EFFECT OF Al CONTENT ON STRUCTURE AND WEAR BEHAVIOR OF AlCoCrFeMoNi HIGH ENTROPY ALLOYS

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Abstract: High-entropy $Al_xCoCrFeMo_{0.5}Ni$ (x=0-2) alloys are prepared by the vacuum arc melting and casting method. The effects of Al content on the microstructure, hardness and wear resistance of the high-entropy alloys (HEAs) are investigated. The HEAs were characterized for phase content by X-ray diffractometer (XRD) and morphology by scanning electron microscope (SEM). Wear tests were performed under dry friction conditions with WC balls at a 5 N normal load and sliding speed of 5 $cm \cdot s^{-1}$ in a ball-on-disc geometry. The worn surfaces of the samples were also examined by SEM to identify the wear mechanism. The hardness starts from 328 HV, at x=0, reach to the maximum, 710 HV, at x=1.0 and then declines to 684 HV, at x=2.0. On the other hand, the wear resistance of HEAs gradually increases with the increasing aluminum content. The correlation between composition, microstructure, hardness and wear properties of these alloys is detailed discussed with in this study.

Keywords: High Entropy Alloys, Wear, Hardness

Introduction

HEAs are the new field of materials science, which are defined as more than five major elements in equi-atomic or near equi-atomic compositions with each elemental concentration between 5 at% and 35 at% (Yeh et al., 2004). In this way, these alloys are perfectly form disordered solid solutions due to the higher mixing entropy (Yeh, 2006). However, many experimental studies show that the intermetallics and ordered solid solutions besides the simple solid solutions can be found in HEAs. Although, the formation of these phases is a contrast to the origin of HEAs, controlling the formation and the amount of phases is crucially important to the design of HEAs according to the desired application. Since its discovery, HEAs have been extensively investigated for the many applications due to their exceptionally high strength and hardness, good wear and corrosion resistance and high-temperature strength properties (Wu, 2006; Mary, 2015).

The AlCoCrFeMoNi system is one of them that has potential for structural and tool industries. The effects of the elements Co, Fe, Cr, Al, Ni and Mo contents on the microstructure of the AlCoCrFeMoNi HEAs that have been widely studied by Hsu et al. (2010a, 2010b, 2011, 2013a, 2013b) and Zhu et al. (2010). The alloy system exhibits the face-centered cubic (FCC), body-centered cubic (BCC), ordered body-centered cubic (B2) and body-centered tetragonal (σ) phases for the various contents. The BCC and B2 phases are promoted by Al, where Co and Ni promoted FCC, Cr and Mo promoted σ, and Fe inhibited the σ phase in alloy system (Hsu et al., 2013c).

To investigate the mechanical properties of alloys, commonly hot-hardness measurements were performed by the same groups while wear behavior only examined for the $AlCoCrFe_xMo_{0.5}Ni$ HEAs, where x changes between the 0.6-2.0 in molar ratio. Both hardness and wear resistance declines as the Fe content increases that is related to the decreased volume fraction of the σ phase in structure. From the examination of worn surface and worn debris, they found that the wear mechanism of alloys is abrasion (Hsu et al., 2010b).

In HEAs, wear is an important phenomena and gives a good indication for the aforementioned potential applications. Thus, the purpose of this paper is to elucidate the effect of aluminium on wear behavior related with microstructural and compositional phase changes in alloys.

Materials and Methods

$Al_xCoCrFeMo_{0.5}Ni$ high-entropy alloys with different aluminium contents (x = 0-2.0 molar ratio) (these alloys are designated: Al0.0, Al0.5, Al1.0, Al1.5, Al2.0) were prepared by the vacuum arc melting and casting method in high purity argon atmosphere. The purity of each constituent elements were above 99.95%. For the chemical homogeneity of alloys, the melting procedure was repeated at least four times. As-cast microstructures and phases of the alloys were characterized with SEM (ZEISS SUPRA 50 VP) and XRD (Panalytical EMPYREAN). Microhardness measurements (Future Tech FM-700) were performed with a load of 100 g and duration time of 10 s. Sample surfaces were polished with the standard metallographic procedure. The wear behavior of the alloys under the dry sliding condition was examined using ball-on-disk testing machine (CSM Instrument) according to ASTM G99 standard. The 3mm WC ball was used as the counter body with a normal load of 5N. The rotation diameter, sliding speed and sliding distance were 5 mm, 5 $cm \cdot s^{-1}$, 100 m, respectively. After the wear tests, specific wear rates of the alloys were calculated from track profiles, which measured with a surface profilometer (Mitutoyo SJ-400) and rear tracks were also examined by SEM.

