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(54) HIGH-ENTROPY MULTIELEMENT ALLOYS

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(57) **ABSTRACT**

The present invention is related to high-entropy multielement alloys. The features of the alloys are that there are five to eleven major metallic elements and with or without minor elements, the minor elements are selected from the element group other than the major metallic elements, the mole fraction of each major metallic element in the alloy is between 5% and 30%, and the mole fraction of each minor element in the alloy is less than 3.5%. The high-entropy multielement alloys in the present invention are high in hardness, heat resistance, and corrosion resistance.

HIGH-ENTROPY MULTIELEMENT ALLOYS

BACKGROUND OF THE INVENTION

[0001] The present invention relates to high-entropy multielement alloys and, in particular, to those which are composed of five to eleven major metal elements.

[0002] Traditionally, the alloy systems can be divided by the major element, i.e., the host element, such as iron, copper, aluminum, magnesium, titanium, zirconium, lead, chromium, zinc, gold, and sliver. In well-known alloys, one element is the major element, and the others are minor elements. For example, steel is mainly made of iron, and aluminum alloy is mainly made of aluminum. Recently, some new alloys were developed, such as rapidly-solidified alloys, mechanical-alloying alloys, and metal-matrix composite materials. However, the concept of the alloy design and selection are still based on the "one major element" principle.

[0003] Because the traditional concept of alloy design, which was mentioned above, obviously limits the degree of freedom in the alloy compositions, the development of new crystal structure, microstructure, and new performance of materials may be restricted. To break through this traditional limitation, the present invention provides new alloy design concept for high-entropy multielement alloys.

SUMMARY OF THE INVENTION

[0004] The alloys of the present invention are made of multiple metallic elements by melting and casting processes or other synthesis methods. Basically, the alloys of the present invention are not made of one major element, two major elements, three major elements or four major elements, but each of the invented alloys consists essentially of five to eleven major metallic elements. The mole fraction of each major metallic element in the alloy is between 5% and 30%.

[0005] The major metallic elements in an alloy of the present invention can be selected from the metallic group: beryllium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, palladium, silver, hafnium, tantalum, tungsten, platinum, gold, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, and so on. It is preferred that the major metallic elements in an alloy of the present invention is selected from the metallic group consisting of aluminum, titanium, vanadium, chromium, iron, cobalt, nickel, copper, zirconium, molybdenum, palladium, silver and gold.

[0006] Besides the major metallic elements mentioned above, some other minor elements could be added into the high-entropy multielement alloys of the present invention. The reason why they are named "minor elements" is that their individual mole fractions in the alloy are less than 3.5%. In an alloy of the present invention, the minor elements can be metallic elements or nonmetallic elements. The minor metallic elements can be selected from the metallic element group consisting of lithium, beryllium, sodium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, gallium, germanium, strontium, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, palladium, silver, cadmium, indium, tin, antimony, hafnium, tantalum, tungsten, platinum, gold, lead, bismuth, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium and terbium. The nonmetallic elements can be, for example, carbon, boron, silicon, phosphorus, sulfur, hydrogen, oxygen and nitrogen and so on.

[0007] None elements have the mole fractions higher than 30% in the high-entropy multielement alloys of the present invention. Thus there will be no matrix built by a single element in an alloy. The microstructure and properties of the invented alloy are obviously different from those of conventional alloys. Due to the high entropy phenomenon in the atomic configuration as compared with the conventional alloys, the invented alloys are named "high-entropy multielement alloys". This could be explained from the comparison of the mixing entropy between the invented alloys and conventional alloys based on statistical thermodynamics.

