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The microstructure and phase equilibrium of new high performance high-entropy alloys

Ker-Chang Hsieh[a,*], Cheng-Fu Yu[a], Wen-Tai Hsieh[a], Wei-Ren Chiang[a], Jin Son Ku[a], Jiun-Hui Lai[b], Chin-Pan Tu[b], Chih Chao Yang[b]

[a] *Department of Materials and Optoelectronic Science, Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University, Kaohsiung 804, Taiwan*
[b] *Materials Research Laboratory, Industrial Technology Research Institute, Chutung 310, Taiwan*

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ABSTRACT

In recent years, series of high-entropy alloy have been well developed with high hardness and high temperature stability. These properties could apply in hard surface welding technology. Several AlCrFeMnNi high-entropy alloys have been developed and made as welding rods to apply in the hardface welding on carbon steel using nickel-based alloy as bond coating layer. The hardness of hardface can reach Hv 900 after aging at 700 °C for 4 h. One of alloys performed resistant with the thermal effect during hardfacing operation and maintain better hardness in the multiple overlays.

An electron probe microanalyzer (EPMA) was used to verify the phase compositions of hardfacing microstructure. There is nanoprecipitate phase formed within the matrix grain and might contribute the high hardness. A primitive phase diagram calculation was done by using the Calphad method. The calculated results show that the hardening mechanism is due to bcc order/disorder coherent strengthening within the matrix grain. Two high-entropy alloys were equilibrated at 700 °C for 10 days. The equilibrium phases are consistent with the calculated isopleth. The new phase may relate with FCC phase structure and still under investigation.

1. Introduction

The practical alloy system has been developed for centuries and is mainly based on one principle element such as ferrous alloys, nickel-based alloys, etc. Recently, Yeh's research group of Tsing-Hua University followed a completely different route to produce high-entropy alloys consisting of several metals in equal proportions so that it can no longer be classified as particular metal alloy [1,2]. Yeh reported [3–6] several alloys with more than five components such as AlCoCrCuFeNi, AlCoCrCuFeNiTiV, etc. new alloys. They are forming solid solutions with simple bcc and fcc structures. The alloys exhibit very high hardness that varies widely depending on the contents of the component elements. Some of the alloys could retain their high hardness levels after annealing at 800 °C for 12 h [7]. Among those previous studies, AlCrFeMnNi type high-entropy alloys with bcc structure is work hardenable and strong at high temperature up to 800 °C, indicating that this alloy has potential application in the wear resistance and high-temperature strength [8]. Therefore, two selected alloy compositions (type A: $Al_{0.3}CrFe_{1.5}MnNi_{0.5}$ and type B: $Al_{0.5}CrFe_{1.5}MnNi_{0.5}$) of this alloy system, were prepared as welding electrode in order to evaluate their welding capability in the hardfacing application. The contents of this report are (I) the hardfacing samples preparation with optimal welding conditions, (II) the Vickers hardness measurement, (III) microstructure analysis, and (IV) the hardening mechanism.

2. Experimental procedure

The high-entropy alloys were applied as hardfacing material to overlay structural steel by tungsten inert gas (TIG) welding process. The structural steel was preheated with gas torch around 150–180 °C and maintained around 250–300 °C during the hardfacing TIG process. There was a nickel-based bond coat before applying the high-entropy alloys overlays. The layer thickness of bond coat and each overlay high-entropy alloys was around 2 mm each. The samples were prepared with four overlays for each type of high-entropy alloys and the area of overlay was 45 mm^2. Post-weld heat treatment of overlays was done at a constant temperature of 700 °C from 1 h to 10 days in a tube furnace under air to evaluate the variation of hardness with time at high temperature. The alloy samples are also treated at 900 °C for 10 days in order to determine the equilibrium phase compositions. A transverse section of the hardfaced steel was metallographically polished using conventional metallographic polishing techniques and etched in nital solution. An optical microscope was used to examine the microstructure of as welded and heat-treated samples. An electron probe microanalyzer (EPMA) was used to verify the phase compositions. A Shimadzu HMV-2000 micro-hardness tester was used to measure the micro-hardness of each overlays coating and interface.

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* Corresponding author.
E-mail address: khsieh@mail.nsysu.edu.tw (K.-C. Hsieh).