Results and Discussion

XRD patterns of the alloys are presented in Fig. 1. Alloys with different aluminum content show different phases, including FCC, BCC, B2 and σ. XRD examination of alloys indicated that Al0.0 and Al0.5 alloys consist of the FCC and σ phases. The addition of aluminium to the alloys causes formation of the B2 phase, while the FCC phase totally disappeared when aluminium content higher than x=0.5. Also, the BCC phase appeared in Al1.5 alloy. The σ phase, which exists in all alloys except the Al2.0 alloy that contains only the B2 and BCC phases. This trend can be explained by Al acts as a stabilizer of the BCC and B2 phase [Hsu et al., 2013a], and also increasing the aluminum content hinders the formation of σ phase in alloy.

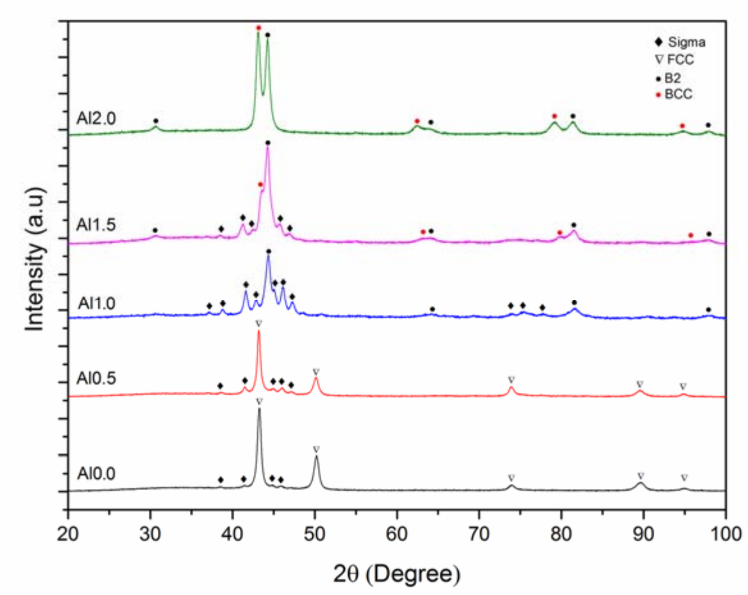

Figure 1. XRD patterns of as-cast $Al_xCoCrFeMo_{0.5}Ni$ alloys.

Fig. 2. presents the microstructures of as-cast $Al_xCoCrFeMo_{0.5}Ni$ alloys. The observed phases in microstructures are labelled on SEM images based on XRD analysis. Also, this is supported from hardness measurements. The Al0.0, Al0.5, Al1.5 and Al2.0 alloys exhibit a dendritic structure, while the Al1.0 alloy has a equiaxial grain structure with visible grain boundaries, where richer σ phase.

Fig. 3. shows the hardness and specific wear rate of alloys as a function of Al content. The hardness of alloys starts from 328 HV, at x=0, reach to the maximum, 710 HV, at x=1.0 and then declines to 684 HV, at x=2.0. Hardness value of alloys is fairly consistent with a presented phases in the structure. Although the Al0 and Al0.5 alloys, which consist of the same phase crystal structures, the hardness of Al0.5 higher than the Al0 alloy due to difference in amount and distribution of the σ phase. The hardness is the maximum in Al1.0 alloy resulting from the formation of a harder the B2 phase. In Al1.5 and Al2.0 alloys hardness slightly decrease compared to the Al1.0 alloy. This is linked with decreasing amount of the σ phase. Also, hardness of phases can be ranked as follows σ>B2>BCC>FCC in alloy system.