[0008] In forming a liquid or solid solution from pure elements, the free energy of mixing could be expressed as $\Delta G_{mix}=\Delta H_{mix}-T\Delta S_{mix}$ where ΔH_{mix} is the enthalpy of mixing, T the temperature and ΔS_{mix} the entropy of mixing. For a liquid or solid solution system containing 8 elements in equal mole, as an example, the configurational entropy change per mole, ΔS_{Conf}, upon mixing can be calculated as follows since entropy of a system is quantitatively related to the randomness by the Boltzmann equation, S=−k ln w in which k is Boltzmann's constant and w the number of possible ways of a state,

$$\Delta S_{conf}=-k\ ln\ w=-R(\tfrac{1}{8}ln\ \tfrac{1}{8}+\tfrac{1}{8}ln\ \tfrac{1}{8}+\ldots+\tfrac{1}{8}ln\ \tfrac{1}{8})=-R\ ln\ \tfrac{1}{8}=3R\ ln2\approx 2.08R$$

[0009] where R is the universal gas constant and equal to 8.314 jouls/mole K.

[0010] This entropy change is quite large. According to the well-known Richards' rule, the molar entropy change of fusion for most metals is $\Delta S_f=\Delta H_f/T_m=R$ where T_m is the melting temperature. Thus the configurational entropy change of mixing is almost double that of the metal fusion in which the atoms get a much higher degree of randomness in the liquid state than solid state. If T_m is 1400° C. for example, then $T_m\Delta S_{conf}$=14.56 kJ/mole. This value indicates that the configurational entropy change is quite large in lowering the Gibbs free energy of liquid or solid solution. From the point of view of thermodynamic equilibrium, the state of a system with lower free energy is more stable than that with higher free energy. That means the liquid or solid solution of such alloy system tends to become chaotic rather than segregated or ordered in atomic configuration as found in the conventional alloys based on the "one major element" principle.

[0011] Similarly, for a liquid or solid solution system containing 1 (i.e. pure element), 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, or 13 elements in equal mole, ΔS_{conf} is around OR, 0.69R, 1.1R, 1.39R, 1.61R, 1.95R, 2.2R, 2.3R, 2.4R, 2.49R, or 2.57R, respectively. This demonstrates that the configurational entropy of mixing increases as the number of elements increases. It should be emphasized that the entropy of mixing in equal-mole alloys with three elements has already exceeded the large entropy increase, R, in fusion of most metals. Based on this comparison, it can be realized that the invented alloys with at least five major elements have high mixing entropy. This is the reason why the invented alloys are called "high-entropy multielement alloys".

[0012] The basic characteristics of high-entropy multielement alloys of the present invention are as follows:

[0013] 1. Very high in hardness: their hardnesses in the as-cast state are very high, essentially varying from Hv450 to Hv900, depending on the chemical composition. The hardness level is similar to or higher than that of a fully quenching-hardened carbon steel or alloy steel.

[0014] 2. Very high in heat resistance: after a thermal treatment at 1,000° C. for 12 hours and subsequent cooling in a furnace, the alloy could remain their high hardness level and do not show the effect of temper softening.

[0015] 3. Very high in corrosion resistance: when soaked in high-concentration solution of sulfuric acid, hydrochloric acid, or nitric acid, the alloy could exhibit an excellent corrosive resistance.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0016] The high-entropy multielement alloys of the present invention can be manufactured by using the following synthesis methods: resistance melting, induction melting, electric arc melting, rapid solidification, mechanical alloying, and powder metallurgy, etc.. The technologies involved in these methods are not mentioned here since they are well known. Here only electric arc melting and casting is illustrated for an example. In arc melting, raw materials of various elements are first stacked up in a water-cooled copper mold inside a melting furnace with increasing melting point. Then, after putting on the top cover of the furnace for air sealing, the chamber is vacuumed and filled with pure argon. This process is repeated for several times before arc-melting starts. After the melt solidifies in the copper mold, it is reversed and arc-melted again. In order to assure that all metallic elements melt and are uniformly mixed such melting operations are repeated for several times. Finally, after the mold is cooled, the alloy ingot is taken out.

[0017] The high-entropy multielement alloys of the present invention are made of multiple major metallic elements by various synthesis methods. Their chemical compositions contain essentially five to eleven major metallic elements, and the mole fraction of each major metallic element in the alloys is between 5% and 30%. The major metallic elements in the alloy can be beryllium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, palladium, silver, hafnium, tantalum, tungsten, platinum, gold, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, and so on.