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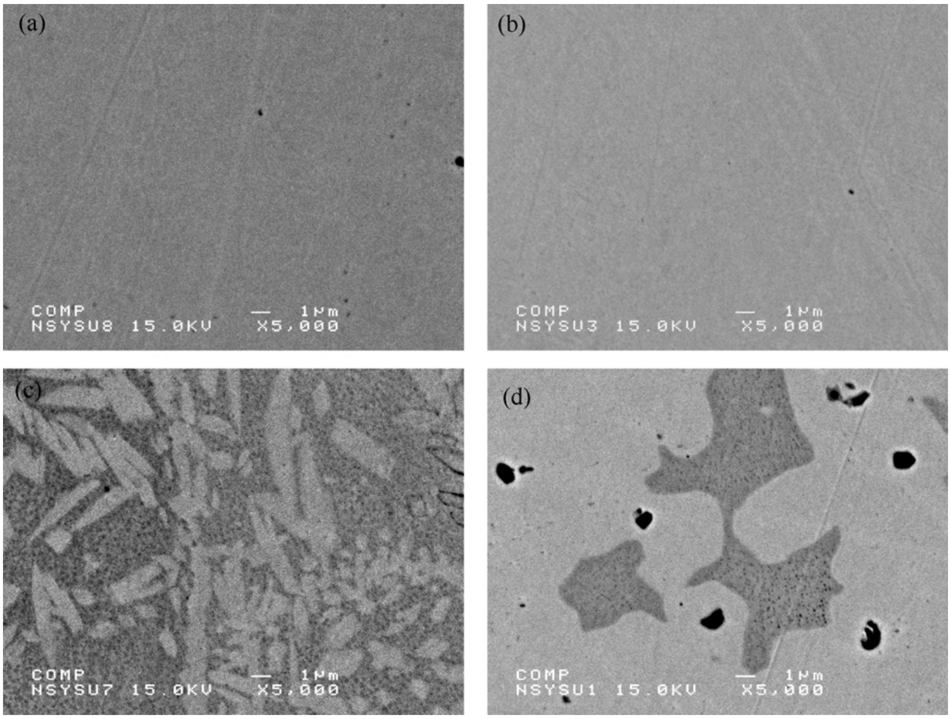

Fig. 1. The as welded microstructure of type A high-entropy alloy for (a) the 4th overlay, (b) the 3rd overlay, (c) the 2nd overlay and (d) the 1st overlay.

3. Results and discussion

3.1. Hardness test results

The Vickers hardness of overlay coatings was tested as welded and after aging treatment. For type A high-entropy alloy, it was observed that the Vickers hardness range of the overlays between 200 Hv and 400 Hv in the as welded condition and heat treatment enhanced the hardness became 700–930 Hv. For type B high-entropy alloy, the Vickers hardness was around 400 Hv in the as welded condition and reached 900 Hv after heat treatment. The Vickers hardness of the first overlay was always lower. This is primarily attributed to alloy dilution with the bond-coat alloy. Dilution results in an overlay having a composition different from that of the

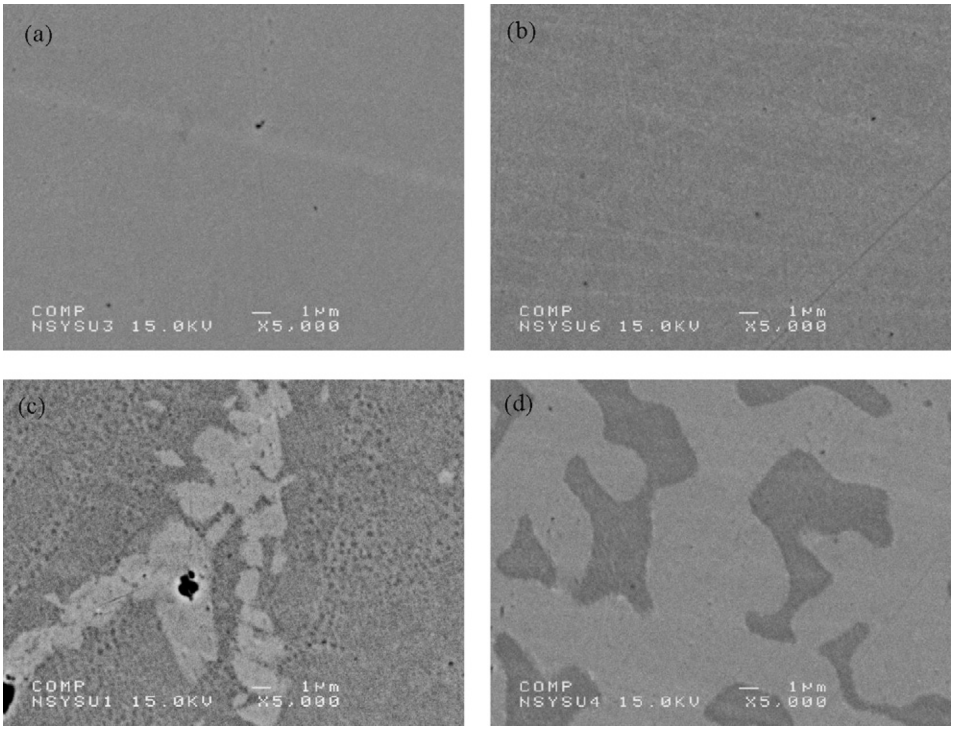

Fig. 2. The as welded microstructure of type B high-entropy alloy for (a) the 4th overlay, (b) the 3rd overlay, (c) the 2nd overlay and (d) the 1st overlay.