At low Al content, Cr2O3 oxide scale was observed on the outside surface of the HEA, whereas AlN and Al2O3 precipitates were observed internally (Butler et al., 2015). At higher Al content, small mass gains with Al2O3 scales were observed externally.

In another study, the effect of iron on the oxidation performance of Fe2CoCrNi HEA coating was investigated at 950°C. After 5 and 100 h, the results showed that the high temperature oxidation resistance of the alloy was decreased with an increase in volume fraction of iron (Fe) attributed to the formation of Fe2O3 on the outer side of the coating (Cai et al., 2018). Another study probed the effect of Cu on the oxidation behavior of arc-melted AlCoCrCuFe HEAs (Dąbrowa et al., 2017). The results showed that the oxidation resistance reduced with an increase in Cu content with drastic changes noticed in the microstructure between 100 and 500 h attributed to the tendency of Cu to segregate, which severely influenced the oxidation behavior of the alloy (Singh et al., 2011; Tung et al., 2007; Wen et al., 2009).

The Al0.5CrCoFeNi HEA was fabricated via arc melting and the oxidation resistance of the alloy at several temperatures and compositions for 100 h was investigated (Lihua et al., 2015). The results showed excellent oxidation resistance at 800°C and 900°C; however, a decline in oxidation resistance was observed as the temperature increased from 1,000°C to 1,100°C. The oxidation behavior of the alloy followed the parabolic law at 800°C and 900°C. Nonetheless, at 1,000°C, the alloy showed both a linear oxidation rate and a parabolic rate law at x = 0.97 and 0.56, respectively (Abbaspazadeh et al., 2020). The oxidation rate of CrMnFeCoNi HEA was noticed to be both linear and parabolic at 500°C–900°C. The oxides formed at 700°C and 800°C were Cr enriched Mn2O3 and a Cr2O3 thin layer, whereas Mn3O4 oxides were formed at 900°C (Laplanch e et al., 2016). Chang et al. (2019) also studied the influence of Cr on the laser-deposited FeCrxCoNiB HEA where 0.5 ≤ x ≤ 3.0 and the authors stated that the oxidation characteristics of the coating was...
improved, attributed to the Cr₂O₃, CoFe₂O₄ and Fe₂O₃ oxides formed on the surface of the coating. Consequently, the addition of alloying element and fabrication technique will significantly alter the physical properties of HEAs (Amendola et al., 2015; Alaneme et al., 2016; Farina et al., 2016).

Cui et al. (2020b) and Xu et al. (2020a) studied the oxidation behavior and the influence of Ti in AlCoCrFeNiTi₀.₅ laser-deposited HEAs and the influence of Cu in CuAlNiCrFe laser-deposited HEAs, respectively; however, there are limited literature reports on the electrical resistivity and oxidation behavior of AlCoCrFeNi HEAs with regard to the comparative influence of Cu and Ti alloying elements on the physical properties of AlCoCrFeNi–Cu and AlCoCrFeNi–Ti laser deposited HEAs. Therefore, this study comparatively investigates the physical properties of AlCoCrFeNi–Cu (Cu-based) and AlCoCrFeNi–Ti (Ti-based) HEAs fabricated via laser additive manufacturing to understand the influence of alloying elements on the physical properties of the HEAs and investigates the potential application of these as-built alloys in the aerospace industry.

Materials and methods

Sample preparation

Baseplates with dimension 50 × 50 × 5 mm were sandblasted with silica grit using SBC 350 vertical sandblasting machine and wiped clean with acetone to increase the laser absorption and reduce laser reflection during deposition. There were no infringements of human or animal rights during fabrication. Table 1 shows the chemical composition of the HEA powder with an average particle size of 45–106 μm comprising Al, cobalt (Co), Cr, Fe, nickel (Ni), Cu and Ti having (99.9%) purity which were mixed together to form AlCoCrFeNiCu (Cu-based) and AlCoCrFeNiTi (Ti-based) HEAs fabricated via laser additive manufacturing to understand the influence of alloying elements on the physical properties of the HEAs and investigates the potential application of these as-built alloys in the aerospace industry.

<table>
<thead>
<tr>
<th>Element</th>
<th>Al (at.%)</th>
<th>Co (at.%)</th>
<th>Cr (at.%)</th>
<th>Fe (at.%)</th>
<th>Ni (at.%)</th>
<th>Cu (at.%)</th>
<th>Ti (at.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>16.6</td>
<td>16.6</td>
<td>16.6</td>
<td>16.6</td>
<td>16.6</td>
<td>16.6</td>
<td>16.6</td>
</tr>
<tr>
<td>Cu-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEA</td>
<td>42.95</td>
<td>11.09</td>
<td>10.24</td>
<td>13.52</td>
<td>10.36</td>
<td>11.84</td>
<td></td>
</tr>
<tr>
<td>Ti-based</td>
<td>44.12</td>
<td>10.23</td>
<td>10.96</td>
<td>12.55</td>
<td>10.96</td>
<td>11.18</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 SEM micrograph of the powder morphology

Notes: (a) Ti-based HEA; (b) Cu-based HEA
composition and that the thickness of the clad was between 500 and 1,000mm for all alloys, comprising clad-zone, bond-zone and heat-affected zone with no obvious microstructural defects as shown in Figure 2.