[0018] Beside the major metallic element mentioned above, some other minor elements, each is less than 3.5 mole %, could be added into the high-entropy multielement alloys of the present invention. The minor elements can be metallic or nonmetallic. The minor metallic elements can be selected from the metallic group of lithium, beryllium, sodium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, gallium, germanium, strontium, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, palladium, silver, cadmium, indium, tin, antimony, hafnium, tantalum, tungsten, platinum, gold, lead, bismuth, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium and terbium. The minor nonmetallic elements can be selected from the nonmetallic group of carbon, boron, silicon, phosphorus, sulfur, hydrogen, oxygen and nitrogen.

EXAMPLES 1

[0019] Raw materials of copper, titanium, vanadium, iron, nickel, and zirconium were weighed at the same mole number, to be 17.3 g, 13.0 g, 13.9 g, 15.2 g, 16.0 g, and 24.8 g, respectively, so that a total weight about 100 g was obtained. The metallic elements were stacked up in a water-cooled copper mold inside an arc-melting furnace with increasing melting point. Then the top lid of the furnace was put on, and vacuum was created for about 5 min. When the chamber pressure decreased to 0.01 atm, pure argon was introduced to raise the pressure up to about 0.2 atm. After another repetition of the above operation, the melting was started. The melting current was 500 Amps. After each time the materials melted and then solidified, the alloy was reversed and the electric arc was turned on again. Such operations were repeated several times to assure that all metallic elements are uniformly mixed. Finally, the solidified round tablet with a diameter of 5 cm was taken out for analysis. Its composition is the alloy No. 1 as shown in Table 1. Furthermore, a portion of the alloy tablet was cut off for heat treatment. It was put in an air furnace of 1,000° C. for 12 hours, and then cooled in the furnace to obtain a heat-treated state. The properties for both the as-cast and heat-treated states were measured.

EXAMPLES 2 TO 20

[0020] Manufacturing operations in example 1 were repeated, but the compositional elements were changed. The compositions of alloy tablets in examples 2 to 20 are alloy No.2 to No.20 in Table 1, respectively.

TABLE 1

Compositional elements and Hv hardnesses of the high-entropy multielement alloys

Alloy Number	Compositional elements (all elements are in the same mole fraction except boron, which is 3%)	Hardness (Hv) (as-cast state)	Hardness (Hv) (1000° C. heat treatment for 12 hr and cooling in the furnace)
1	Copper, titanium,vanadium,	590	600
2	Aluminum, titanium, vanadium, iron, nickel, zirconium	800	790
3	Molybdenum, titanium, vanadium, iron, nickel, zirconium	740	760
4	Copper, titanium, vanadium, iron, nickel, zirconium, 3% boron	620	620
5	Aluminum, titanium, vanadium, iron, nickel, zirconium, 3% boron	780	790
6	Copper, titanium, vanadium, iron, nickel, zirconium, cobalt	630	620
7	Aluminum, titanium, vanadium, iron, nickel, zirconium, cobalt	790	800
8	Molybdenum, titanium, vanadium, iron, nickel, zirconium, cobalt	790	790
9	Copper, titanium, vanadium, iron, nickel, zirconium, cobalt, 3% boron	670	690
10	Aluminum, titanium, vanadium, iron, nickel, zirconium, cobalt, 3% boron	780	790
11	Copper, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium	680	680
12	Aluminum, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium	780	890

TABLE 1-continued

Compositional elements and Hv hardnesses of the high-entropy multielement alloys

Alloy Number	Compositional elements (all elements are in the same mole fraction except boron, which is 3%)	Hardness (Hv) (as-cast state)	Hardness (Hv) (1000° C. heat treatment for 12 hr and cooling in the furnace)
13	Molybdenum, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium	850	850
14	Copper, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, 3% boron	720	720
15	Aluminum, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, 3% boron	840	870
16	Copper, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, palladium	670	630
17	Aluminum, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, palladium	780	800
18	Molybdenum, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, palladium	830	820
19	Copper, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, palladium, 3% boron	700	630
20	Aluminum, titanium, vanadium, iron, nickel, zirconium, cobalt, chromium, palladium, 3% boron	840	840

[0021] Vickers Hardness Test

[0022] The hardness of alloy tablets No. 1 to No. 20 was measured by using the Vickers hardness tester. Before testing by the tester, the surface of each tablet was ground by # 120, # 240, # 400, and # 600 carborundum sandpaper in series. The applied load during testing was 5 kgf, and the loading time was 10 sec. The hardness of each tablet was measured at seven different locations, and the average value of the medium five data points was used to determine the hardness. The results were shown in Table 1.

