

Impact of chemical composition on tribological properties of $\text{Al}_x\text{CoCrFeNi}$ high-entropy alloys

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Abstract: High-entropy alloys were first extensively described in 2004 [1]. Despite the increasing scientific interest in these materials, there is still much to discover. The AlCoCrFeNi alloy is one of the most popular HEAs. Scientists often study the mechanical properties of this alloy and the effect of varying the different component contents on its properties [2,3]. There are also studies on the effects of alloying additives on structure and properties [4,5]. In this study, high-entropy alloys were obtained by induction melting. The influence of aluminium content and titanium addition on tribological properties of $\text{Al}_x\text{CoCrFeNi}$ alloy was tested. Furthermore, the alloys were characterised by X-ray diffraction (XRD), hardness, and microstructure examination. The occurring wear mechanisms and tribological properties of the tested high-entropy alloys were analysed and compared with the results obtained for C45 steel. The received results confirm the influence of Al content in $\text{Al}_x\text{CoCrFeNi}$ alloy and Ti addition on tribological properties.

Keywords: HIGH-ENTROPY ALLOY, INDUCTION MELTING, TRIBOLOGICAL PROPERTIES, MICROSTRUCTURE

1. Introduction

High-entropy alloys (HEAs) are a relatively new group of materials that have good functional and structural properties according to the literature. HEAs differ from conventional alloys, because they are composed of 5 to 13 elements in amounts varying from 5 to 35% [6]. In this study, the tribological properties of $\text{Al}_x\text{CoCrFeNi}$, $\text{AlCoCrFeNiTi}_{0.5}$ alloys and, for comparison, the common steel C45 were investigated. Additionally, the presence of phases, hardness, and microstructure were examined.

2. Materials and methods

High-entropy alloys $\text{Al}_x\text{CoCrFeNi}$ ($x = 0.5, 0.7, 1$) and $\text{AlCoCrFeNiTi}_{0.5}$ were obtained by induction melting in a protective argon atmosphere. The C45 steel that was used to compare results was hardened in water and low tempered. Hardness was measured by the Vickers method under a load of 10 kG. A high-resolution SEM/FIB SIOS 2 electron microscope was used to analyse the microstructure and chemical composition. Friction paths were analysed using a HITACHI S-3000N scanning electron microscope. Tribological tests were carried out on a T-11 disk-ball type tribometer. Each series was tested a minimum of two times, where the test parameters were:

- pressure $F=10$ N
- time $T=2$ h= 7200 s
- linear speed $v=0.1$ m/s

Alloys obtained by induction melting may exhibit a slightly changed content of particular elements. This occurs because of the material deposition on the crucible (metal adhesion effect). The chemical composition of the produced specimens is presented in Table 1.

Table 1: Chemical composition of obtained alloys.

Materials	Element (at. %)					
	Al	Cr	Fe	Co	Ni	Ti
$\text{Al}_{0.5}\text{FeCrCoNi}$	11,22	14,24	24,95	25,07	24,53	-
$\text{Al}_{0.7}\text{FeCrCoNi}$	14,66	15,37	23,90	23,36	22,71	-
AlFeCrCoNi	18,72	21,26	21,22	20,07	18,72	-
$\text{AlFeCrCoNiTi}_{0.5}$	17,94	17,04	19,87	18,28	17,00	9,86

3. Results

The influence of the chemical composition on the crystal structure of high-entropy alloys was investigated (Fig. 1) In the $\text{Al}_{0.5}\text{FeCrCoNi}$ alloy, mainly the fcc phase appears, one small peak corresponding to the bcc phase is visible. For the $\text{Al}_{0.7}\text{FeCrCoNi}$ alloy the amount of the bcc phase increases, and for the AlFeCrCoNi alloy only bcc is present. In the $\text{AlFeCrCoNiTi}_{0.5}$ sample, titanium caused the appearance of additional intermetallic

phases with a complex chemical composition and a complicated crystal structure.

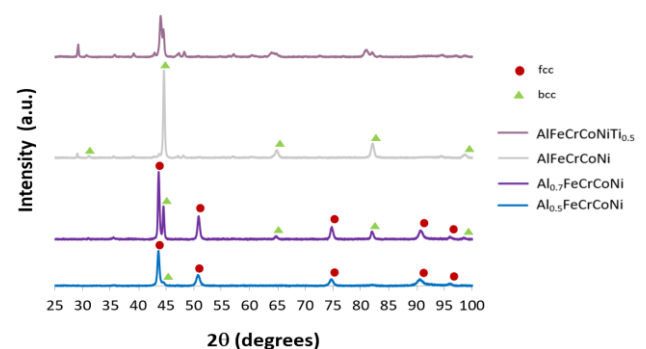


Fig. 1 XRD patterns of high-entropy alloy samples.

