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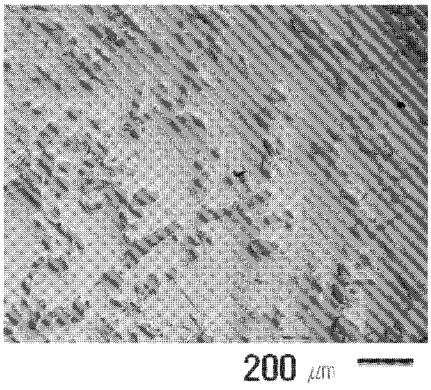
(54) HEAT RESISTANT ALUMINUM ALLOY, AND METHOD FOR MANUFACTURING SAME

(57) Disclosed is a heat-resistant aluminum alloy including aluminum and two types of alloy elements which are combined while forming a homogeneous solid solution reinforcing phase. The disclosed heat-resistant aluminum alloy includes the alloy elements that form a homogeneous solid solution and do not have a solvus line with respect to aluminum as a matrix metal and, therefore, the formed homogeneous solid solution reinforcing phase does not react with aluminum even at a temperature up to 300°C, thus not becoming coarse or undergoing phase decomposition. Consequently, the disclosed aluminum alloy may have remarkably enhanced heat resistance.

Fig.11



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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to a heat-resistant aluminum alloy and a method for manufacturing the same and, more particularly, to a heat-resistant aluminum alloy including aluminum and additional elements having no solvus line or a solvus line of less than 1 wt.% with respect to aluminum, which form a homogeneous solid solution, thus being stable even at a high temperature, as well as a method for manufacturing the same.

Description of the Related Art

[0002] Currently developed heat-resistant aluminum alloys have heat resistance properties realized by dispersing and controlling an Al-Si-transition element intermetallic compound or Al-X (Fe, Cu, Cr, Mn, Ti) intermetallic compound in the form of a crystalline phase created by solidification, that is a phase transformation from liquid to solid, as well as a precipitation phase created on a solid phase through heat treatment, on an aluminum and/or aluminum alloy matrix.

[0003] However, such alloys having enhanced heat resistance through crystallization and/or precipitation of intermetallic compounds on the aluminum and/or aluminum alloy matrix entail a problem of deteriorated heat resistance at a temperature of 200°C or higher.

[0004] FIG. 1 is a schematic drawing illustrating high temperature behavior of elements added to a heat-resistant aluminum alloy in the related art. As shown in the figure, in the case where the typical heat-resistant aluminum alloy is kept at a temperature of 200°C or higher for a long period of time, the crystallized and/or precipitated intermetallic compound reacts with aluminum as the matrix to form a new intermediate phase in order to retain thermodynamic equilibrium or, otherwise, the intermetallic compound becomes coarse. As a result, problems such as occurrence of cracks and/or transition may be encountered, which in turn deteriorates heat resistance. Accordingly, the foregoing alloys entail limitation in usage under high temperature conditions of 200°C or higher.

[0005] Meanwhile, aluminum composite has heat resistance obtained by dispersing nitride, boride, oxide and/or carbide in a reinforcing phase on an aluminum alloy matrix. Such an aluminum matrix composite material shows superior heat resistance over a heat-resistant alloy using an intermetallic compound.

[0006] However, an aluminum matrix composite material has a difficulty in uniformly controlling the reinforcing phase, while a powder based composite material has a disadvantage of poor price competitiveness. In the case where an interfacial reaction occurs between a matrix metal type aluminum and/or aluminum alloy and a reinforcing phase, characteristics of the aluminum based composite material are drastically degraded.

[0007] In other words, for the heat-resistant alloy having the controlled intermetallic compound and composite material reinforcing phase described above, the intermetallic compound or reinforcing-phase may undesirably react, thus causing a problem such as considerable degradation in heat resistance of the heat-resistant alloy.

[0008] Furthermore, each of aluminum alloys commercially available on the market, which include the heat-resistant alloys current developed in the related art, generally contains at least 10 kinds of additional elements. Therefore, in the case where the aluminum alloy is reused (or recycled), aluminum may undesirably react with the additional elements during remelting, which in turn causes difficulties with active selection (or screening), thus entailing limitation in reusing the same.

SUMMARY OF THE INVENTION

[0009] Therefore, the present invention is directed to solving the above problems and it is an object of the present invention to provide a heat-resistant aluminum alloy having a stable reinforcing-phase which does not coarse or is not phase decomposed by reaction with aluminum as a matrix metal at a high temperature, manufactured using aluminum and alloy elements having no solvus line with respect to aluminum and, in addition, a method for manufacturing the foregoing alloy.

[0010] Another object of the present invention is to provide a predetermined content of alloy elements enabling retention of a stable reinforcing phase.

[0011] In order to accomplish the objects described above, there is provided a heat-resistant aluminum alloy, characterized in that two types of alloy elements having no solvus line with respect to aluminum are combined while forming a homogeneous solid solution reinforcing phase.

[0012] The alloy elements are contained in an amount of 0.5 to 10 wt.% relative to the aluminum.