[0023] Table 1 shows the hardness of alloys No. 1 to No. 20, in either as-cast state or heat-treated state. It can be seen that the alloy hardness changes with element number and composition. Generally speaking, more major elements may yield higher hardness, and adding minor element boron may further increase the hardness. The hardnesses of the alloys No. 2, 6, 16, 18 and 19 show a small decrease by heat treatment. However, those of others may be unchanged or increased. In Table 1, the hardness ranges from Hv590 to Hv890. Fully quenching-hardened carbon steels and alloy steels, with 0.35% to 1.0% carbon, provide a similar hardness range. On the other hand, the hardness of quartz is about Hv700, which falls in the above hardness range. Therefore, this demonstrates that the multielement alloys in the present invention are very high in hardness. Furthermore, carbon steels or alloy steels will show temper softening at the temperature higher than 550° C. If the temperature exceeds 550° C., they will soften and decrease in room-temperature strength. However, the high-entropy alloys in the present invention almost show no temper softening at 1000° C., and possess a much better heat resistance than carbon steels and alloy steels.

[0024] Acid Resistance Test

[0025] The multielement alloys of the present invention were cut and weighed to obtain 2 g of granules, and the granules were soaked in hydrochloric acid, sulfuric acid, or nitric acid at concentrations of 1M or 0.01M for 24 hours. The reactions between alloy tablets and various acid solutions and the tablet weight loss were observed to determine the acid resistance. The results are shown in Table 2.

TABLE 2

Acid resistance of the high-entropy multielement alloys to common acid solutions

	HCl solution		H_2SO_4 solution		HNO_3 solution	
Alloy No.	1M	0.01M	1M	0.01M	1M	0.01M
1	x	x	x	x	Δ	x
2	x	x	x	x	Δ	x
3	x	x	x	x	Δ	x
4	x	x	x	x	Δ	x
5	x	x	x	x	x	x
6	x	x	x	x	x	x
7	x	x	x	x	x	x
8	x	x	x	x	x	x
9	x	x	x	x	x	x
10	x	x	x	x	x	x
11	x	x	x	x	x	x
12	x	x	x	x	x	x
13	x	x	x	x	x	x
14	x	x	x	x	x	x
15	x	x	x	x	x	x
16	x	x	x	x	x	x
17	x	x	x	x	x	x
18	x	x	x	x	x	x
19	x	x	x	x	x	x
20	x	x	x	x	x	x

x: no reaction, no color change, and no weight loss
Δ: small reaction, slight color change, and almost no weight loss

[0026] Table 2 shows that without any surface treatments, the high-entropy multielement alloys of the present invention provide very high acid resistance. On the contrary, carbon steels or alloy steels do not provide such high acid resistance.

EXAMPLES 21 TO 24

[0027] Manufacturing procedure in example 1 was repeated, but the components and their mole fractions were shown in Table 3. About 2.5 g of granules were cut from the obtained alloy tablets, and the granules were placed in the arc-melting furnace for another melting. A graphite hammer was used to hit the melting liquid to obtain thin pieces in thickness of about 200 μm (the cooling rate was as fast as 10^3 to 10^4 K/sec). Then the properties were measured. The hardness values are shown in Table 4. The data show that even when the mole fraction of each element was away from the average mole fraction, alloys with very high hardness can still be obtained by using the rapid solidifying method. In the example 22, the hardness of the alloy is as high as Hv1049.

