Materials & Design 83 (2015) 651–660

Contents lists available at ScienceDirect

Materials & Design

journal homepage: www.elsevier.com/locate/matdes

Phase composition and solid solution strengthening effect in TiZrNbMoV high-entropy alloys

Y.D. Wu, Y.H. Cai, X.H. Chen, T. Wang, J.J. Si, L. Wang, Y.D. Wang, X.D. Hui *

State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, PR China

ARTICLE INFO

Article history:
Received 9 May 2015
Accepted 7 June 2015
Available online 19 June 2015

Keywords:
High-entropy alloys
TiZrNbMoV
Phase composition
Solid solution phase
Compressive properties

ABSTRACT

$TiZrNbMo_xV_y$ high-entropy alloys (HEAs) with $x = 0–2$, $y = 1$ and $y = 0.3$, respectively, were designed and prepared by copper mold casting technology. The phase composition and stability of these HEAs were investigated. It is shown that the HEAs with low content of V are composed of only one type of bcc solid solution phase (SSP), and demonstrate excellent phase stability at 1273 K. The high content of V and Mo results in the formation of two types of bcc SSPs and the decrease of phase stability in the HEAs. Based on the previously proposed criteria, the formation ability of solid solution phase for this kind of HEAs was comprehensively evaluated. The compressive mechanical properties of the as-cast and annealed HEAs were measured. It has been found that Mo plays a strong solid solution strengthening effect on this kind of HEAs. Especially, $TiZrNbMo_{0.3}V_{0.3}$ has the yield strength and plastic strain of 1312 MPa and >50%, respectively, and still maintains the excellent plastic deformation ability even after annealed at 1273 K for 72 h. The strengthening effect in this kind of HEAs is considered to be due to the shear modulus mismatch. The solubility limit of HEAs is correspondent to shear modulus mismatch of 29.

1. Introduction

Historically, metallic materials have being principally designed in the way that an alloy has one or two kinds of predominant elements, and all the other elements in this alloy only play an ancillary role. In recent years, this dogma in the composition design of metallic materials has been broken by a subversive concept named as "high-entropy". The high-entropy alloys (HEAs) were designed according to the principle of equal-molar or near-equalmolar fraction for all the components, which then results in a high configurational entropy in the alloy [1,2]. The high-entropy is beneficial to the stabilization of disordered solid solution phases such as a body- or face-centered cubic (fcc), and disadvantageous to the formation of ordered intermetallic crystalline phases. Nevertheless, it is noticed that the configurational entropy only takes into account of a part of the entire entropy for a certain alloy. This means that only a few of, but not all the alloy system can form single solid solution phase such as face-centered cubic (fcc) [3–5], body-centered cubic (bcc) [6–9], and orthorhombic [10] phase.

HEAs have attracted great attraction due to their high strength and ductility, excellent oxidation resistance and thermal stability, etc. [2,11,12,37–40]. Of the HEAs discovered to date, bcc type of HEAs exhibit enhanced strength and excellent phase stability at high temperature. For instance, the tensile strengths of FeCoCrNiMn HEAs are under 600 MPa [13,14] when they have fcc type of structure. As Al element is added into FeCoCrNiMn HEAs, the tensile strength can be increased up to 1150 MPa [14] due to the formation of bcc type of crystalline structure. For high temperature applications, Senkov et al. developed refractory NbMoTaWV and TaNbHfZrTi HEAs [6,7], which have bcc type of structure and demonstrate high temperature strength and excellent phase stability at 1473 K. However, it is seen that these HEAs still have the deficiencies of high cost and density due to the existence of Hf and Ta elements. In order to decrease the density and further improve the oxidation resistance of refractory HEA, Senkov et al. investigated the CrNbTiVZr HEAs [36]. They found that the Cr bearing HEAs contain a lot of Laves phases and exhibit great brittleness at room temperature. Therefore, it is significant to explore new refractory HEAs with low cost, low density and high ductility. Alternatively, TiZrNbMoV HEAs are promising for high temperature engineering and manufacture industries considering that they are cheaper and lighter than NbMoTaW HEAs. As for TiZrNbMoV HEAs, Tian et al. studied the equilibrium bulk properties of TiZrNbMoV HEAs by using *ab initio* method [15]. Zhang et al. investigated the effect of V on the phase formation and mechanical properties [16]. It has been shown that the alloying effect of V element in this kind of HEAs can be negligible.

* Corresponding author.
E-mail address: xdhui@ustb.edu.cn (X.D. Hui).

http://dx.doi.org/10.1016/j.matdes.2015.06.072
0264-1275/

Mo is one of the most important alloying elements in high temperature Ti-based alloys [17,18]. It is reasonable to deduce that Mo may also play a critical role in this kind of Ti bearing HEAs because Mo has highest melting point among all the components of TiZrNbMoV alloy. However, Laves phases may be also formed in this kind of HEAs if excessive Mo is added. Therefore, it is necessary to investigate the effects of Mo on the phase evolution and mechanical properties of this kind of HEAs. It is also noticed that most bcc HEAs discovered to date usually exhibit insufficient plasticity, which may be unfavorable to the practical engineering application. The shortage of poor plastic deformation for bcc HEAs is not only due to the crystalline structure but also affected by the properties of the components. Therefore, it is highly needed to optimize the compositions of this kind of HEAs so as to achieve high comprehensive properties.

