



US 20200056272A1

(19) **United States**(12) **Patent Application Publication**
HONG et al.(10) **Pub. No.: US 2020/0056272 A1**(43) **Pub. Date: Feb. 20, 2020**(54) **TWINNING/TRANSFORMATION INDUCED
PLASTICITY HIGH ENTROPY STEELS AND
METHOD OF MANUFACTURING THE SAME***C21D 11/00* (2006.01)*C22C 38/04* (2006.01)*C22C 38/06* (2006.01)*C22C 38/32* (2006.01)*C22C 38/46* (2006.01)*C22C 38/54* (2006.01)*C22C 38/58* (2006.01)(71) Applicant: **The Industry & Academic
Cooperation in Chungnam National
University(IAC), Daejeon (KR)**(72) Inventors: **Sun Ig HONG, Daejeon (KR); Jae
Sook SONG, Daejeon (KR); Byung Ju
LEE, Daejeon (KR)**(52) **U.S. Cl.**CPC *C22C 38/52* (2013.01); *C21D 6/004*
(2013.01); *C21D 11/005* (2013.01); *C22C*
38/04 (2013.01); *C22C 38/58* (2013.01); *C22C*
38/32 (2013.01); *C22C 38/46* (2013.01); *C22C*
38/54 (2013.01); *C22C 38/06* (2013.01)(21) Appl. No.: **16/507,474**(22) Filed: **Jul. 10, 2019**(30) **Foreign Application Priority Data**

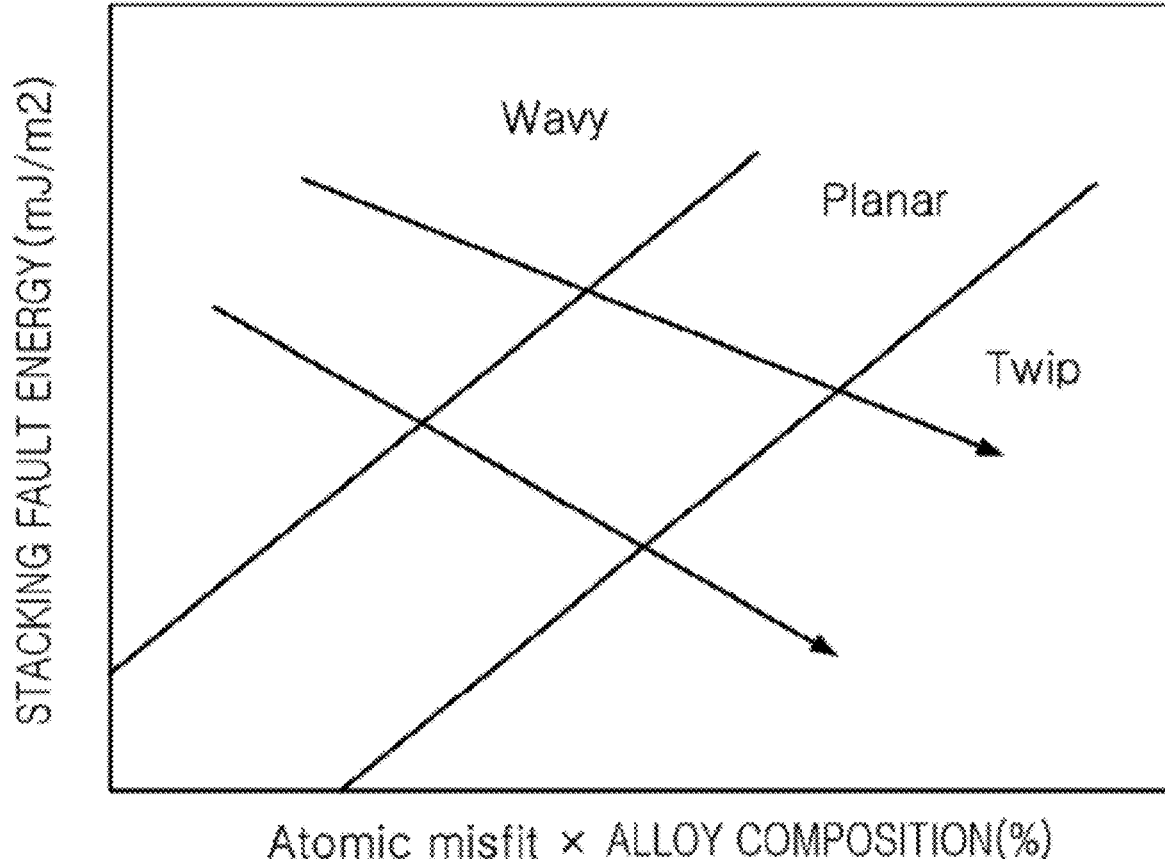
Aug. 14, 2018 (KR) 10-2018-0095007

Publication Classification(51) **Int. Cl.***C22C 38/52* (2006.01)*C21D 6/00* (2006.01)

(57)

ABSTRACT

A high entropy steel in which twinning and phase transformation are simultaneously performed, and a method of manufacturing the same, are provided. The high entropy steel includes three or more alloying elements selected from the following, by atomic percentage: iron (Fe) from 35% to 80%, nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35%