[0013] Moreover, there is provided a method of manufacturing a heat-resistant aluminum alloy, including; adding alloy elements to an aluminum melt composed of molten aluminum and casting the melt after the alloy elements are fused in the melt, resulting in the aluminum alloy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The above and other objects, features and other advantages of the present invention will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic view illustrating high temperature behavior of elements added to a heat-resistant alloy in the related art;

FIG. 2 is a schematic view illustrating a stable high temperature behavior of a homogeneous solid solution reinforcing phase in a heat-resistant aluminum alloy according to the present invention;

FIGS. 3 to 10 illustrate binary alloy phase diagrams of various alloy elements; in particular, FIG. 3 is a chromium-tungsten (Cr-W) phase diagram, FIG. 4 is a copper-nickel (Cu-Ni) phase diagram, FIG. 5 is an iron-chromium (Fe-Cr) phase diagram, FIG. 6 is an iron-manganese (Fe-Mn) phase diagram, FIG. 7 is a manganese-vanadium (Mn-V) phase diagram, FIG. 8 is a cobalt-nickel (Co-Ni) phase diagram, FIG. is an iron-nickel (Fe-Ni) phase diagram , and FIG. 10 is a copper-manganese (Cu-Mn) phase diagram;

FIG. 11 is an optical micrograph of the microstructure of a specimen prepared in Preparative Example 1;

FIGS. 12 to 14 are each a photograph illustrating mapping results of the microstructure of specimens prepared in Preparative Examples 1 to 3, using an electron probe micro-analyzer (EPMA), in particular, FIG. 12 is of Preparative Example 1, FIG 13 is of Preparative Example 2 and FIG. 14 is of Preparative Example 3, respectively;

FIG. 15 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 1 to 300°C for 200 hours;

FIG. 16 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 1 then casting the same;

FIG. 17 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 4, depending upon content of additional alloy elements;

FIG. 18 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 5;

FIG. 19 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 5, using an EPMA;

FIG. 20 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 5 to 300°C for 200 hours;

FIG. 21 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 5 then casting the same;

FIG. 22 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 6, depending upon content of additional alloy elements;

FIG. 23 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 7;

FIG. 24 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 7, using an EPMA;

FIG. 25 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 7 to 300°C for 200 hours;

FIG. 26 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 7 then casting the same;

FIG. 27 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 8;

FIG. 28 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 8, using an EPMA;

FIG. 29 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 8 to 300°C for 200 hours;

FIG. 30 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 8 then casting the same;

FIG. 31 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 9, depending upon content of additional alloy elements;

FIG. 32 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 10;

FIG. 33 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 10, using an EPMA;

FIG. 34 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 10 to 300°C for 200 hours;

FIG. 35 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 10 then casting the same;

FIG. 36 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 11, depending upon content of additional alloy elements;

FIG. 37 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 12;

FIG. 38 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 12, using an EPMA;

FIG. 39 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 12 to 300°C for 200 hours;

FIG. 40 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 12 then casting the same;

FIG. 41 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 13, depending upon content of additional alloy elements;

FIG. 42 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 14;

FIG. 43 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 14, using an EPMA;

FIG. 44 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 14 to 300°C for 200 hours;

FIG. 45 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 14 then casting the same;

FIG. 46 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 15, depending upon content of additional alloy elements;

FIG. 47 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 16;

FIG. 48 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 16, using an EPMA;

FIG. 49 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after heating the specimen prepared in Preparative Example 16 to 300°C for 200 hours;

FIG. 50 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 16 then casting the same;

FIG. 51 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 17, depending upon content of additional alloy elements;

DETAILED DESCRIPTION OF THE INVENTION

[0015] Hereinafter, preferred embodiments of the present invention will be described in detail with reference to the annexed drawings.

[0016] FIG. 2 is a schematic view illustrating a stable high temperature behavior of a homogeneous solid solution reinforcing phase formed in a heat-resistant aluminum alloy according to the present invention. As shown in FIG. 2, the heat-resistant aluminum alloy of the present invention is characterized in that it comprises alloy elements having no solvus line or a solvus line of less than 1% with respect to aluminum while forming a homogeneous solid solution to each other on an aluminum matrix, thereby not undergoing thermal decomposition or becoming coarse even at a high temperature.

[0017] Briefly, the present invention provides a heat-resistant aluminum alloy including; two kinds of alloy elements, which form a homogeneous solid solution, thus being combined while forming a homogeneous solid solution reinforcing phase. For the foregoing heat-resistant aluminum alloy, an alloy element having no solvus line or a solvus of less than 1% with respect to aluminum and, therefore, not forming an intermetallic compound with aluminum but forming a homogenous solid solution reinforcing phase, even when adding the alloy element to the aluminum, wherein the homogeneous solid solution reinforcing phase is present in a single phase and thermodynamically stable, may be used.

[0018] Accordingly, the homogenous solid solution reinforcing phase does not react with aluminum even at a high temperature of 200°C or higher, the reinforcing phase does not coarsen or is not thermally decomposed and, even when heating the same to a melting point of aluminum, the homogeneous solid solution formed in the aluminum may be stably maintained. In addition, even when the prepared heat-resistant aluminum alloy undergoes remelting, the formed homogeneous solid solution reinforcing phase may be stably maintained. These effects may be identified by the following experimental results.

[0019] According to the present invention, the foregoing two types of alloy elements may include chromium (Cr) and tungsten (W). The solid solution reinforcing phase made of these alloy elements, that is, Cr and W, may maintain a stable single phase at a temperature up to 1800°C and have a size ranging from 1 to 200μm.

[0020] Alternatively, the two alloy elements used herein may be copper (Cu) and nickel (Ni). A homogeneous solid solution reinforcing phase made of these alloy elements, that is, Cu and Ni, may be stable at a temperature up to 873°C and have a crystal interface shape with a size ranging from 1 to 50μm.

[0021] Alternatively, the two alloy elements used herein may be iron (Fe) and chromium (Cr). A homogeneous solid solution reinforcing phase made of Fe and Cr may be maintained in a stable single phase at a temperature up to 1500°C and have a facet shape with a size ranging from 1 to 60μm.