TABLE 3

Compositions and mole fractions of the high-entropy multielement alloys								
Alloy	Mole Fraction of Major Element (%)							
No.	Iron	Cobalt	Nickel	Chromium	Vanadium	Titanium	Alumium	copper
21	16.6	18.4	22.9	22.8	19.3	—	—	—
22	21.9	14.1	17.3	16.1	14.7	15.9	—	—
23	15.0	14.4	14.5	14.9	13.8	13.7	13.7	—
24	14.4	10.8	13.5	12.6	12.6	12.2	12.9	11.0

[0028]

TABLE 4

The hardness values of the high-entropy multielement alloys			
Alloy No. 21	Alloy No. 22	Alloy No. 23	Alloy No. 24
Hv571	Hv1,049	Hv760	Hv666

EXAMPLES 25 TO 29

[0029] Manufacturing operations in example 1 were repeated, but the compositional elements were changed. The compositions of alloy tablets in examples 25 to 29 are alloy No.25 to No.29 in Table 5, respectively.

TABLE 5

Compositions and hardness values of high-entropy multielement alloys								
Alloy	Major Elements (mole %)						Minor Element (mole %)	Hardness
No.	Iron	Cobalt	Nickel	Chromium	Vanadium	Titanium	Boron	(Hv)
25	All major elements are in the same mole fraction.						0	760
26	All major elements are in the same mole fraction.						0.4	880
27	All major elements are in the same mole fraction.						0.8	980
28	All major elements are in the same mole fraction.						1.7	1030
29	All major elements are in the same mole fraction.						3.3	1067

[0030] Table 5 shows the effect of minor element, boron, on the hardness value of a high-entropy alloy having iron, cobalt, nickel, chromium, vanadium, and titanium in the same mole fraction. It indicates that minor addition of boron has a remarkable improvement on hardness. The hardening effect becomes diminishing when the amount approaching 3.3%. This means a suitable amount of boron could be effective and important if a higher hardness is desired.

EXAMPLES 30 TO 34

[0031] Manufacturing operations in example 1 were repeated, but the compositional elements were changed. The compositions of alloy tablets in examples 30 to 34 are alloy No.30 to No.34 in Table 6, respectively.

TABLE 6

Compositions and hardness values of high-entropy multielement alloys							
Alloy	Major Elements (mole %)					Minor Element (mole %)	Hardness
No.	Iron	Cobalt	Nickel	Chromium	Aluminum	Silicon	(Hv)
30	All major elements are in the same mole fraction.					0	480
31	All major elements are in the same mole fraction.					0.3	500
32	All major elements are in the same mole fraction.					0.8	520

TABLE 6-continued

Compositions and hardness values of high-entropy multielement alloys

Alloy No.	Major Elements (mole %) Iron	Cobalt	Nickel	Chromium	Aluminum	Minor Element (mole %) Silicon	Hardness (Hv)
33	All major elements are in the same mole fraction.					1.8	540
34	All major elements are in the same mole fraction.					3.5	570

[0032] Table 6 shows the effect of minor element, silicon, on the hardness value of a high-entropy alloy having iron, cobalt, nickel, chromium, and aluminum in the same mole fraction. It indicates that minor addition of silicon has a moderate improvement on hardness. Since silicon might also improve the fluidity and corrosion resistance, a suitable amount of silicon could be beneficial in several respects.

EXAMPLES 35 TO 39

[0033] Manufacturing operations in example 1 were repeated, but the compositional elements were changed. The compositions of alloy tablets in examples 35 to 39 are alloy No.35 to No.39 in Table 7, respectively.

TABLE 7

Compositions and hardness values of high-entropy multielement alloys

Alloy No.	Major Elements (mole %) Iron	Cobalt	Nickel	Chromium	Aluminum	Titanium	Minor Element (mole %) Copper	Hardness (Hv)
30	All major elements are in the same mole fraction.						0	760
31	All major elements are in the same mole fraction.						0.4	750
32	All major elements are in the same mole fraction.						0.8	730
33	All major elements are in the same mole fraction.						1.6	690
34	All major elements are in the same mole fraction.						3.2	630

[0034] Table 7 shows the effect of minor element, copper, on the hardness value of a high-entropy alloy having iron, cobalt, nickel, chromium, aluminum, and titanium in the same mole fraction. It indicates that minor addition of copper can cause a moderate decrease in hardness. But since copper has an improvement on toughness and thermal conductivity, a suitable amount of copper could be beneficial when toughness and thermal conductivity are important.