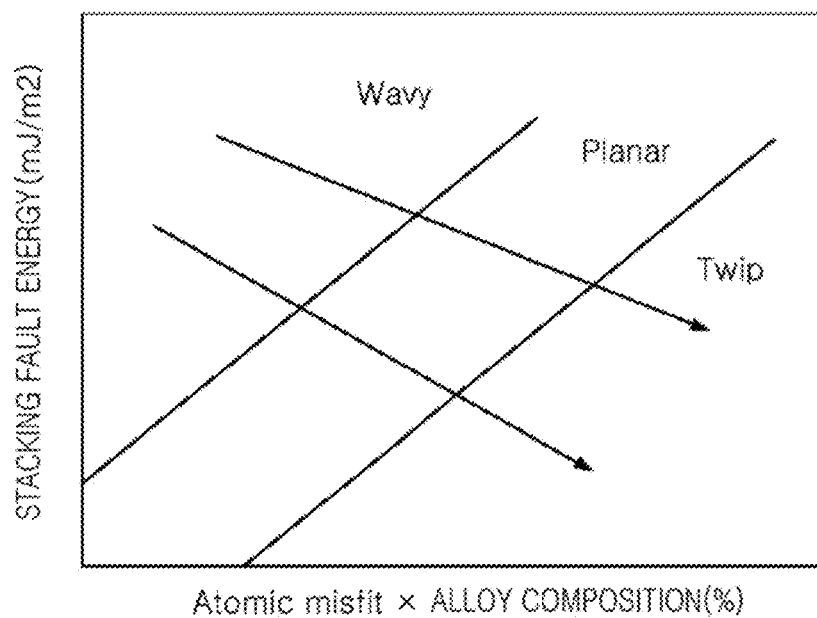


FIG. 1

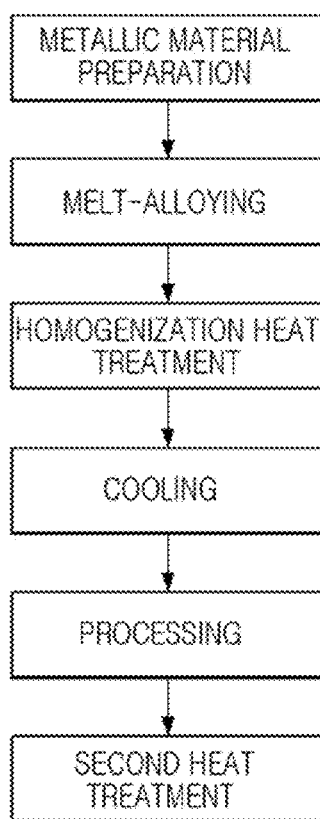


FIG. 2

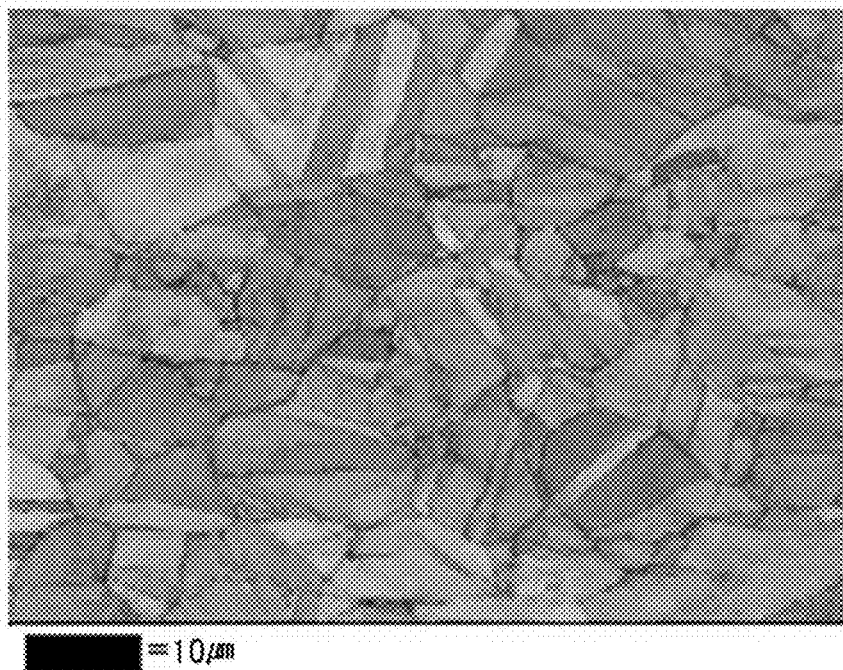
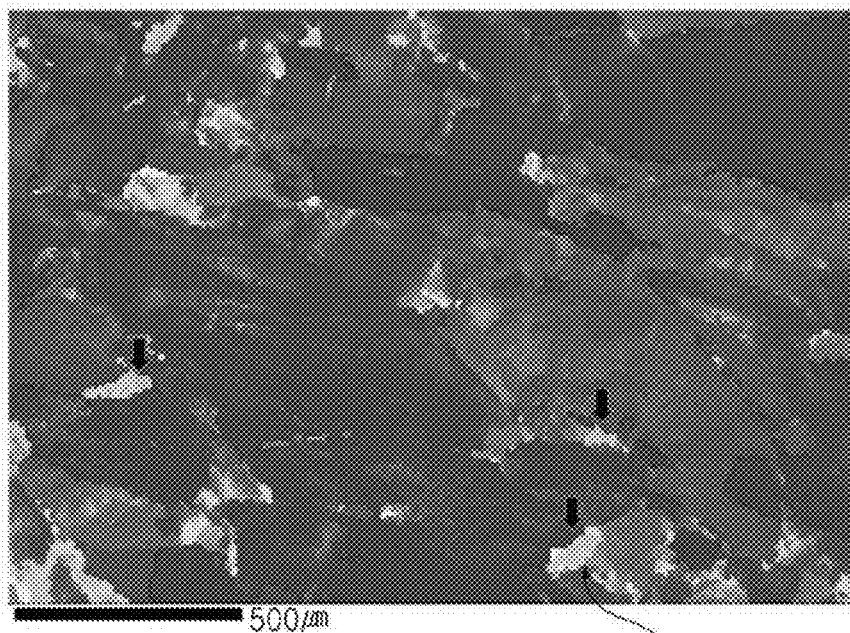
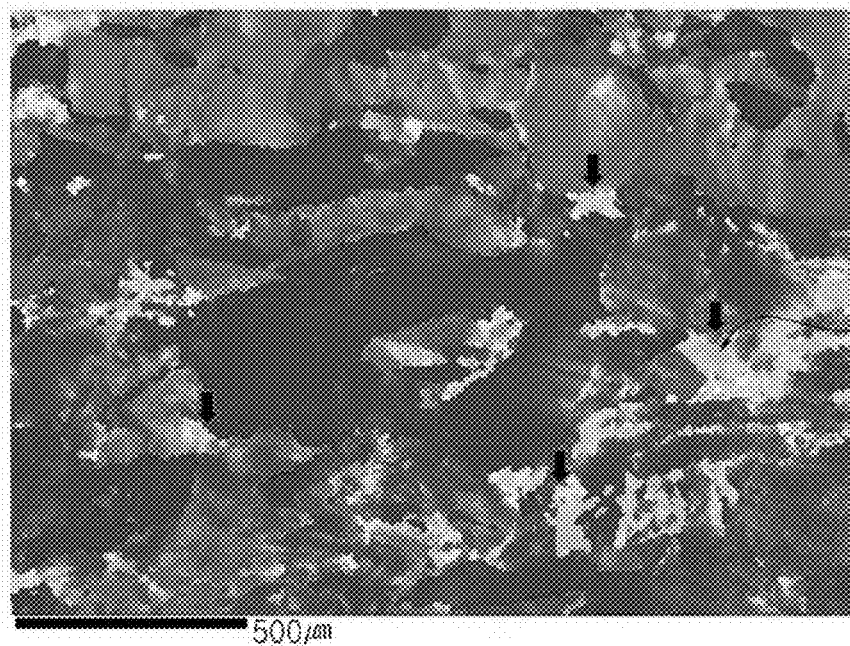


