

## Equiatomic NiCoAlFeMoTiCr<sub>x</sub> (x= 0,1) High Entropy Alloys Produced by Mechanical Alloying.

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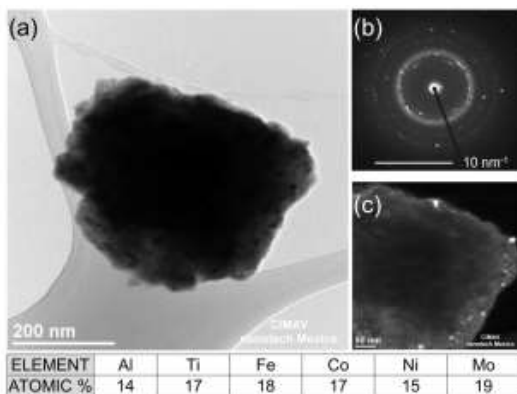
High entropy alloys (HEA) have been known as a new type of materials with unusual properties. HEAs contain at least five major elements in equiatomic or near-equiatomic proportions [1] and in general tend to form simple FCC and/or BCC microstructures in form of solid solutions (SS) [2]. Several chemical systems in HEA have been investigated, but Mo and Ti couple has been barely reported. The aim of this work was to characterize the microstructure of HEA with Mo-Ti produced by mechanical alloying (MA) and the effect of Cr addition on material hardness.

Elemental powders with purity higher than 99.5% were used as raw materials to synthesize equiatomic NiCoAlFeMoTiCr<sub>x</sub> (x = 0 and 1) HEA. The MA was performed in a high-energy ball mill (SPEX-8000M) for 10 h periods, under an argon atmosphere. Methanol was used as a process control agent to avoid metal agglomeration. The as-milled powders were compacted at 1.5 GPa and sintered at 1200°C during 3 h in sealed quartz ampoule in vacuum and cooled into the furnace until room temperature. The microstructural evolution of powder samples was investigated by transmission electron microscopy (TEM) and X-ray diffraction (XRD). The microstructural and hardness characterization of consolidated specimens were analysed by scanning electron microscopy (SEM), atomic force microscopy (AFM) and Vickers microhardness test under a load of 50 g applied during 10 s.

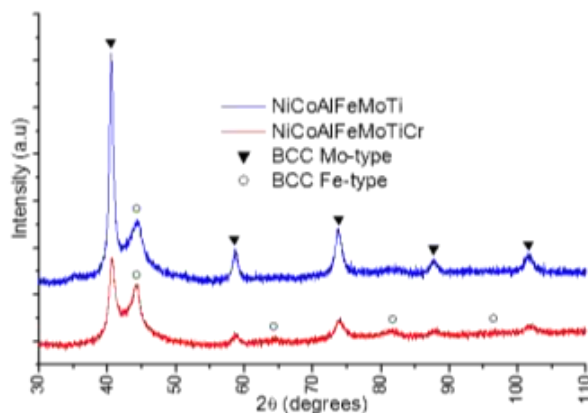
In the Fig. 1 a TEM micrograph of a single powder particle after milling is presented. EDS-TEM results show a near-equiatomic composition in powders after 10 h of milling. Diffraction rings in selected area electron diffraction pattern give evidence about the nanocrystalline condition of powders. The XRD peaks broadening supports the TEM observations and exhibit the presence of BCC SS phases (Fig. 2). In the Fig. 3 a representative microstructure of sintered alloys are shown. A dark phase with high Ni, Al and Ti content and a bright phase with high Mo and Fe concentration are observed. Meanwhile Co is homogeneously distributed in the microstructure. The effect of Cr addition is revealed by the high concentration of this element in the bright phase. After sintering, the studied alloys exhibit the formation of two major phases and rounded-like nano-precipitates (Fig. 4). In AFM images the fine precipitates can be easily distinguished. The microhardness of NiCoAlFeMoTiCr and NiCoAlFeMoTi alloys are 887 and 778 HV, respectively. The Cr addition has a slight contribution in the increase of hardness, however, the greater pores density in the NiCoAlFeMoTiCr alloy lead to a higher variation in the measurements. It is evident that Cr addition promotes the reduction of plasticity in the synthesized alloy.