[0035] Consequently, though in the as-cast state process, the "high-entropy multielement alloys" of the present invention can obtain a hardness level as high as or higher than fully quenching-hardened carbon steels or alloy steels. Furthermore, in the heat-treated state, i.e., annealed at 1,000° C. for 12 hours, the alloys do not soften, but might be hardened in most cases. This demonstrates that they show better resistance to temper softening than carbon steels and alloy steels. Besides, the alloys are much better in acid resistance than carbon steels and alloy steels. In summary, there are no conventional alloys that can possess all these excellent properties after casting. The alloys in the present invention can be applied to special purposes. For example, they might be fabricated into tools, molds, and structural components for low and high temperature applications by the precision casting method. Both machining and heat-treatment cost could be saved and no worry about temper softening even at 1,000° C. are needed. They can also be fabricated as a coating layer on the surface of structural components by electric plasma or flame spraying for the purposes of friction, heat, and corrosion resistances.

[0036] From the foregoing description, one skilled in the art can easily ascertain the essential characteristics of this invention, and without departing from the scope thereof, can make various changes and modifications of the invention to adapt it to various usages and conditions. Thus, other embodiments are also within the claims.

What is claimed is:

1. A high-entropy multielement alloy consisting essentially of: five to eleven major metallic elements, the mole fraction of each major metallic element in the alloy is between 5% and 30%.

2. The high-entropy multielement alloy of claim 1, wherein said major metallic elements are selected from the metallic element group consisting of beryllium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, palladium, silver, hafnium, tantalum, tungsten, platinum, gold, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium and terbium.

3. The high-entropy multielement alloy of claim 1, wherein said major metallic elements are selected from the metallic element group consisting of aluminum, titanium, vanadium, chromium, iron, cobalt, nickel, copper, zirconium, molybdenum, palladium, silver and gold.

4. The high-entropy multielement alloy of claim 1, wherein said alloy is produced by an electric arc melting method.

5. The high-entropy multielement alloy of claim 1, wherein said alloy is produced by a rapid solidification method.

6. A high-entropy multielement alloy consisting of: five to eleven major metallic elements and at least one minor element, said minor elements are selected from the element group other than the major metallic elements, the mole fraction of each major metallic element in the alloy is between 5% and 30%, and the mole fraction of each minor element in the alloy is less than 3.5%.

7. The high-entropy multielement alloy of claim 6, wherein said major metallic elements are selected from the metallic element group consisting of beryllium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, yttrium, zirconium, niobium, molybdenum, ruthenium, palladium, silver, hafnium, tantalum, tungsten, platinum, gold, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium and terbium.

8. The high-entropy multielement alloy of claim 6, wherein said major metallic elements are selected from the metallic element group consisting of aluminum, titanium, vanadium, chromium, iron, cobalt, nickel, copper, zirconium, molybdenum, palladium, silver and gold.

9. The high-entropy multielement alloy of claim 6, wherein said minor element is selected from the metallic element group consisting of lithium, beryllium, sodium, magnesium, aluminum, scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, gallium, germanium, strontium, yttrium, zirconium, niobium, molybdenum, ruthenium, rhodium, palladium, silver, cadmium, indium, tin, antimony, hafnium, tantalum, tungsten, platinum, gold, lead, bismuth, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium and terbium.

10. The high-entropy multielement alloy of claim 6, wherein said minor element is selected from the nonmetallic element group consisting of carbon, boron, silicon, phosphorus, sulfur, hydrogen, oxygen and nitrogen.

11. The high-entropy multielement alloy of claim 6, wherein said alloy is produced by an electric arc melting method.

12. The high-entropy multielement alloy of claim 6, wherein said alloy is produced by a rapid solidification method.

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