FIG. 3



INDUCED-PLASTICITY
TRANSFORMATION PHASE

FIG. 4A



INDUCED-
PLASTICITY
TRANSFORMATION
PHASE

FIG. 4B

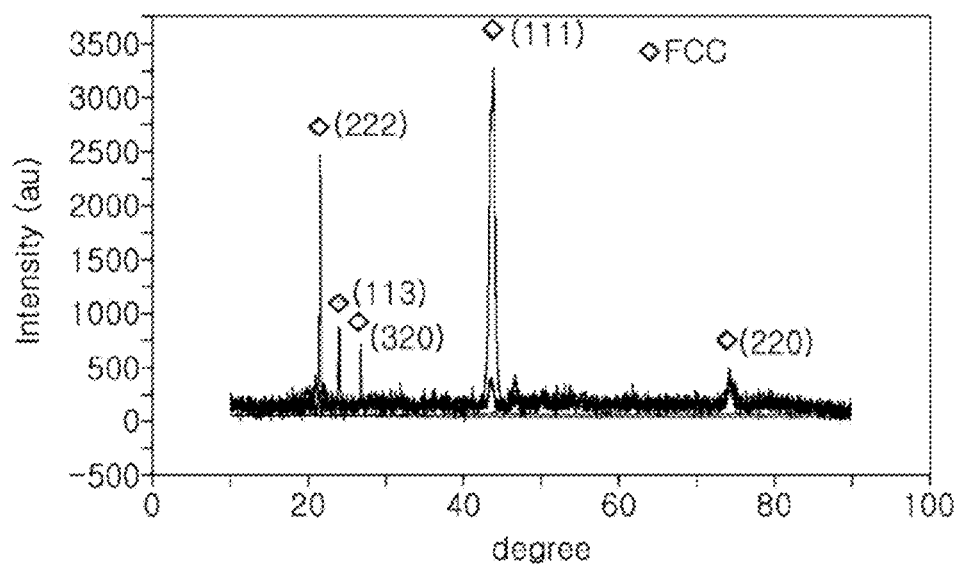


FIG. 5A

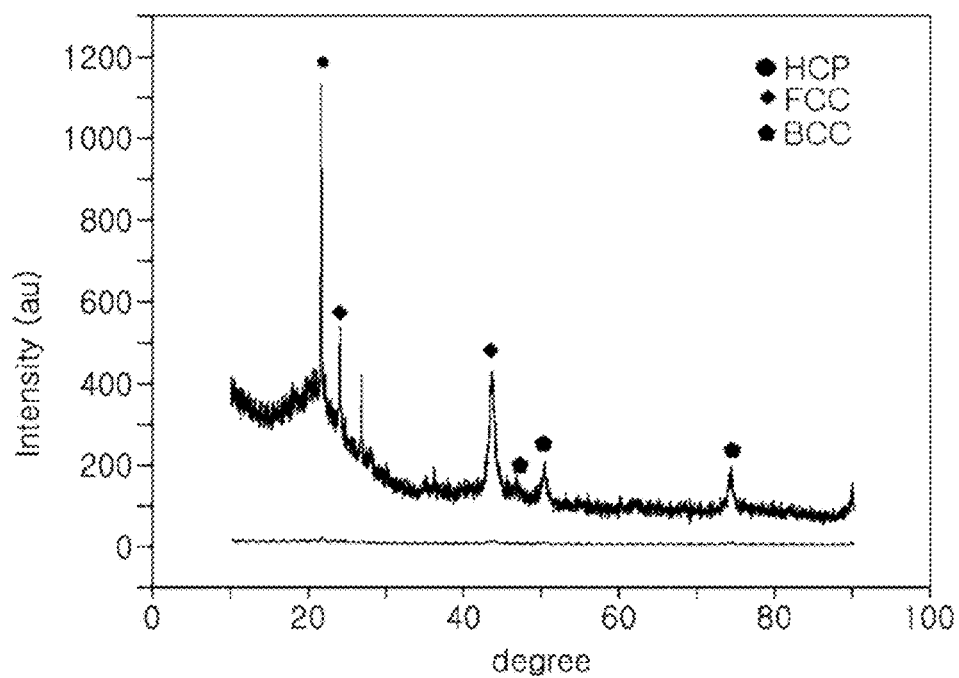


FIG. 5B

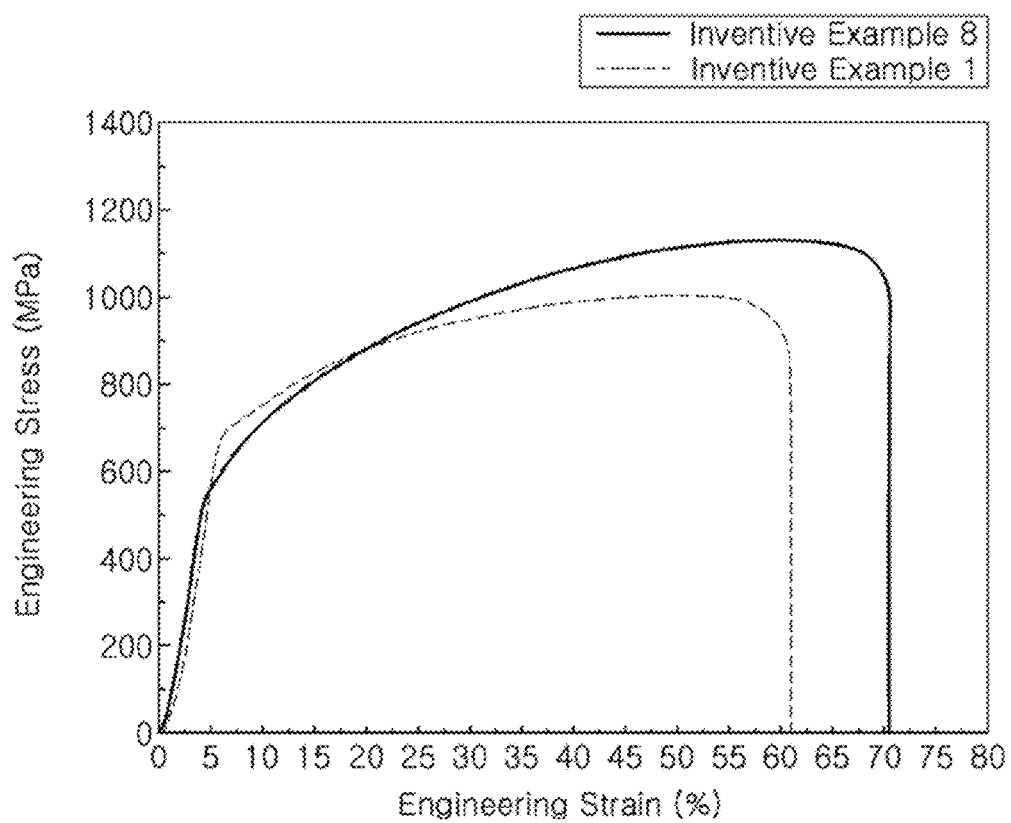


FIG. 6

TWINNING/TRANSFORMATION INDUCED PLASTICITY HIGH ENTROPY STEELS AND METHOD OF MANUFACTURING THE SAME

BACKGROUND

[0001] The present disclosure relates to a high entropy steel exhibiting twinning and transformation induced plasticity characteristics, and more particularly, to a high entropy steel having improved mechanical properties, by increasing a work hardening rate and simultaneously increasing strength and ductility as a twin boundary or a phase boundary caused by twinning and phase transformation interferes with dislocation movement, and a method of manufacturing the same.

[0002] With the rapid development of the industrial technology, the demand for various materials that cannot be met by conventional metals and steels have increased. To meet this demand, a new alloy system known as a high entropy alloy, new types of materials, have recently been proposed and developed.

[0003] A high entropy alloys are those in which an increase in configuration entropy due to the mixing of various elements rather promotes the formation of solid solution than the formation of a compound by the reduction of free energy for solid solution formation. In other words, a solid solution alloy in which a solid solution in which various alloying elements are homogeneously distributed is formed, instead of forming intermetallic compounds or amorphous phase

[0004] The above-mentioned high entropy alloy is known through in Non-Patent Document 1 [Material Science and Engineering A, Volumes 375-377, July 2004, page 213-218]. In Non-Patent Document 1, a multi-element alloy, $\text{Fe}_{20}\text{Cr}_{20}\text{Mn}_{20}\text{Ni}_{20}\text{Co}_{20}$, expected to be formed as an amorphous alloy or a complex intermetallic compound, is unexpectedly