[0022] Alternatively, the two alloy elements used herein may be iron (Fe) and manganese (Mn). A homogeneous solid solution reinforcing phase made of Fe and Mn may have heat resistance at a temperature up to 1245°C and be formed in a facet shape with a size ranging from 1 to 50μm.

[0023] Alternatively, the two alloy elements used herein may be manganese (Mn) and vanadium (V). A homogeneous solid solution reinforcing phase made of Mn and V may maintain a stable single phase at a temperature up to 1245°C and have a facet shape with a size ranging from 1 to 100μm.

[0024] Alternatively, the two alloy elements used herein may be cobalt (Co) and nickel (Ni). A homogeneous solid solution reinforcing phase made of Co and Ni may show heat resistance at a temperature up to 1490°C and be formed in a needle-like shape with a size ranging from 1 to 70μm.

[0025] Alternatively, the two alloy elements used herein may be iron (Fe) and nickel (Ni). A homogeneous solid solution reinforcing phase made of Fe and Ni may maintain a stable single phase at a temperature up to 1245°C and have a granular shape with a size ranging from 1 to 30μm.

[0026] Alternatively, the two alloy elements used herein may be copper (Cu) and manganese (Mn). A homogeneous solid solution reinforcing phase made of Fe and Ni may maintain a stable single phase at a temperature up to 873°C and have a size ranging from 1 to 10μm.

[0027] As described above, the heat-resistant aluminum alloy of the present invention which has a homogeneous solid solution reinforcing phase composed of two types of alloy elements used herein may have improved heat resistance, compared to a heat-resistant aluminum alloy in the related art that losses heat resistance at 200°C or higher. Therefore, the inventive aluminum alloy may be present in a single phase at 300°C or higher and, even when remelting the same, may stably maintain the single phase. Such results may be identified by the following experiments.

[0028] The alloy element may be contained in an amount of 0.5 to 10 wt.% relative to aluminum. If a content of the alloy element is less than 0.5 wt.% relative to aluminum, the content of the alloy element is not sufficient, thus causing a decrease in reinforcing effects of the homogeneous solid solution. In contrast, if the content of the alloy element exceeds 10 wt.% relative to aluminum, the homogeneous solid solution reinforcing phase becomes coarse and, due to a ratio of the coarse reinforcing phase, a problem in casting and/or segregation may be encountered.

[0029] In addition, since the foregoing two kinds of alloy elements are capable of forming a homogeneous solid solution, a mixing ratio thereof is not particularly limited. However, according to the present invention, an amount of one of the alloy elements may range from 10 to 90 wt. % while the other may be contained in an amount of 90 to 10 wt.%.

[0030] The heat-resistant aluminum alloy according to the present invention may be manufactured by adding the alloy elements to an aluminum melt comprising molten aluminum to fuse the alloy elements therein, and then, casting the melt. In this regard, aluminum melting may be executed at about 700°C, 30 to 40°C higher than the melting point of aluminum, that is, 660°C, in consideration of heat loss.

[0031] Further, the present invention may use chromium (Cr) and tungsten (W) as the alloy elements. In this case, Cr and W may be directly added to an aluminum melt or, otherwise, added in a Cr-W master alloy form. The alloy elements may also be added in both of Al-Cr master alloy and Al-W master alloy forms.

[0032] Alternatively, copper (Cu) and nickel (Ni) may be used as the alloy elements. In this case, Cu and Ni may be directly added to an aluminum melt or, otherwise, added in a Cu-Ni master alloy form. The alloy elements may also be added in both of Al-Cu master alloy and Al-Ni master alloy forms.

[0033] Alternatively, iron (Fe) and chromium (Cr) may be used as the alloy elements. In this case, Fe and Cr may be directly added to an aluminum melt or, otherwise, added in an Fe-Cr master alloy form. The alloy elements may also be added in both of Al-Fe master alloy and Al-Cr master alloy forms.

[0034] Alternatively, iron (Fe) and manganese (Mn) may be used as the alloy elements. In this case, Fe and Mn may be directly added to an aluminum melt or, otherwise, added in an Fe-Mn master alloy form. The alloy elements may also be added in both of Al-Fe master alloy and Al-Mn master alloy forms.

[0035] Alternatively, manganese (Mn) and vanadium (V) may be used as the alloy elements. In this case, Mn and V may be directly added to an aluminum melt or, otherwise, added in an Mn-V master alloy form. The alloy elements may also be added in both of Al-Mn master alloy and Al-V master alloy forms.

[0036] Alternatively, cobalt (Co) and nickel (Ni) may be used as the alloy elements. In this case, Co and Ni may be directly added to an aluminum melt or, otherwise, added in a Co-Ni master alloy form. The alloy elements may also be added in both of Al-Co master alloy and Al-Ni master alloy forms.

[0037] Alternatively, iron (Fe) and nickel (Ni) may be used as the alloy elements. In this case, Fe and Ni may be directly added to an aluminum melt or, otherwise, added in an Fe-Ni master alloy form. The alloy elements may also be added in both of Al-Fe master alloy and Al-Ni master alloy forms.

[0038] Alternatively, copper (Cu) and manganese (Mn) may be used as the alloy elements. In this case, Cu and Mn may be directly added to an aluminum melt or, otherwise, added in a Cu-Mn master alloy form. The alloy elements may also be added in both of Al-Cu master alloy and Al-Mn master alloy forms.

[0039] Meanwhile, preparation of a master alloy comprising each of the alloy elements may be executed by a variety of dissolution methods in the related art. According to the present invention, the master alloy may be prepared by: plasma arc melting (PAM) that uses a plasma arc as a heat source and enables dissolution in a wide range from a low vacuum to atmospheric pressure; or vacuum induction melting (VIM) that uses Joule heat generated by eddy current, which flows in a metal conductor in an opposite direction of current of a coil based on electron induction, to heat and melt the conductor, thereby easily controlling temperature and constitutional components via strong agitation in the melt.