The bonding line at the interface of the coating was clear and smooth, showing good metallurgical bonding between the baseplate and the HEAs (Liu et al., 2014). The XRD patterns shown in Figure 3 of the laser-deposited HEAs AlCoCrFeNiCu and AlCoCrFeNiTi reveal the alloys were composed of FCC and BCC phases with the AlCoCrFeNiTi having more predominant peaks with BCC structures than the AlCoCrFeNiCu HEA attributed to the alloying compositional effect.

According to these observations, the volume fraction of the BCC phase in both alloys more than the FCC phase attributed to the rapid solidification feature of the laser-deposition process (Ocelík et al., 2016). The alloys had excellent metallurgical bond without defects. The two samples of the Cu-based and the Ti-based HEAs each showed columnar and equiaxed dendritic microstructures, respectively, attributed to the heat flux direction and rapid solidification process of manufacturing route shown in Figure 4 (Xu et al., 2020b). Similar grain morphologies were observed in other laser-deposited HEAs (Xiang et al., 2019a, 2019b).

The oxidation behavior of the HEAs was investigated in air using PerkinElmer Thermogravimetric Analyzer (TGA 4000). Thermal gravimetric analyzer can be used to determine the thermal stability of the HEAs under a constant heating rate in an inert environment. The variations in weight as a function of temperatures between 37°C and 1,000°C and constant heat rate of 20 C · min⁻¹ are shown in Figure 5.

The results show that the resistance to oxidation can be ranked as sample A > D > C > B in order of the smallest to the largest mass. The Cu-based HEA at 1,400 W and 12 mm/s had the smallest mass suggesting the alloy had the best oxidation resistance. The percentage weight change for each composition is displayed in Figure 6.

Samples C and D exhibited the highest weight change at 0.3% and 0.27%, respectively, attributed to the compositional effect. The Ti-based HEA experienced selective oxidation because of the high affinity Ti has for oxygen at high temperatures, making the alloying composition oxidize more rapidly than the Cu-based HEA (Guleryuz and Cimenoglu, 2009). The laser parameters also influenced the weight difference of the alloys, increasing with an increase in laser power from 1,400 to 1,600 W. The energy density, which increased from 58.3 J/mm² to 80 J/mm² at 1,400 W to 1,600 W, was adequate to support the thermodynamic formation of solid solution phases that are resistant to thermal decomposition (Fargas et al., 2017). The high amount of Al in both alloys promotes the formation of Al₂O₃ protective scales showing

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Optimized laser processing parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>High entropy alloys</td>
<td>Sample</td>
</tr>
<tr>
<td>Cu based</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Ti based</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
</tbody>
</table>

Figure 2  Representative SEM micrograph of laser deposited HEA clad

Note: Dada et al., 2020
similarities with stainless steels (Xu et al., 2011; Pint et al., 2007; Brady et al., 2008). In general, both HEAs had good oxidation resistance with a parabolic growth rate attributed to the lattice distortion effect from the high concentration of alloying elements.

**Figure 3** XRD graph of laser deposited HEAs

![XRD graph of laser deposited HEAs](image)

*Notes:* (a) Cu-based; (b) Ti-based HEA at 1,600 W and 10 mm/s

**Figure 4** Microstructure of as-built HEAs

![Microstructure of as-built HEAs](image)

*Notes:* (a) Cu-based columnar dendrite structure; (b) Ti-based equiaxed dendrite structure

**Figure 5** Oxidation behavior of the Cu- and Ti-based high entropy alloys

![Oxidation behavior of the Cu- and Ti-based high entropy alloys](image)

**Figure 6** Comparative weight change of the Cu- and Ti-based high entropy alloys

![Comparative weight change of the Cu- and Ti-based high entropy alloys](image)

similarities with stainless steels (Xu et al., 2011; Pint et al., 2007; Brady et al., 2008). In general, both HEAs had good oxidation resistance with a parabolic growth rate attributed to the lattice distortion effect from the high concentration of alloying elements.
such as Al, which significantly reduces the diffusivity, thus, prolonging the growth of oxide layers and improving the oxidation resistance (Butler and Weaver, 2016). Some studies in the literature and their results are summarized in Table 3. It was observed that the studies on the oxidation behavior of laser-deposited HEAs were focused on the influence of alloying elements on the thermal properties of the HEAs, hence, showing that alloying elements play a significant role in improving the properties of HEAs and provides proper guidance to future design and development of HEAs (Tong et al., 2020).