formed as a crystalline face centered cubic (FCC) solid solution, thereby raising interest. By comparison with conventional alloys in which other alloying elements are added to primary alloying elements of 60 to 90 at. %, the high-entropy alloy has a specific property that even when alloying elements having a four or five or more element system are mixed at a similar ratio, a single phase is formed, and this is found in alloys having a higher level of configuration entropy due to mixing.

[0005] As Prior art patents relating to high entropy alloys, there are provided Patent Document 1 (U.S. Laid-Open Patent No. US 2013/0108502 A1) and Patent Document 2 (U.S. Laid-Open Patent No. US2009/0074604 A1). In Patent Document 1, the high-entropy alloy is provided as an alloy system containing five or more elements, in which each element such as vanadium (V), niobium (Nb), tantalum (Ta), molybdenum (Mo), titanium (Ti), or the like is included with a deviation of ± 15 atomic % or less, as various metals, and in which all elements, having been added, act as a main element. In addition, the high-entropy alloy is formed as a single phase solid solution having a face-centered cubic and/or body-centered cubic structure. However, in Patent Document 1, different types of relatively expensive and heavy alloying elements are added, and there may be a difficulty in a manufacturing process due to the difference in melting temperatures among added alloying elements.

[0006] Meanwhile, in Patent Document 2, disclosed is a high-entropy alloy having a high degree of hardness, manufactured in a powder metallurgy process using a ceramic

phase (representatively, tungsten carbide) and multi component high-entropy alloy powder. However, in Patent Document 2, since a high temperature process is required when a ceramic material is used to manufacture an alloy with hard ceramic particles, it is difficult to manufacture the alloy using a ceramic-based material because a high-temperature process is required.