[0040] The alloy element may be added in an amount of 0.5 to 10 wt.% relative to aluminum. The reason for this is that the content range defined as above is most preferable to prevent segregation due to coarsening of the homogeneous solid solution reinforcing phase in the heat-resistant aluminum alloy prepared by the manufacturing method described above and, in addition, to maximize reinforcing effects.

[0041] Hereinafter, the following experiments have been executed to demonstrate effects of the heat-resistant alloy according to the present invention.

[0042] FIGS. 3 to 10 show binary alloy phase diagrams of respective alloy elements, in particular, FIG. 3 is a Cr-W alloy phase diagram, FIG. 4 is a Cu-Ni alloy phase diagram, FIG. 5 is a Fe-Cr alloy phase diagram, FIG. 6 is an Fe-Mn alloy phase diagram, FIG. 7 is an Mn-V alloy phase diagram, FIG. 8 is a Co-Ni alloy phase diagram, FIG. 9 is an Fe-Ni alloy phase diagram, and FIG. 10 is a Cu-Mn alloy phase diagram.

[0043] As shown in FIG. 3, it can be seen that Cr and W form a homogeneous solid solution and the homogeneous solid solution is stable as a solid phase up to a temperature of 1800°C, which is considerably higher than a melting point of aluminum, that is, 660°C.

[0044] In other words, the heat-resistant aluminum alloy having a homogeneous solid solution reinforcing phase of Cr and W may maintain a stable single phase at a temperature 3 times higher than the melting point of aluminum and it may be presumed that the homogeneous solid solution reinforcing phase does not coarsen nor is decomposed even at a temperature up to 1800°C. Consequently, the foregoing aluminum alloy may be suitably utilized as a piston of a diesel engine or aircraft parts, which are typically used at a high temperature, for example, 1800°C.

[0045] In addition, FIG. 4 demonstrates that Cu and Ni form a homogeneous solid solution and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 870°C, which is higher than the melting point of aluminum, that is, 660°C.

[0046] Therefore, it may be presumed that the heat-resistant aluminum alloy having a homogeneous solid solution reinforcing phase composed of Cu and Ni does not entail problems such as coarsening or decomposition of the Cu-Ni homogeneous solid solution reinforcing phase at a temperature of about 800°C.

[0047] Further, FIG. 5 demonstrates that Fe and Cr form a homogeneous solid solution and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 1500°C, which is considerably higher than the melting point of aluminum, that is, 660°C.

[0048] Briefly, the heat-resistant aluminum alloy having a homogeneous solid solution composed of Fe and Cr may maintain a single phase even at a temperature 2 times higher than the melting point of aluminum. Therefore, the Fe-Cr homogeneous solid solution reinforcing phase may neither coarsen nor be decomposed even at a high temperature of about 1500°C. Based on such characteristics, the foregoing aluminum alloy may be easily used for parts such as a gas turbine engine block of a turbocharger.

[0049] Further, it can be seen from FIG. 6 that Fe and Mn form a homogeneous solid solution and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 1245°C, which is considerably higher than the melting point of aluminum, that is, 660°C.

[0050] Briefly, the heat-resistant aluminum alloy having a homogeneous solid solution composed of Fe and Mn may maintain a single phase even at a temperature 2 times higher than the melting point of aluminum. Therefore, the Fe-Cr homogeneous solid solution reinforcing phase neither coarsens nor is decomposed even at a high temperature of about 1245°C. Based on such characteristics, the foregoing aluminum alloy may be easily used for, for example, a diesel engine block.

[0051] Further, it can be seen from FIG. 7 that Mn and V form a homogeneous solid solution and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 1245°C, which is considerably higher than the melting point of aluminum, that is, 660°C.

[0052] Briefly, the heat-resistant aluminum alloy having a homogeneous solid solution composed of Mn and V may maintain a single phase even at a temperature 2 times higher than the melting point of aluminum. Therefore, the Mn-V homogeneous solid solution reinforcing phase neither coarsens nor is decomposed even at a high temperature of about 1245°C. Consequently, the foregoing aluminum alloy may be easily used for, for example, a lineless engine block in a gasoline engine and/or other vehicle parts.

[0053] Further, it can be seen from FIG. 8 that Co and Ni form a homogeneous solid solution to each other and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 1490°C, which is 830°C higher than the melting point of aluminum, that is, 660°C.

[0054] Briefly, the heat-resistant aluminum alloy having a homogeneous solid solution composed of Co and Ni may maintain a single phase even at a temperature about 830°C higher than the melting point of aluminum. Therefore, the Co-Ni homogeneous solid solution reinforcing phase neither coarsens nor is decomposed even at a temperature of 300°C or higher, or during remelting. When the foregoing aluminum alloy is applied to a piston of a diesel engine, or the like, engine efficiency may be favorably enhanced.

[0055] Further, it can be seen from FIG. 9 that Fe and Ni form a homogeneous solid solution and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 1245°C, which is considerably higher than the melting point of aluminum.

[0056] Briefly, the heat-resistant aluminum alloy having a homogeneous solid solution composed of Fe and Ni may maintain a single phase even at a temperature about 600°C higher than the melting point of aluminum. Therefore, on the basis of thermodynamic calculation, it may be presumed that the Fe-Ni homogeneous solid solution reinforcing phase neither coarsens nor is decomposed at a temperature up to 1245°C. The foregoing aluminum alloy may be widely applied to existing car engine materials and parts of, for example, an aircraft.