In the microstructure of $\text{Al}_{0.5}\text{FeCrCoNi}$ sample (Fig. 2a), two phases are visible where the bright phase is homogeneous. Large grains of alloy elements with fcc structure are observed. A dark phase is present in the spaces between the grains. The microstructure of the $\text{Al}_{0.7}\text{FeCrCoNi}$ sample (Fig. 2b) differs significantly from the previous one. The fcc and bcc phases are also present, with a higher contribution of the first one. Eutectic mixture (resembling Widmanstätten pattern) of fcc and bcc phases is observed. The AlFeCrCoNi sample (Fig. 2c) shows a diversified structure. The boundaries of large grains and the complex porous structure around them are visible. The structure of the $\text{AlFeCrCoNiTi}_{0.5}$ alloy (Fig. 2d) is much more complicated, which corresponds well with the obtained XRD results. There are equiaxial grains with eutectic mixtures at their periphery. Meanwhile, separations of an additional phase are observed at the grain boundaries.

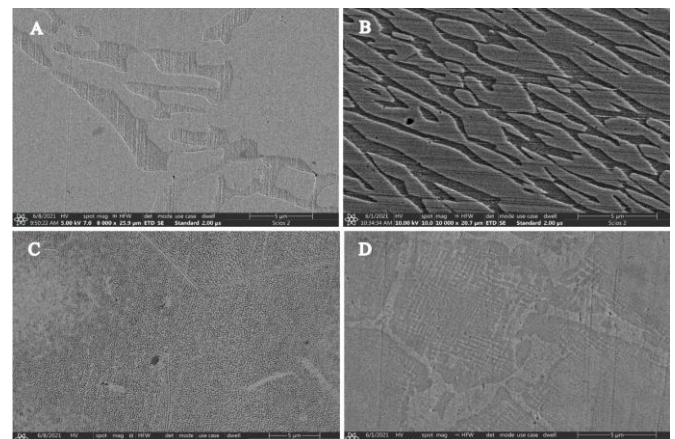


Fig. 2 SEM micrographs of: a) $\text{Al}_{0.5}\text{FeCrCoNi}$, b) $\text{Al}_{0.7}\text{FeCrCoNi}$, c) AlCoCrFeNi , d) $\text{AlCoCrFeNiTi}_{0.5}$ alloys.

The results of the Vickers hardness measurement are shown in Figure 3. Based on the results, it can be concluded that the hardness of $\text{Al}_x\text{CoCrFeNi}$ alloys increases with increasing aluminium content. Also the addition of titanium significantly improved the hardness - it raised by about 100 HV compared to the AlFeCrCoNi alloy.

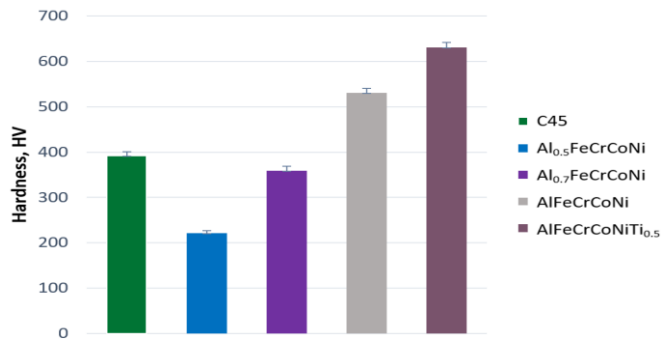


Fig. 3 The average hardness of the tested alloys.

After the friction test, the mass wear of the cooperating materials were measured. The wear of the ceramic balls was negligible in all cases (the highest mass loss was 0.001g). Significant differences were observed in the mass wear of the disks (Fig. 4). There is no analogy between the hardness of the samples and the obtained mass wear results. For $\text{Al}_{0.5}\text{FeCrCoNi}$, the average consumption was less than 0.008g. The $\text{Al}_{0.7}\text{FeCrCoNi}$ sample obtained the worst results - it lost almost 16g in weight. For AlFeCrCoNi , on the other hand, the wear decreased dramatically and reached just over 0.05. The most wear-resistant high-entropy sample turned out to be the one with titanium, which had a significant effect on the reduction of wear. In conclusion, the comparison sample made of C45 steel showed by far the least wear under similar conditions, although its hardness was comparable to that of $\text{Al}_{0.7}\text{FeCrCoNi}$, whose wear was the highest.