### References:

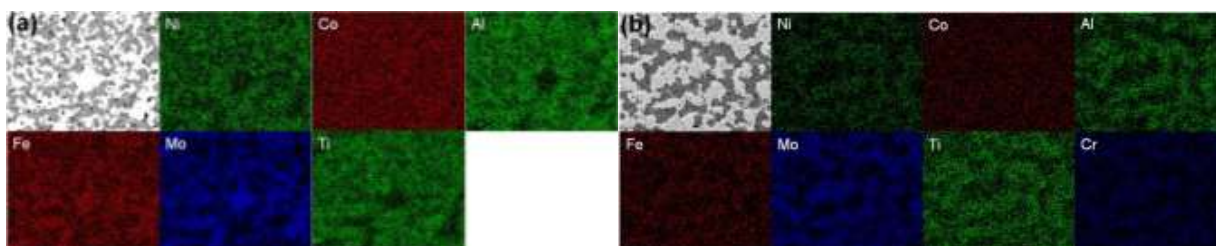
- [1] Y.L. Chen, Y.H. Hu, C.W. Tsai, C.A. Hsieh, S.W. Kao, J.W. Yeh, T.S. Chin and S.K. Chen, *J. Alloys Compd.* **477** (2008) p. 696.
- [2] T.T. Shun and Y.C. Du, *J. Alloys Compd.* **479** (2009) p. 157.



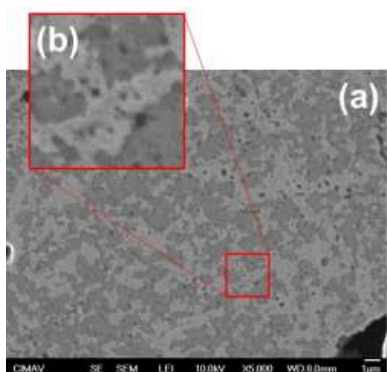
**Figure 1.** TEM micrographs of NiCoAlFeMoTi powder alloy after 10 h of milling: (a) BF-TEM image, (b) SAED pattern and (c) DF-TEM image showing the nanocrystals presence.



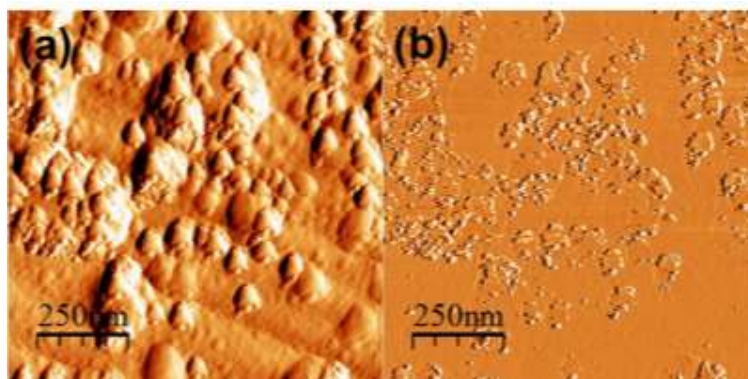
**Figure 2.** XRD patterns of powders after 10 h of milling.



**Figure 3.** SEM-EDS maps of consolidated samples: (a) NiCoAlFeMoTi and (b) NiCoAlFeMoTiCr. The spatial distribution of elements in the formed phases after sintering can be observed.



**Figure 4.** (a) SEM-SE micrographs of the sintered NiCoAlFeMoTi alloy. (b) Higher magnification square shows the distribution of rounded-like nano-precipitates.



**Figure 5.** AFM image: (a) phase-contrast and (b) topography.