[0057] Further, it can be seen from FIG. 10 that Cu and Mn form a homogeneous solid solution and the homogeneous solid solution is stably maintained as a solid phase up to a temperature of 873°C, which is higher than the melting point of aluminum, that is, 660°C.

[0058] Briefly, the heat-resistant aluminum alloy having a homogeneous solid solution composed of Cu and Mn may maintain a single phase even at a high temperature of 300°C or higher, thus exhibiting excellent heat resistance. Moreover, since the Cu-Mn homogeneous solid solution reinforcing phase neither coarsens nor is decomposed at a temperature of about 800°C, which is higher than the melting point of aluminum, aluminum and the additional elements, that is, Cu and Mn, may be actively recycled.

[Example 1]

[0059] Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 1 -

[0060] While an aluminum melt comprising molten aluminum prepared at 700°C, was maintained at 700°C, Cr and W as alloy elements were added in an amount of 1.5 wt.%, respectively, to the melt and the melt was maintained for 30 to 60 minutes to completely fuse Cr and W. Then, the mixture was subjected to casting, resulting in a specimen of a heat-resistant aluminum alloy having a Cr-W homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy').

- PREPARATIVE EXAMPLE 2 -

[0061] While an aluminum melt comprising molten aluminum prepared at 700°C, was maintained at 700°C, an Al-Cr master alloy containing 50 wt.% of Cr and an Al-W master alloy containing 50 wt.% of W were added in an amount of 1.5 wt.%, respectively, to the melt and the melt was maintained for 30 to 60 minutes to completely fuse both the Al-Cr master alloy and the Al-W master alloy. Then, the mixture was subjected to casting, resulting in a specimen of a Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy.

- PREPARATIVE EXAMPLE 3 -

[0062] While an aluminum melt comprising molten aluminum prepared at 700°C, was maintained at 700°C, a Cr-W master alloy, which is prepared with a relative ratio of Cr:W of 50 wt.% to 50 wt.% through Plasma Arc Melting (PAM), was added in an amount of 3 wt.% relative to aluminum to the melt and the melt was maintained for 30 to 60 minutes to completely fuse the Cr-W master alloy. Then, the mixture was subjected to casting, resulting in a specimen of a Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy.

[0063] FIG. 11 is an optical micrograph of the microstructure of a specimen prepared in Preparative Example 1, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. From FIG. 11, it was confirmed that the heat-resistant aluminum alloy according to the manufacturing method of the present invention has a reinforcing phase in a facet shape with a size of 1 to 200μm.

[0064] FIGS. 12 to 14 are each a photograph illustrating mapping results of the microstructure of specimens prepared in Preparative Examples 1 to 3, using an electron probe micro-analyzer (EPMA).

[0065] As shown in FIG. 12, the specimen prepared in Preparative Example 1 demonstrated that the reinforcing phase in the facet shape shown in FIG. 11 is a Cr-W homogeneous solid solution. Also, from respective specimens prepared in Preparative Examples 2 and 3 shown in FIGS. 13 and 14, respectively, it was found that Cr and W in each of the specimens form a homogeneous solid solution.

[0066] With reference to results of FIGS. 12 to 14, it can be understood that a route of adding Cr and W as alloy elements present in the heat-resistant aluminum alloy according to the present invention does not relate to formation of the homogeneous solid solution.

[0067] Further, in order to assay high temperature stability of the Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 1 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heat treated specimen through an optical microscope. The observed results are shown in FIG. 15.

[0068] As shown in FIG. 15, the reinforcing phase composed of the Cr-W homogeneous solid solution exhibited a reinforcing phase in the same facet shape as the microstructure shown in FIG. 11, as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Cr-W homogeneous solid solution reinforcing phase of the Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy is stable even at 300°C.

[0069] FIG. 16 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 1 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 1 to a melting point of aluminum, and casting the treated specimen.

[0070] As shown in FIG. 16, it can be seen that the homogeneous solid solution formed in the Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 3, instead, it maintained the reinforcing phase. From these results, it may be presumed that, when being recycled, the heat-resistant aluminum alloy according to the present invention may be effectively utilized to actively recycle aluminum as a matrix metal, as well as Cr and W as alloy elements, to eco-friendly Virgin levels thereof.

- PREPARATIVE EXAMPLE 4 -

[0071] While an aluminum melt comprising molten aluminum prepared at 700°C, was maintained at 700°C, a Cr-W master alloy, which is prepared with a relative ratio of Cr:W of 50 wt.% to 50 wt.% through Plasma Arc Melting (PAM), was added in amounts of 0.5 wt.%, 1 wt.%, 3 wt.%, 5 wt.%, 7 wt.%, 9 wt.%, 10 wt.% and 11 wt.%, respectively, relative to aluminum, to the melt. Following this, the melt was maintained for 30 to 60 minutes to completely fuse the added Cr-W master alloy, followed by casting the melt, resulting in a specimen of a Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy.

[0072] FIG. 17 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 4, depending upon the content of additional alloy elements. After assaying an image of the microstructure of each specimen prepared in Preparative Example 4 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0073] As a result, it was confirmed that, if 0.5 wt.% of Cr-W master ally is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was also small to about 10μm. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is 300μm or more, thus coarsening too much.

[0074] Consequently, the Cr-W homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution formed therein, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to coarsening may be prevented.

[Example 2]

[0075] Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 5 -

[0076] A specimen of a heat-resistant aluminum alloy having a Cu-Ni homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Cu and Ni were used as alloy elements in an amount 1.5 wt.% for each.

[0077] FIG. 18 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 5, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observing a structure of the specimen through an optical microscope. As a result, it was found that the Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy specimen prepared in Preparative Example 5 has a reinforcing phase in a crystal interface shape with a size of 1 to 50μm.