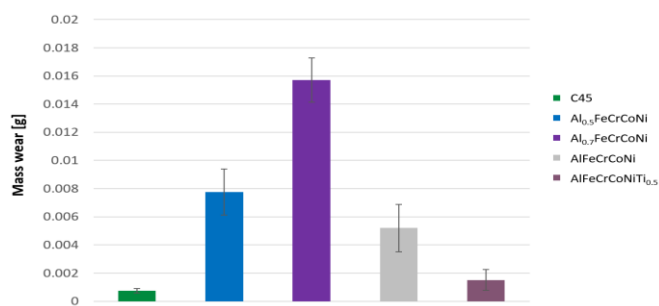


Fig. 4 Mass wearing of the samples after the friction test.

Pictures of the friction paths are shown in Fig. 5. In the case of the $\text{Al}_{0.5}\text{FeCrCoNi}$ sample, the wear mechanism is mixed. Traces of abrasive friction caused by abrasive contact with a ceramic ball can be identified. On the edges of the friction trace, plastically deformed microscopic fragments of material lifted outside the contact area can be seen. Oxide films covering a large part of the friction trace are also visible. The presence of oxide films may be responsible for reduction of material wear. There is much less protective oxide film in the $\text{Al}_{0.7}\text{FeCrCoNi}$ sample. The surface of the friction trace of the AlFeCrCoNi sample differs from the previous ones. It is more homogeneous, individual wear products are visible, which may be crushed oxide films. The grained microstructure of the material is also visible. The friction trace of the $\text{AlFeCrCoNiTi}_{0.5}$ sample is much narrower, which indicates less wear. The wear character itself is similar to the other high-entropy alloys. In sample C45, it is possible to observe the occurrence of an abrasive-adhesive mechanism. This created wear products which then contributed to adhesive wear.

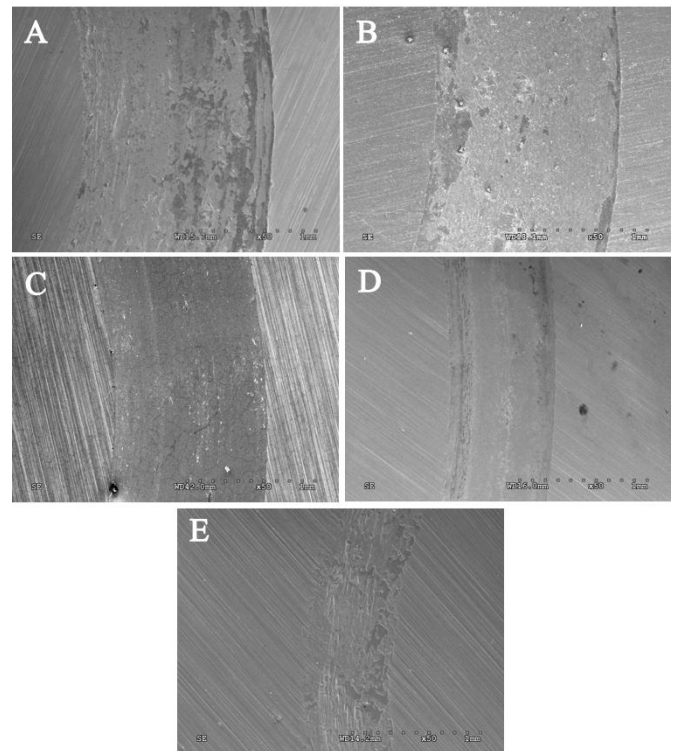


Fig. 5 Friction trace images of: a) $\text{Al}_{0.5}\text{FeCrCoNi}$, b) $\text{Al}_{0.7}\text{FeCrCoNi}$, c) AlCoCrFeNi , d) $\text{AlCoCrFeNiTi}_{0.5}$, e) C45 under magnification $\times 50$ (SEM).

4. Conclusions

- With higher amounts of aluminium the hardness of $\text{Al}_x\text{CoCrFeNi}$ alloys increases. The crystal structure also changes from fcc to bcc. The addition of titanium also had a positive effect on the hardness of the alloy (100 HV increase compared to $\text{Al}_{1.2}\text{CoCrFeNi}$ alloy).
- Steel has a completely different friction mechanism, accompanied by the formation of a large number of secondary layers to protect against wear. In the case of high-entropy alloys, the amount of secondary layers was dependent on the chemical compositions, but in each sample it was smaller than in C45 steel. The beneficial effect of the presence of titanium on tribological properties can be associated with a significant increase in sample hardness.

5. References

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