[0007] As in Patent Documents 1 and 2, high entropy alloys using a metal or ceramic alloying elements are attracting attention as new materials because of their excellent mechanical properties. Recently, it has been known that such entropy alloys exhibit excellent properties in extreme environmental properties such as high temperature mechanical properties and low temperature mechanical properties, and various studies are continuing. However, since most of the researches have been made to evaluate the mechanical and physical properties of high-entropy alloys composed of equiatomic alloys which are easy to form high entropy alloys, there is not much research on the development of alloys for obtaining more improved mechanical characteristics based on a high entropy alloy.

[0008] In addition, despite the possibility of inducing new properties or improving existing properties by applying changes in structure and mechanical properties due to the increase of entropy in non-ferrous and steel materials, there have been few studies to improve the properties of existing alloys by applying the concept of entropy.

SUMMARY

[0009] An aspect of the present disclosure is to provide high entropy steels having excellent workability and work hardening performance by suppressing the formation of brittle intermetallic compounds due to an increase in entropy with the addition of various alloying elements designed to increase the entropy, through the application of the concept of solid solution formation due to the increased configurational entropy of high entropy alloy steels, and a method of manufacturing the same.

[0010] An aspect of the present disclosure is to provide a high entropy steels having improved mechanical properties by providing obstacles to dislocation movement such as twin boundary or phase boundaries due to twinning and phase transformation and increasing the work hardening rate, thereby simultaneously increasing strength and ductility, and a method of manufacturing the same.

[0011] In the present disclosure, we present a high entropy steel with excellent workability and work hardening performance that can include three or more alloying elements selected from the following, by atomic percentage: iron (Fe) from 35% to 80%, nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35%.

[0012] One or more alloying element from the following can be added to the high entropy steel, by atomic percentage: carbon (C) from 0.01% to 5.0%, nitrogen (N) from 0.01% to 5.0%, boron (B) from 0.01% to 5.0%, silicon (Si) from 0.01% to 10%, copper (Cu) from 0.01% to 10%, vanadium (V) from 0.01% to 10%, and aluminum (Al) from 0.01% to 10%.

[0013] For the high entropy steel to exhibit such characteristics, its stacking fault energy may be 40 mJ/m² or less, and corresponding 'atomic size difference x alloy composition % value' may be 0.05 or more.

[0014] The present disclosure describes a method of manufacturing a type of high entropy steel with excellent workability and work hardening performance, which includes the following steps: preparing a metallic material with composition as mentioned before; producing the prepared metallic material as molten alloy; applying a homogenizing heat treatment on the alloy in the temperature range between 850° C. and 1250° C., and then cooling the alloy in the room temperature; and after processing the cooled alloy, applying a second heat treatment where the alloy is maintained in the temperature range between 350° C. and 850° C. for 0.5 to 72 hours.

[0015] The metallic material can be produced as a molten alloy from any one of following methods: casting, arc melting, powder metallurgy, thermal spray casting, thermal spray coating, spray coating, and 3D-printing.

[0016] The produced alloy can be processed through forging, extrusion, rolling or drawing.

BRIEF DESCRIPTION OF DRAWINGS

[0017] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing (s) will be provided by the Office upon request and payment of the necessary fee.

[0018] The above and other aspects, features, and advantages of the present disclosure will be more clearly understood from the following detailed description, taken in conjunction with the accompanying drawings, in which:

[0019] FIG. 1 is a conceptual diagram illustrating a design of a twin induced alloy by stacking fault energy and an alloy composition of a high entropy steel according to an embodiment of the present disclosure;

[0020] FIG. 2 is a process flow chart illustrating a schematic procedure of a method of manufacturing a high entropy steel according to an embodiment of the present disclosure;

[0021] FIG. 3 is an image of a microstructure of Inventive Example 1 of an embodiment of the present disclosure;

[0022] FIGS. 4A and 4B are images of microstructures of Inventive Example 6 of the embodiment of the present disclosure, FIG. 4A illustrating a microstructure when a strain rate is 20% and FIG. 4B illustrating a microstructure when a strain rate is 40%, at a tension test;

[0023] FIGS. 5A and 5B are XRD analysis graphs of a specimen of Inventive Example 1 of the embodiment of the present disclosure, FIG. 5A being an XRD analysis graph before a deformation and FIG. 5B being an XRD analysis graph after the deformation in Inventive example 1 of the embodiment of the present disclosure; and

[0024] FIG. 6 is a graph illustrating a stress-strain curve for Inventive Example 1 and Inventive Example 8 of the embodiment of the present disclosure.

DETAILED DESCRIPTION

[0025] In order to overcome difficulties posed by environmental problems such as greenhouse gas as well as rising costs of raw materials due to recent shortage in resources, we explored novel materials that could exhibit mechanical properties such as high strength and high ductility. Through our research, we applied the concept of high entropy alloy to steels, in which a variety of alloying elements with various quantities were brought together in such a way that

increases entropy and, therefore, suppresses formation of brittle intermetallic compounds, resulting in high entropy steel with excellent workability and work hardening properties, which is the focus of this present disclosure. In other words, the present disclosure is unique in the fact that twinning and phase transformation cause a twin boundary or a phase boundary that block displacement, resulting in an increase in work hardening rate and thereby producing a high entropy steel with more strength and ductility than conventional high entropy alloy.

[0026] The focus of the present disclosure is on the high entropy steel with excellent work hardening properties, which includes 3 or more alloying elements selected from the following: (by atomic percentage) iron (Fe) from 35% to 80%, nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35%.

[0027] Hereinafter, we are going to describe the high entropy steel in detail. First, we will explain the reason for selecting these specific alloying elements and their corresponding limits in terms of composition.

[0028] The high entropy steel in the present disclosure includes three or more alloying elements selected from the following, by atomic percentage: iron (Fe) from 35% to 80%, nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35%. In any composition that satisfies these conditions, iron (Fe) is always the highest in contents.

[0029] Fe, Ni, Mn, Co, and Cr make up to form high entropy alloy, and all of them are transition elements in the fourth period of the periodic table. Their atomic radii are not so different from each other, which makes it easier for these elements to form a solid solution and such. Mn and Ni promote formation of face-centered cubic (FCC) solid solutions, Co develops finer microstructures, and Cr increases resistance to corrosion.