[0078] FIG. 19 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 5, using an EPMA. From this figure, it was confirmed that the reinforcing phase in the crystal interface shape is a Cu-Ni homogeneous solid solution.

[0079] Further, in order to assay high temperature stability of the Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 5 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 20.

[0080] As shown in FIG. 20, the reinforcing phase composed of the Cr-W homogeneous solid solution exhibited a reinforcing phase in the same crystal interface shape as the microstructure shown in FIG. 18, as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Cu-Ni homogeneous solid solution reinforcing phase of the Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy is stable even at 300°C.

[0081] FIG. 21 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 5 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 5 to the melting point of aluminum, and casting the treated specimen.

[0082] As shown in FIG. 21, it can be seen that the homogeneous solid solution formed in the Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 4, instead, it maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics and a feature that the Cu-Ni homogeneous solid solution reinforcing phase has 3.3 times the specific gravity of aluminum, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively select and recycle aluminum as a matrix metal, as well as Cr and W as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum is recycled.

- PREPARATIVE EXAMPLE 6 -

[0083] A specimen of a Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy was prepared by the same procedures as described in Preparative Example 4, except that a Cu-Ni master alloy prepared with a relative ratio of Cu:Ni of 50 wt.% to 50 wt.%, through Plasma Arc Melting (PAM), was used.

[0084] FIG. 22 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 6, depending upon the content of additional alloy elements thereof. After assaying an image of the microstructure of each specimen prepared in Preparative Example 6 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0085] As a result, it was confirmed that, if 0.5 wt.% of Cu-Ni master alloy is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was too small to about 1μm, thus not being measurable. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is 300μm or more, thus coarsening too much. Consequently, the Cu-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution formed therein, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to size coarsening may be prevented.

[Example 3]

[0086] Fe-Cr homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 7 -

[0087] A specimen of a heat-resistant aluminum alloy having an Fe-Cr homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Fe-Cr homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Fe and Cr were used as alloy elements in an amount 1.5 wt.% for each.

[0088] FIG. 23 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 7, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. As a result, it was found that the heat-resistant aluminum alloy specimen prepared in Preparative Example 7 has a reinforcing phase in a facet shape with a size of 1 to 60μm.

[0089] FIG. 24 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 7, using an EPMA. From this figure, it was confirmed that the reinforcing phase in the facet shape is an Fe-Cr homogeneous solid solution.

[0090] Further, in order to assay high temperature stability of the Fe-Cr homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 7 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 25.

[0091] As shown in FIG. 25, the reinforcing phase composed of the Fe-Cr homogeneous solid solution exhibited a reinforcing phase in the same facet shape as the microstructure shown in FIG. 23, as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Fe-Cr homogeneous solid solution reinforcing phase of the Fe-Cr homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention is stable even at 300°C.

[0092] FIG. 26 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 7 then casting the same. Here, a cast specimen is substantially obtained by remelting the specimen prepared in Preparative Example 7 to a melting point of aluminum, and casting the treated specimen.

[0093] As shown in FIG. 26, it can be seen that the homogeneous solid solution formed in the Fe-Cr homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 5, instead, it maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics and a feature that the Fe-Cr homogeneous solid solution reinforcing phase has 2.78 times the specific gravity of aluminum, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively select and recycle aluminum as a matrix metal, as well as Fe and Cr as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum is recycled.

[Example 4]

[0094] Fe-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 8 -

[0095] A specimen of a heat-resistant aluminum alloy having an Fe-Mn homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Fe-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Fe and Mn were used as alloy elements in an amount of 1.5 wt.% for each.

[0096] FIG. 27 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 8, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. It was found from FIG. 27 that the heat-resistant aluminum alloy specimen prepared in Preparative Example 8 has a reinforcing phase in a facet shape with a size of 1 to 50μm.

[0097] FIG. 28 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 8, using an EPMA. It was confirmed that the reinforcing phase in the facet shape shown in FIG. 27 is an Fe-Mn homogeneous solid solution.

[0098] Further, in order to assay high temperature stability of the Fe-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 8 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 29.

[0099] As shown in FIG. 28, the reinforcing phase composed of the Fe-Mn homogeneous solid solution exhibited a reinforcing phase in the same facet shape as the microstructure shown in FIG. 27, as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Fe-Mn homogeneous solid solution reinforcing phase of the Fe-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention is stable even at 300°C.

[0100] FIG. 30 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 8 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 8 to a melting point of aluminum, and casting the treated specimen.

[0101] As shown in FIG. 30, it can be seen that the homogeneous solid solution formed in the Fe-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 6, instead, it maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics and a feature that the Fe-Cr homogeneous solid solution reinforcing phase has 2.8 times the specific gravity of aluminum, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively select and recycle aluminum as a matrix metal, as well as Fe and Mn as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum is recycled.

- PREPARATIVE EXAMPLE 9 -

[0102] A specimen of a heat-resistant aluminum alloy was prepared by the same procedures as described in Preparative Example 4, except that a Fe-Mn master alloy comprising a relative ratio of Fe:Mn of 50 wt.% to 50 wt. % prepared through Plasma Arc Melting (PAM), was used.

[0103] FIG. 31 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 9, depending upon the content of additional alloy elements. After assaying an image of the microstructure of each specimen prepared in Preparative Example 9 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0104] As a result, it was confirmed that, if 0.5 wt.% of Fe-Mn master alloy is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was small to about 5μm or less. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is about 250μm or more, thus coarsening too much. Consequently, the Fe-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution formed therein, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to size coarsening may be prevented.