**Electrical resistivity and conductivity properties**

The electrical resistivity of the HEAs was measured at room temperature. The values of resistivity were inversed to derive the electrical conductivity, $\sigma$ of the alloys (Amendola et al., 2015). The resistivity of the laser-deposited HEAs in this study is relatively higher than those in the literature fabricated by casting technique attributed to the rapid solidification of the additive manufacturing process, which causes a high distortion of the lattice promoting the scattering of electron waves in the as-built HEA system (Zhu et al., 2013). Generally, the electrical resistivity of most materials is controlled by the composition and temperature. However, the resistivity of the HEAs is influenced by the phonon ($T^3$), electron–electron interaction ($T^{1.5}$), temperature ($T$) and the magnetic effect ($T^2$), but at intermediate temperatures of about 300 and 400 K, the electrical resistivity is mostly influenced by the temperature and magnetic effect, whereas at temperatures between 300 and 400 K, the resistivity is influenced only by the phonon (Alaneme et al., 2016). The graph of electrical resistivity, electrical conductivity and International Annealed Copper Standard (IACS) as a function of the composition and laser parameter is shown in Figure 7. Electrical resistivity is influenced by the composition and temperature (Zhu et al., 2013). The results showed that resistivity increases with an increase in laser power in both alloys. The resistivity of the Ti-based HEA at $3.6 \times 10^{-6} \Omega m$ was higher than that of the Cu-based HEA at $2.9 \times 10^{-6} \Omega m$ attributed to the compositional effect. Ti has about 3% conductivity as Cu with much higher resistivity. The atomic bonding of the Ti-based HEA is improved attributed to the predominant BCC solid solution phase which was more observed in the Ti-based HEA, thus improving the electrical resistivity of the alloy (Jin et al., 2018).

![Figure 7](image-url)

**Table 3** Summary of the compositional effect on the oxidation behavior of high entropy alloys and their fabrication techniques

<table>
<thead>
<tr>
<th>High entropy alloy</th>
<th>Condition of exposure</th>
<th>Fabrication technique</th>
<th>Results</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlCoCrFeNiCu and AlCoCrFeNiT2</td>
<td>1,000°C</td>
<td>Laser deposition</td>
<td>High Al content, with continuous and protective $Al_2O_3$ scale observed obeying parabolic growth law. Cu-based had better oxidation than the Ti-based alloy</td>
<td>This study</td>
</tr>
<tr>
<td>AlCoCrFeNiT2 and AlCoCrFeNiCu</td>
<td>Thermal gravimetric analyzer</td>
<td></td>
<td>Cr2O3/spinel and $Al_2O_3$ oxide observed.</td>
<td>Chen et al. (2018)</td>
</tr>
<tr>
<td>AlCoCrFeNi and AlCoCrFeNiSi0.3</td>
<td>800°C–1,000°C</td>
<td>Arc melting</td>
<td>The effect of $Si$ positively influenced the oxidation behavior only at 800°C</td>
<td>Erdogan et al. (2019)</td>
</tr>
<tr>
<td>AlCoCrFeNiTi and AlCoCrFeNiTi0.5</td>
<td>1,000°C</td>
<td>Induction melting</td>
<td>Al and Ti oxides. $Al$ improves oxidation, whereas $Ti$ deteriorates oxidation</td>
<td></td>
</tr>
<tr>
<td>AlCoCrFeNiCu and AlCoCrFeNiT2</td>
<td>1,000°C</td>
<td>Arc melting</td>
<td>$\alpha-Al_2O_3$ oxide formed, spallation with increase in Cu content and phase changes observed</td>
<td>Dąbrowa et al. (2017)</td>
</tr>
<tr>
<td>AlCoCrFeNiSi and AlCoCrFeNiCu</td>
<td>Furnace exposure at 1,050°C</td>
<td>Casting</td>
<td>With low $Al$ content $Cr_2O_3$ and high $Al$ content $Al_2O_3$ scale obeying parabolic growth law</td>
<td>Butler et al. (2015)</td>
</tr>
<tr>
<td>AlCoCrFeNiTi and AlCoCrFeNiT2</td>
<td>Electric furnace at 700°C and 800°C</td>
<td>Laser metal deposition</td>
<td>$Cr_2O_3$ and $Al_2O_3$ oxides were formed attributed to the improvement of the oxidation resistance</td>
<td>Cui et al. (2020)</td>
</tr>
<tr>
<td>AlCuCrFeNi</td>
<td>Industrial tube furnace at 1,050°C</td>
<td>Laser cladding</td>
<td>$\alpha-Al_2O_3$ oxide was formed which prevented the formation of spinel structures and other oxides</td>
<td>Xu et al. (2020)</td>
</tr>
</tbody>
</table>
On the other hand, Cu in the Cu-based HEA had the highest electrical conductivity at $1.8 \times 10^2$ (31% IACS) attributed to the compositional effect of Cu, Al and Ni alongside the orderliness of the lattice, which is significantly associated with the electron transportation. Therefore, the more distorted the lattice, the easier the transportation of electrons. Free electron movement in the lattice influences the increment of the electrical conductivity (Farina et al., 2016). Therefore, energy is transmitted better in the Cu-based HEA than the Ti-based HEA. Comparatively, the chart in Figure 8 shows that the Ti-based HEA generally had the better physical properties compared with the Cu-based HEA, whereas the comparative electrical resistivity values of HEAs and their various fabrication techniques are shown in Table 4.