[0030] The reason for selecting Fe content range as such (35%-80%) is to maximize entropy as much as possible while making Fe content to be higher than other constituent elements so that the matrix can have steel-like characteristics.

[0031] The reason for selecting Ni content range as such (5%-35%) is to maximize entropy while promoting FCC structure in the matrix. The reason for selecting Mn content range as such (5%-35%) is to maximize entropy while lowering stacking fault energy and promoting FCC structure in the matrix. The reason for selecting Co content range as such (5%-35%) is to maximize entropy while developing finer microstructures and optimizing induction of phase transformation. The reason for selecting Cr content range as such (5%-35%) is to maximize entropy while optimizing corrosion resistance.

[0032] As described above, the high entropy steel according to an embodiment of the present disclosure may essentially include Fe and may include three or more elements among the remaining four elements, the content of Fe being greater than that of other added constituent elements, in a manner different from an existing high entropy alloy selectively including five kinds of alloying elements of Co, Cr, Fe, Mn and Ni. Thus, for example, when 'an atomic size difference x an alloy composition % value' is increased, alloying elements react with dislocations to induce dislocation movement suppression or expansion of partial twinning dislocation to induce deformation twinning. Thus, twinning

induced plasticity deformation and work hardening behavior may be exhibited in the case of relatively high stacking fault energy as well as low stacking fault energy.

[0033] The high entropy steel according to the embodiment may further include, by atomic %, one or more of 0.01 to 5.0% of carbon (C), 0.01 to 5.0% of nitrogen (N), 0.01 to 5.0% of boron (B), 0.01 to 10% of silicon (Si), 0.01 to 10% of copper (Cu), 0.01 to 10% of vanadium (V), and 0.01 to 10% of aluminum (Al).

[0034] C, N and B are interstitial elements, and Si, Cu, V and Al are substitutional elements, which react with dislocation or twin partial dislocation to induce twinning and phase transformation, such that a twin boundary or a phase boundary interferes with dislocation movement to increase a work hardening rate of a material.

[0035] In the embodiment, the content of each of C, N and B is limited to 0.01 to 5%, which is because if the content of these elements is less than 0.01%, reaction stress with dislocation is relatively low, and if the content thereof exceeds 5%, lattice distortion is severe, the base is brittle by deviating from solid solution limit, and efficiency of reaction with dislocation decreases.

[0036] The above Si, Cu, V and Al have a great difference in atomic radius from Fe, Cr, Ni, Mn and Co that are main elements constituting the base of the high entropy steel and have a great difference in valence or the like therefrom, and are thus segregated at the dislocation, inhibiting dislocation movement and a combination of partial dislocations to induce twin and phase transformation. Thus, the twin boundary or the phase boundary interferes with the dislocation movement, thereby increasing a work hardening rate.

[0037] In the embodiment, the content of each of Si, Cu, V and Al is 0.01 to 10 atomic %, which is the reason why, if the content is less than 0.01 atomic %, segregation and reaction effects with the dislocation are relatively too small, while if the content exceeds 10 atomic %, lattice distortion is severe, the base is brittle by deviating from solid solution limit, and efficiency of reaction with dislocation decreases.

[0038] As described above, the high entropy steel according to the embodiment may include a composition of more than 35% and not more than 80% of Fe, and at least one of Ni, Mn, Co and Cr, as basic constituents, and may also include one or more additional elements selected from C, N, B, Si, Cu, V and Al, thereto, to increase strength and workability. These additional elements are segregated at the dislocations to inhibit or suppress movement of complete dislocations or twin partial dislocations to induce deformation twinning. In this case, deformation twinning may be activated even in a case in which atomic size misfit of the additive element is relatively great, as well as the case of relatively low stacking fault energy (SFE).

[0039] Hereinafter, the work hardening of the high entropy steel in an embodiment and a strength and ductility increasing mechanism thereby will be described.

[0040] FIG. 1 is a conceptual diagram illustrating a design of a twin induced alloy by stacking fault energy and an alloy composition of a high entropy steel according to an embodiment

[0041] As illustrated in FIG. 1, wavy slip is exhibited in a relatively high stacking fault energy region. In addition, as 'an atomic size difference x an alloy composition % value' (the total content of alloy components except Fe) increases, alloying elements react with dislocations, to induce suppression of dislocation movement or expansion of partial twin

dislocation, causing deformation twinning. Thus, a wavy slip region may change to a planar slip region and a TWIP region even in the case of relatively high stacking fault energy as well as the case of low stacking fault energy. As described above, in the case of the high entropy alloy having reduced stacking fault energy, a twin boundary or a phase boundary due to twinning and phase transformation interferes with dislocation movement, thereby increasing a work hardening rate and exhibiting excellent strength and ductility as compared with an existing high entropy alloy.

[0042] In detail, in the embodiment, for example, when the stacking fault energy is 40 mJ/m² or less, and the atomic size difference x the alloy composition % value is 0.05 or more, a high entropy steel may exhibit excellent strength and ductility through the above-described work hardening mechanism.

[0043] Next, a method of manufacturing a high entropy steel according to an embodiment will be described in detail.

[0044] The method of manufacturing a high entropy steel according to an embodiment may include preparing a metallic material having the above-mentioned composition components, producing the prepared metallic material as a molten alloy, subjecting the produced alloy to a homogenization heat treatment in a temperature range of 850° C. to 1250° C., and then, cooling the alloy to room temperature, and performing a second heat treatment process in which the cooled alloy is processed and maintained at a temperature within a temperature range of 350° C. to 850° C. for 0.5 to 72 hours.

[0045] FIG. 2 is a process flow chart illustrating a schematic procedure of manufacturing a high entropy steel according to an embodiment.

[0046] As illustrated in FIG. 2, in an embodiment, first, a metallic material including, by atomic %, three or more alloying elements selected from the following, by atomic percentage: iron (Fe) from 35% to 80%, nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35 may be prepared.