[Example 5]

[0105] Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 10 -

[0106] A specimen of a heat-resistant aluminum alloy having an Mn-V homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Mn and V were used as alloy elements in an amount of 1.5 wt.% for each.

[0107] FIG. 32 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 10, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. It was found from FIG. 32 that the Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy specimen prepared in Preparative Example 10 has a reinforcing phase in a facet shape with a size of 1 to 100μm.

[0108] FIG. 33 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 10, using an EPMA. It was confirmed that the reinforcing phase in the facet shape shown in FIG. 32 is an Mn-V homogeneous solid solution.

[0109] Further, in order to assay high temperature stability of the Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 10 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 34.

[0110] As shown in FIG. 34, the reinforcing phase composed of the Mn-V homogeneous solid solution exhibited a reinforcing phase in the same facet shape as the microstructure shown in FIG. 32, as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Mn-V homogeneous solid solution reinforcing phase of the Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention is stable even at 300°C.

[0111] FIG. 35 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 10 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 10 to a melting point of aluminum, and casting the treated specimen.

[0112] As shown in FIG. 35, it can be seen that the homogeneous solid solution formed in the Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 7, instead, it has maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics and a feature that the Fe-Cr homogeneous solid solution reinforcing phase has 2.4 times the specific gravity of aluminum, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively select and recycle aluminum as a matrix metal, as well as Fe and V as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum alloy is recycled.

- PREPARATIVE EXAMPLE 11 -

[0113] A specimen of a heat-resistant aluminum alloy was prepared by the same procedures as described in Preparative Example 4, except that an Mn-V master alloy comprising a relative ratio of Mn:V of 50 wt.% to 50 wt.% prepared through Plasma Arc Melting (PAM) was used.

[0114] FIG. 36 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 11, depending upon the content of additional alloy elements. After assaying an image of the microstructure of each specimen prepared in Preparative Example 11 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0115] As a result, it was confirmed that, if 0.5 wt.% of Mn-V master alloy is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was small to about 4μm or less. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is about 300μm or more, thus coarsening too much. Consequently, the Mn-V homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution formed therein, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to size coarsening may be prevented.

[Example 6]

[0116] Co-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 12 -

[0117] A specimen of a heat-resistant aluminum alloy having a Co-Ni homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Co-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Co and Ni were used as alloy elements in an amount of 1.5 wt.% for each.

[0118] FIG. 37 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 12, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. It was found from FIG. 37 that the heat-resistant aluminum alloy specimen prepared in Preparative Example 12 has a reinforcing phase in a needle-like shape with a size of 1 to 70μm.

[0119] FIG. 38 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 12, using an EPMA. It was confirmed that the reinforcing phase in the facet shape shown in FIG. 37 is a Co-Ni homogeneous solid solution.

[0120] Further, in order to assay high temperature stability of the Co-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 12 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 39.

[0121] As shown in FIG. 39, the reinforcing phase composed of the Co-Ni homogeneous solid solution exhibited a reinforcing phase in the same needle-like shape as the microstructure shown in FIG. 37 as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Co-Ni homogeneous solid solution reinforcing phase of the Co-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention is stable even at 300°C.

[0122] FIG. 40 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 12 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 12 to a melting point of aluminum, and casting the treated specimen.

[0123] As shown in FIG. 40, it can be seen that the homogeneous solid solution formed in the Co-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nore decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 8, instead, it maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively select and recycle aluminum as a matrix metal, as well as Co and Ni as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum is recycled.

- PREPARATIVE EXAMPLE 13 -

[0124] A specimen of a heat-resistant aluminum alloy was prepared by the same procedures as described in Preparative Example 4, except that an Co-Ni master alloy comprising a relative ratio of Co:Ni of 50 wt.% to 50 wt. % prepared through Plasma Arc Melting (PAM) was used.

[0125] FIG. 41 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 13, depending upon the content of additional alloy elements. After assaying an image of the microstructure of each specimen prepared in Preparative Example 13 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0126] As a result, it was confirmed that, if 0.5 wt.% of Co-Ni master alloy is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was small to about 5μm or less. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is about 300μm or more, thus coarsening too much. Consequently, the Co-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution formed therein, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to size coarsening may be prevented.

[Example 7]

[0127] Fe-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 14 -

[0128] A specimen of a heat-resistant aluminum alloy having an Fe-Ni homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Fe-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Fe and Ni were used as alloy elements in an amount of 1.5 wt.% for each.

[0129] FIG. 42 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 14, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. It was found from FIG. 42 that the heat-resistant aluminum alloy specimen prepared in Preparative Example 12 has a reinforcing phase in a granular shape with a size of 1 to 30μm.

[0130] FIG. 43 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 14, using an EPMA. It was confirmed that the reinforcing phase in the facet shape shown in FIG. 42 is an Fe-Ni homogeneous solid solution.

[0131] Further, in order to assay high temperature stability of the Fe-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 14 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 44.

[0132] As shown in FIG. 44, the reinforcing phase composed of the Fe-Ni homogeneous solid solution exhibited a reinforcing phase in the same granular shape as the microstructure shown in FIG. 42 as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Fe-Ni homogeneous solid solution reinforcing phase of the Fe-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention is stable even at 300°C.

[0133] FIG. 45 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 14 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 14 to a melting point of aluminum, and casting the treated specimen.

[0134] As shown in FIG. 45, it can be seen that the homogeneous solid solution formed in the Fe-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 9, instead, it maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively select and recycle aluminum as a matrix metal, as well as Fe and Ni as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum alloy is recycled.