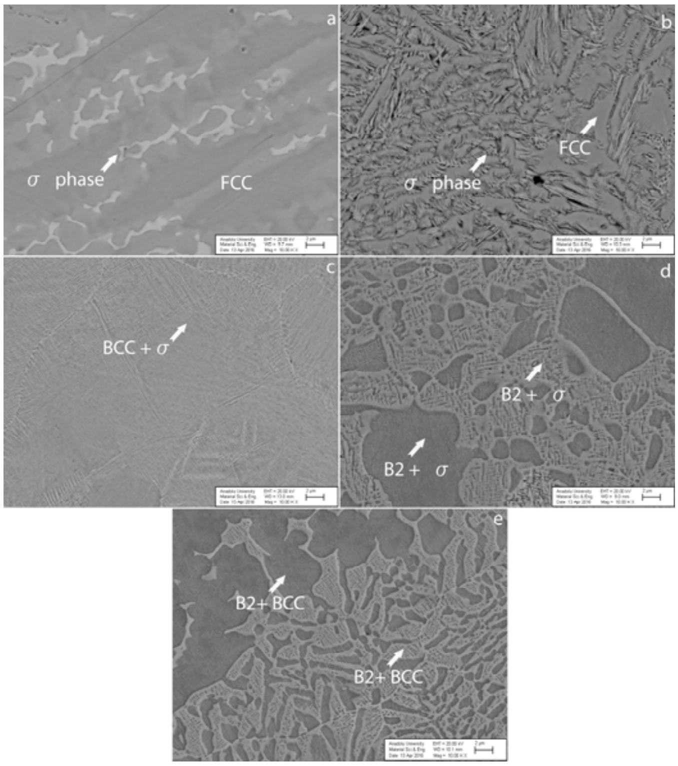

Figure 2. SEM images of as-cast $Al_xCoCrFeMo_{0.5}Ni$ alloys (a) x=0.0, (b) x=0.5, (c) x=1.0, (d) x=1.5, (e) x=2.0.

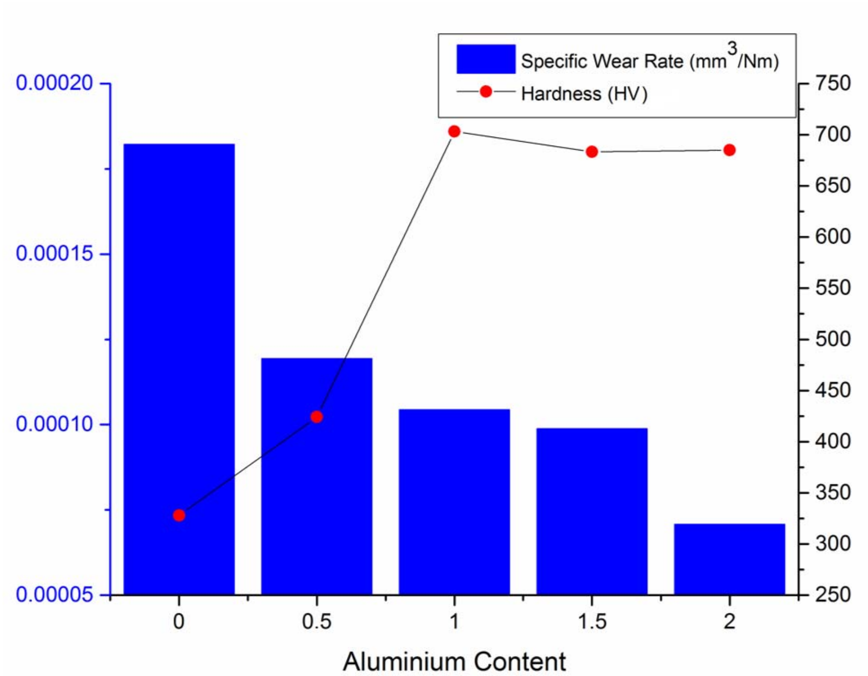

Figure 3. Hardness values of $Al_xCoCrFeMo_{0.5}Ni$ alloys plotted with obtained specific wear rate by wear track profile analysis.

To better understand the wear mechanism for the $Al_xCoCrFeMo_{0.5}Ni$ alloys in dry-sliding conditions, SEM analysis was carried out after wear tests. Fig. 4 presents the worn surfaces and debris of the alloys. Fig. 4 a and b shows the wear surface of the Al0.0 and Al0.5 alloys. The worn surface of these alloys is similar, appearing delamination without oxides. This finding is reasonable since delamination wear is a typical mechanism for ductile metals and Al0.0 and Al0.5 alloys are contained ductile FCC phase [Wu et al., 2006]. In sharp contrast to the wear surfaces of these two alloys, abrasive scratches and significant oxidation features are observed on the worn surfaces of Al1.0, Al1.5 and Al2.0 (Fig. 4 c, d and e) alloys. The dominant wear mechanism was abrasion and oxidation for these alloys.