[0047] In the embodiment, the metallic material may further include, by atomic %, one or more alloying element from carbon (C) from 0.01% to 5.0%, nitrogen (N) from 0.01% to 5.0%, boron (B) from 0.01% to 5.0%, silicon (Si) from 0.01% to 10%, copper (Cu) from 0.01% to 10%, vanadium (V) from 0.01% to 10%, and aluminum (Al) from 0.01% to 10%.

[0048] The melting process is to alloy the produced metallic material, and a method thereof according to an embodiment is not particularly limited. For example, the melting process may be a general method performed in the art. For example, the alloy may be produced through casting, arc melting, powder metallurgy, thermal spray casting, thermal spray coating, spray coating, 3D-printing, or the like.

[0049] Next, the produced alloy is homogenized and heat-treated. Since the high entropy steel is manufactured by mixing various elements, homogenization heat treatment is performed to induce sufficient diffusion. The homogenization heat treatment may be carried out in a temperature range of 850° C. to 1250° C. for 1 to 48 hours.

[0050] Subsequently, the homogenized and heat-treated alloy may be cooled to room temperature. In the embodiment, a cooling method thereof is not particularly limited, and various methods such as water cooling, oil cooling, air cooling or the like may be used. Through this cooling

process, some metallic components, which are not solid dissolved in the matrix structure, may be uniformly distributed in the microstructure.

[0051] In the embodiment, the cooled alloy is processed. As the processing method in the embodiment, a method such as forging, extrusion, rolling, drawing, or the like may be

[0057] On the other hand, with the high-entropy steel produced as described above, a steel sheet having a thickness of 1 mm was produced and subjected to a tensile test to evaluate mechanical properties thereof, and the results are shown in Table 1 below. 'An atomic size difference x an alloy composition % value' and stacking fault energy were measured and are also shown in Table 1.

TABLE 1

Classification	Alloy	Stacking Fault Energy (mJ/m ²)	Atomic Size Difference x Alloy %	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Comparative Example 1	Co ₂₀ Cr ₂₀ Fe ₂₀ Mn ₂₀ Ni ₂₀	35	N.A.	496	336	68
Comparative Example 2	Co ₂₅ Ni ₂₅ Fe ₂₅ Mn ₂₅	33	N.A.	784	532	60
Inventive Example 1	Fe ₆₀ Cr _{18.8} Ni ₁₀ Co ₁₀ C _{1.2}	38	0.1908	1000	570	59
Inventive Example 2	Fe ₆₀ Cr _{18.8} Ni ₁₀ Mn ₁₀ N _{1.2}	36	0.1932	1040	630	63
Inventive Example 3	Fe ₆₀ Cr ₁₀ Co _{18.8} Mn ₁₀ B _{1.2}	35	0.1352	896	492	48
Inventive Example 4	Fe ₆₀ Co ₁₅ Ni ₁₀ Mn ₁₀ Cu ₅	34	0.5280	1152	672	69
Inventive Example 5	Fe ₆₀ Cr ₁₅ Ni ₁₀ Co ₁₀ Si ₅	33	0.3515	1032	612	60
Inventive Example 6	Fe ₆₀ Cr ₁₅ Ni ₁₀ Mn ₁₀ Al ₅	36	0.3235	1096	636	62
Inventive Example 7	Fe ₆₀ Cr ₁₅ Ni ₁₀ Co ₁₀ Al _{4.5} N _{0.5}	35	0.3190	1080	696	68
Inventive Example 8	Fe ₆₀ Cr ₁₅ Co ₁₀ Mn ₁₀ Cu _{4.5} C _{0.5}	34	0.4880	1128	738	70
Inventive Example 9	Fe ₆₀ Co ₁₅ Ni ₁₀ Mn ₁₀ Si _{4.5} B _{0.5}	33	0.3195	1072	609	65
Inventive Example 10	Fe ₆₀ Cr ₁₉ Ni ₁₀ Mn ₁₀ N _{0.5} C _{0.5}	34	0.4110	1100	642	67
Inventive Example 11	Fe ₆₀ Cr ₁₅ Mn ₁₀ Co ₁₀ V ₅	38	0.3215	1128	657	69
Inventive Example 12	Fe ₆₀ Cr ₂₀ Ni ₁₀ Co ₁₀	36	0.0694	1032	627	65
Inventive Example 13	Fe ₆₀ Cr ₂₀ Mn ₁₀ Co ₁₀	37	0.0842	1000	597	63
Inventive Example 14	Fe ₆₀ Mn ₂₀ Ni ₁₀ Co ₁₀	35	0.0687	1016	588	59

used, by which various deformation defects may be introduced into the cooled alloy material.

[0052] Subsequently, in the embodiment, a second heat treatment in which the cooled alloy is maintained in the temperature range of 350° C. to 850° C. for 0.5 to 72 hours may be performed. The second heat treatment process may be a process to uniformly precipitate phase transformation precipitates having various shapes by twinning and phase transformation, on a matrix. In this process, a microstructure in which phase transformation precipitates having various shapes by twinning and phase transformation are simultaneously present on a single-phase solid solution base structure, may be manufactured.

[0053] Next, in the embodiment, the second heat treated steel alloy may be cooled to room temperature. In this case, various cooling methods such as water cooling, oil cooling, air cooling, furnace cooling or the like may be used.

[0054] Hereinafter, embodiments of the present disclosure will be described in detail with reference to examples of embodiments.

EXAMPLE EMBODIMENTS

[0055] First, high entropy steels of Comparative Examples 1 to 2 and Embodiment Examples 1 to 14 were produced as shown in Table 1 below.

[0056] In detail, a metallic material having a composition (atomic %) shown in Table 1 below was prepared and arc-melted in a vacuum atmosphere to prepare an alloy. Thereafter, a homogenization heat treatment was performed on the prepared alloy, at 1050° C. for 24 hours, and then, the alloy was cooled to room temperature. Subsequently, the cooled alloy was subjected to a second heat treatment at 850° C. for 10 minutes after rolling to promote grain refinement, and then cooled to room temperature to produce a final high entropy steel.