In this work, the microstructural evolution and phase composition of TiZrNbMo$_x$V$_y$ HEAs with $x = 0$–2, while $y = 1$ and $y = 0.3$, respectively are investigated. The phase stability of these HEAs is also explored at 1273 K to provide a reference for the high temperature application. The room temperature compressive properties are studied, and the optimal compositions which have fine comprehensive mechanical properties are hopefully to be pin-pointed out. Finally, the strengthening mechanism for this kind of HEAs is discussed in detail.

2. Experimental details

Two groups of TiZrNbMo$_x$V$_y$ HEAs were designed and investigated in this work. One group of HEAs is TiZrNbMo$_x$V (denoted

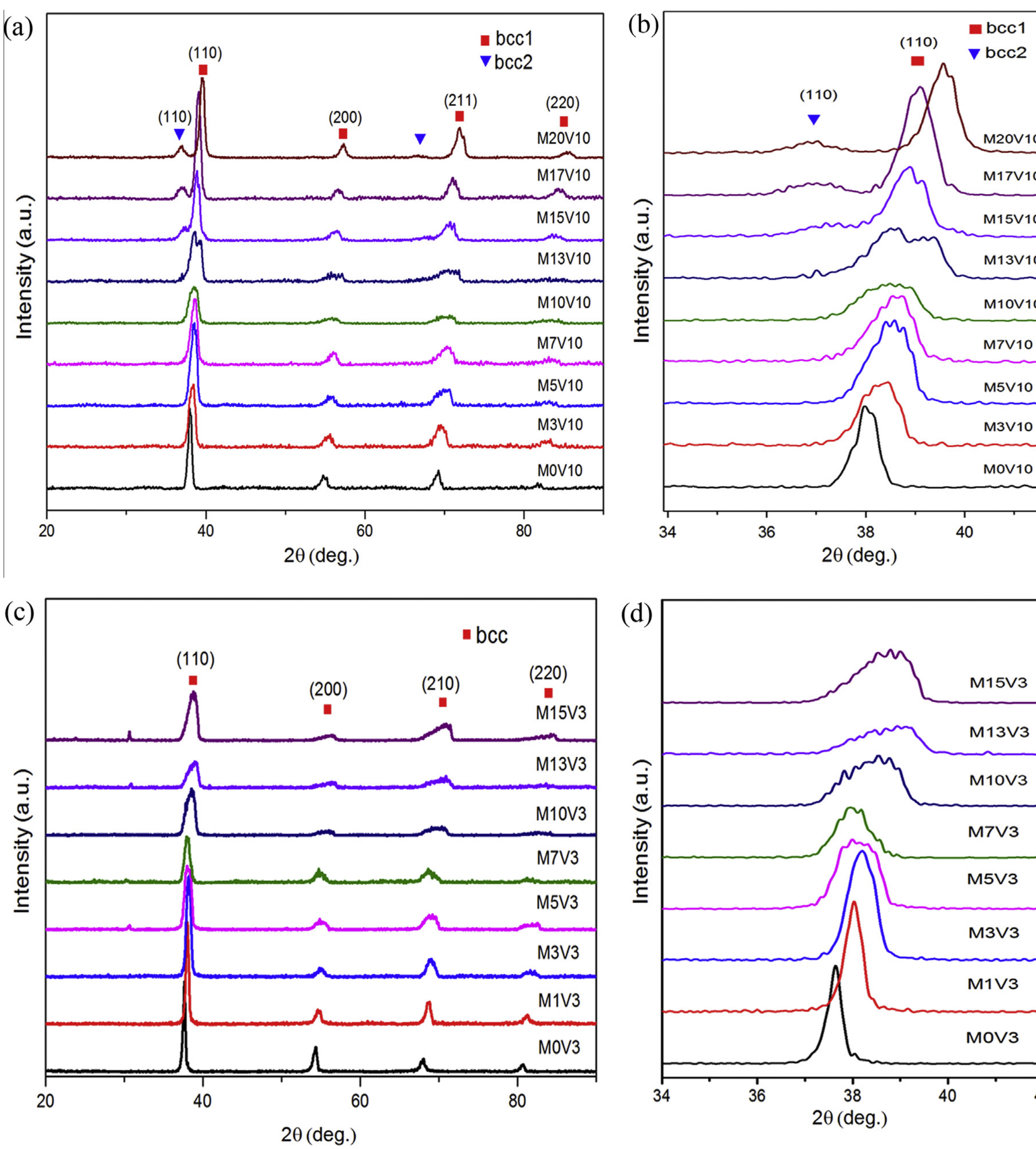

Fig. 1. (a) and (c) The XRD patterns of G-MV10 and G-MV3 HEAs, (b) and (d) the magnified (110) peaks as shown in (a) and (c), respectively.