Fig. 5 displays the wear tracks of alloys. It can be seen from Fig. 5 that the wear tracks of Al0.0 were significantly wide, showing a severe wear occurred in the sliding process. Clearly, the alloys which contain Al exhibited much lower wear rates compared to the Al0.0 alloy.

The highest wear resistance was obtained with the Al2.0 alloy, followed by the Al1.5, Al1.0 and Al0.5, respectively.

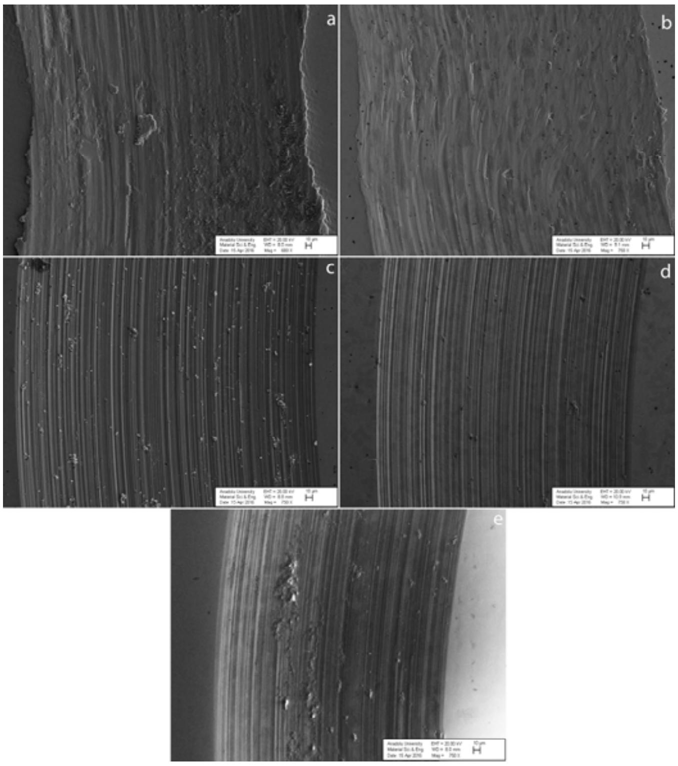

Figure 4. SEM images of worn surface of as-cast $Al_xCoCrFeMo_{0.5}Ni$ alloys (a) x=0.0, (b) x=0.5, (c) x=1.0, (d) x=1.5, (e) x=2.0.

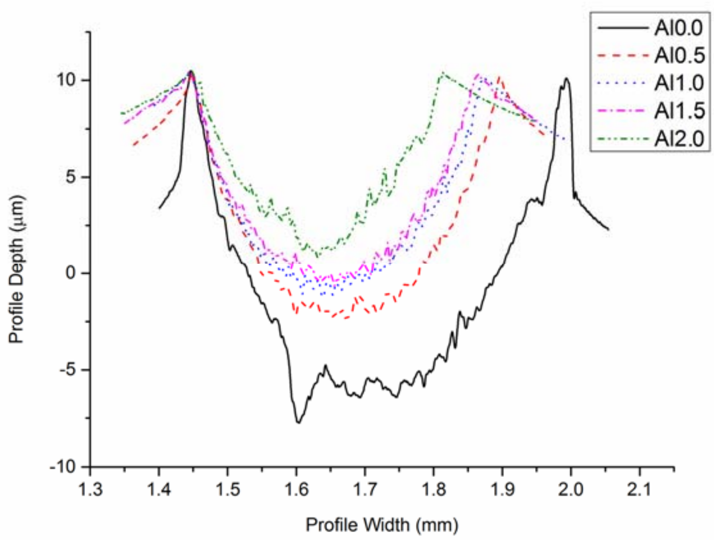

Figure 5. Cross-section profiles of the wear track.

Conclusion

High entropy $Al_xCoCrFeMo_{0.5}Ni$ alloys in different aluminum contents (x=0-2) were successfully produced by vacuum arc melting and casting method. The aluminum content greatly affected the wear performance due to bringing in microstructural and compositional phase changes in alloys. The Al1.0 alloy composed of the B2 and the σ phases has the highest hardness of 710 HV, while the lowest specific wear rate was found 0.00007 mm^3/Nm in the Al2.0 alloy composed of the BCC and B2 phases. Thus, controlling the number and amount of phases was highly important to achieve desired wear performance from HEAs.

Acknowledgements

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