**Conclusion**

In this study AlCoCrFeNi–Cu (Cu-based) and AlCoCrFeNi–Ti (Ti-based) HEAs were fabricated using a direct blown powder technique via laser additive manufacturing on an A301 steel baseplate. The thermal properties, the electrical resistivity and thermal conductivity of the as-built Cu- and Ti-based alloys were investigated to understand the compositional effect, the high entropy core effect and the effect of the laser processing parameters on the physical properties of the alloys.

![Figure 8](image)

**Figure 8** Chart showing the physical properties of the Cu-based HEAs (samples A and B) and Ti-based HEAs (samples C and D)

<table>
<thead>
<tr>
<th>High entropy alloy</th>
<th>Resistivity</th>
<th>Fabrication technique</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlCoCrFeNi</td>
<td>1.42 Ωm</td>
<td>Casting</td>
<td>Kao et al. (2011)</td>
</tr>
<tr>
<td>AlCoCrFeNiCu</td>
<td>2.9 Ωm</td>
<td>Laser deposition</td>
<td>This study</td>
</tr>
<tr>
<td>CoCrFeNi</td>
<td>2.21 Ωm</td>
<td>Casting</td>
<td>Kao et al. (2011)</td>
</tr>
<tr>
<td>AlCoCrFeNiTi</td>
<td>3.6 Ωm</td>
<td>Laser deposition</td>
<td>This study</td>
</tr>
<tr>
<td>Al2CoCrFeNi</td>
<td>2.11 Ωm</td>
<td>Casting</td>
<td>Kao et al. (2011)</td>
</tr>
</tbody>
</table>

The Cu-based HEA had slightly better oxidation properties, whereas the Ti-based HEA had better resistivity attributed to the compositional effect. The Ti-based HEA experienced selective oxidation because of the high affinity Ti has for oxygen at high temperatures, making the alloying composition oxidize more rapidly than the Cu-based HEA. The lattice distortion effect had the most influence on the physical properties of the laser-deposited HEAs, which invariably promotes the scattering of electron and phonons waves that increase the resistivity and reduce the thermal conductivity. Also, the laser power had the most effect on the resistivity of both alloys, increases with an increase in laser power. Generally, the physical properties of as-built HEAs were significantly influenced by the variation of alloying elements. Nonetheless, more studies need to be done on the cost implication of the compositional combination of both alloys and the influence of heat treatment on the physical properties of the as-built HEAs.

**References**


Cui, W., Li, W., Chen, W.T. and Liou, F. (2020a), “Laser metal deposition of an AlCoCrFeNiTi0. 5 high-entropy alloy coating on a Ti6Al4V substrate: microstructure and oxidation behavior”, Crystals, Vol. 10 No. 8, pp. 638.


Dąbrowa, J., Cieślak, G., Stęgar, M., Mroczka, K., Berent, K., Kulik, T. and Danielewski, M. (2017), “Influence of Cu content on high temperature oxidation behavior of AlCoCrCuFeNi high entropy alloys (x= 0; 0.5; 1)”, Intermetallics, Vol. 84, pp. 52-61.


**About the authors**

Modupeola Dada is a research student at the Tshwane University of Technology. Modupeola Dada is the corresponding author and can be contacted at: dadadupeola@gmail.com

Popoola Patricia is a Professor of metallurgy at the Tshwane University of Technology and the Leader of the Advanced Surface Engineering Research Centre at the same university in South Africa.

Ntombi Mathe is a doctor of philosophy in chemistry and the Senior Researcher at the Council of Scientific and Industrial Research, National Laser Center.

Sisa Pityana is a Professor of physics at the National Laser Centre, Council of Scientific and Industrial Research (NLC-CSIR) Centre, South Africa.

Samson Adeosun is a Professor in metallurgical and materials engineering at the University of Lagos, Akoka, Nigeria.

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm

Or contact us for further details: permissions@emeraldinsight.com