[0058] As shown in Table 1, in Inventive Examples 1 to 14 in which the composition according to an embodiment of the present disclosure was satisfied and phase-transformation precipitates having various shapes due to twinning and phase transformation were simultaneously present in a single-phase solid solution matrix structure, it can be confirmed that excellent strength and ductility may be secured in a balanced manner, as compared with the comparative examples. In detail, compared to Comparative Examples 1 and 2, it can be confirmed that the high entropy steel according to an embodiment of the present disclosure has a twin boundary or a phase boundary due to twinning or phase transformation in a single-phase solid-solution matrix structure, interfering with displacement movement to improve a work hardening rate, thereby securing excellent strength and ductility as compared with an existing high entropy alloy.

[0059] FIG. 3 is an image of microstructure observed in Inventive example 1. As illustrated in FIG. 3, it can be confirmed that deformation twinning is formed in the matrix structure.

[0060] FIGS. 4A and 4B are images of microstructures of Inventive Example 6 of the present disclosure. FIG. 4A shows a microstructure when strain was 20% at a tensile test, and FIG. 4B shows a microstructure when the strain was 40% at the tensile test. As can be seen from FIGS. 4A and 4B, a second phase due to induced phase transformation can be confirmed, and the second phase increases as the amount of strain increases.

[0061] FIG. 5 is an XRD analysis graph of a specimen of Inventive Example 1 of the present disclosure. FIG. 5A is an XRD analysis graph before a deformation, and FIG. 5B is an XRD analysis graph after the deformation. As illustrated in FIGS. 5A and 5B, Inventive example 1 has a matrix structure of a single-phase face-centered cubic structure before deformation, while BCC and HCP peaks are observed on XRD data after the deformation, and thus, it can be confirmed that the second phase due to the phase transformation is present.

[0062] FIG. 6 is a graph illustrating stress-strain curves of Inventive examples 1 and 8 in the present disclosure. As illustrated in FIG. 6, in the case of Inventive Example 1, the strength is 1,000 MPa and the elongation is 60%, and in Inventive example 8, the strength is 1128 MPa and the elongation is 70%. Thus, it can be confirmed that excellent strength and ductility may be secured, as compared with an existing high entropy alloy.

[0063] As set forth above, according to an embodiment of the present disclosure with the above-described structure, a high entropy steel may have excellent mechanical properties and economical efficiency as compared to a high entropy alloy at the same equiatomic alloy, by inducing twinning induced plastic deformation, work hardening, and phase transformation induced hardening behavior, in the case of relatively high stacking fault energy as well as a low stacking fault energy, differently from an existing technique.

[0064] In addition, a high entropy steel according to an embodiment may have significantly improved mechanical properties and thus be used as a material of an offshore plant requiring high toughness and high strength at a relatively low temperature, or a structural material in an extreme environment.

[0065] For example, when ‘an atomic size difference x an alloy composition % value’ is increased, alloying elements react with dislocations to induce dislocation movement suppression or expansion of partial twin dislocation to induce deformation twinning. Thus, twinning induced plasticity deformation and work hardening behavior may be exhibited in the case of relatively high stacking fault energy as well as low stacking fault energy. The high entropy steel may be applicable as a high-temperature material, for applications such as nuclear pressure vessels, cladding tubes, turbine blades for thermal power generation, or the like, due to high mechanical properties through phase transformation induced hardening, and thus, high entropy alloys may be used more diversely.

[0066] While embodiments have been shown and described above, it will be apparent to those skilled in the art that modifications and variations could be made without departing from the scope of the present invention as defined by the appended claims.

What is claimed is:

1. A high entropy steel having excellent workability and hardening performance, comprising:

three or more alloying elements selected from the following, by atomic percentage: iron (Fe) from 35% to 80%,

nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35.

2. The high entropy steel of claim 1, further comprising, by atomic %, one or more selected from carbon (C) from 0.01% to 5.0%, nitrogen (N) from 0.01% to 5.0%, boron (B) from 0.01% to 5.0%, silicon (Si) from 0.01% to 10%, copper (Cu) from 0.01% to 10%, vanadium (V) from 0.01% to 10%, and aluminum (Al) from 0.01% to 10%.

3. The high entropy steel of claim 1, wherein stacking fault energy is 40 mJ/m² or less, and ‘an atomic size difference x an alloy composition % value’ is 0.05 or more.

4. A method of manufacturing a high entropy steel having excellent workability and work hardening performance, the method comprising:

preparing a metallic material including an three or more alloying elements selected from the following, by atomic percentage: iron (Fe) from 35% to 80%, nickel (Ni) from 5% to 35%, manganese (Mn) from 5% to 35%, cobalt (Co) from 5% to 35%, and chromium (Cr) from 5% to 35;

producing the prepared metallic material as molten alloy; applying a homogenizing heat treatment on the alloy in the temperature range between 850° C. and 1250° C., and then cooling the alloy in the room temperature; and after processing the cooled alloy, applying a second heat treatment where the alloy is maintained in the temperature range between 350° C. and 850° C. for 0.5 to 72 hours.

5. The method of claim 4, wherein the high entropy steel further comprises, by atomic %, one or more selected from carbon (C) from 0.01% to 5.0%, nitrogen (N) from 0.01% to 5.0%, boron (B) from 0.01% to 5.0%, silicon (Si) from 0.01% to 10%, copper (Cu) from 0.01% to 10%, vanadium (V) from 0.01% to 10%, and aluminum (Al) from 0.01% to 10

6. The method of claim 4, wherein the metallic material is produced as a molten alloy, using one method selected from casting, arc melting, powder metallurgy, thermal spray casting, thermal spray coating, spray coating, and 3D-printing.

7. The method of claim 4, wherein the processing of the cooled alloy is performed using one of forging, extrusion, rolling and drawing.

* * * * *