- PREPARATIVE EXAMPLE 15 -

[0135] A specimen of a heat-resistant aluminum alloy was prepared by the same procedures as described in Preparative Example 4, except that an Fe-Ni master alloy comprising a relative ratio of Fe:Ni of 50 wt.% to 50 wt.% prepared through Plasma Arc Melting (PAM) was used.

[0136] FIG. 46 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 15, depending upon the content of additional alloy elements. After assaying an image of the microstructure of each specimen prepared in Preparative Example 15 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0137] As a result, it was confirmed that, if 0.5 wt.% of Fe-Ni master alloy is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was small to about 3μm or less. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is about 280μm or more, thus coarsening too much. Consequently, the Fe-Ni homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution formed therein, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to size coarsening may be prevented.

[Example 8]

[0138] Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy

- PREPARATIVE EXAMPLE 16 -

[0139] A specimen of a heat-resistant aluminum alloy having a Cu-Mn homogeneous solid solution reinforcing phase (hereinafter, referred to as 'Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy') was prepared by the same procedures as described in Preparative Example 1, except that Cu and Mn were used as alloy elements in an amount of 1.5 wt.% for each.

[0140] FIG. 47 is an optical micrograph illustrating observed results of the microstructure of a specimen prepared in Preparative Example 16, wherein the specimen was ground using SiC Emery paper #200, 400, 600, 800, 1000, 1500 and 2400 and then finely ground using 1μm Al_2O_3 powder, followed by observation of a structure of the specimen through an optical microscope. It was found from FIG. 47 that the heat-resistant aluminum alloy specimen prepared in Preparative Example 12 has a reinforcing phase in a crystal interface shape with a size of 1 to

10μm.

[0141] FIG. 48 is a photograph illustrating mapping results of the microstructure of the specimen prepared in Preparative Example 16, using an EPMA. It was confirmed that the reinforcing phase in the crystal interface shape shown in FIG. 48 is a Cu-Mn homogeneous solid solution.

[0142] Further, in order to assay high temperature stability of the Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention, the specimen prepared in Preparative Example 16 was first heated to 300°C for 200 hours, followed by observation of the microstructure of the heated specimen through an optical microscope. The observed results are shown in FIG. 49.

[0143] As shown in FIG. 49, the reinforcing phase composed of the Cu-Mn homogeneous solid solution exhibited a reinforcing phase in the same crystal interface shape as the microstructure shown in FIG. 47, as compared to the existing intermetallic compound that becomes coarse or undergoes phase decomposition in an aluminum matrix at a high temperature. Also, since coarsening or phase decomposition of the reinforcing phase was not observed, it can be understood that the Cu-Mn homogeneous solid solution reinforcing phase of the Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention is stable even at 300°C. Consequently, the Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy may increase the limits of heat resistance of an automobile engine, thus improving fuel efficiency.

[0144] FIG. 50 is an optical micrograph illustrating observed results of the microstructure of a specimen obtained after remelting the specimen prepared in Preparative Example 16 then casting the same. Here, a cast specimen after remelting is substantially obtained by remelting the specimen prepared in Preparative Example 16 to a melting point of aluminum, and casting the treated specimen.

[0145] As shown in FIG. 50, it can be seen that the homogeneous solid solution formed in the Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention never coarsened nor was decomposed even during remelting, as expected from the binary alloy phase diagram shown in FIG. 10, instead, it maintained the reinforcing phase. Moreover, it may be presumed that, if using the foregoing characteristics, the foregoing heat-resistant aluminum alloy may be effectively utilized to actively screening and recycle aluminum as a matrix metal, as well as Cu and Mn as alloy elements to eco-friendly Virgin levels thereof, in the case where the heat-resistant aluminum is recycled.

- PREPARATIVE EXAMPLE 17 -

[0146] A specimen of a heat-resistant aluminum alloy was prepared by the same procedures as described in Preparative Example 4, except that a Cu-Mn master alloy comprising a relative ratio of Cu:Mn of 50 wt.% to 50 wt.% prepared through Plasma Arc Melting (PAM) was used.

[0147] FIG. 51 shows a graph of average sizes of homogeneous solid solutions of respective specimens prepared in Preparative Example 17, depending upon the content of additional alloy elements. After assaying an image of the microstructure of each specimen prepared in Preparative Example 17 through an optical microscope, an average size of homogeneous solid solutions with different contents of alloy elements was determined from the assayed image using an image analyzer.

[0148] As a result, it was confirmed that, if 0.5 wt.% of Cu-Mn master alloy is added, an amount of the formed homogeneous solid solution is decreased and a size thereof was small to about 2μm or less. On the other hand, when the added amount is 10 wt.% or more, a size of the homogeneous solid solution is about 250μm or more, thus coarsening too much. Consequently, the Cu-Mn homogeneous solid solution reinforcing type heat-resistant aluminum alloy according to the present invention may include a sufficient amount of homogeneous solid solution, to thereby exhibit favorable alloy effects, in the case where a content of each alloy element added to aluminum ranges from 0.5 wt.% to 10 wt.%. Moreover, problems such as segregation due to size coarsening may be prevented.

[0149] As is apparent from the foregoing, the heat-resistant aluminum alloy according to the present invention is characterized in that a homogeneous solid solution reinforcing phase composed of two types of alloy elements, which have no solvus line with respect to aluminum as a matrix metal while forming a homogeneous solid solution reinforcing phase, does not react with aluminum even at a high temperature of 300°C or higher, which in turn, does not coarsen or undergoes phase decomposition. Accordingly, remarkably improved heat resistance may be attained. Also, when recycling the used alloy elements as well as aluminum, these may be screened based on a difference in melting points or specific gravities thereof after remelting, therefore, may be eco-friendly applied in various fields. Although aluminum could not yet be used at a temperature of 200°C or higher in some applications, for example, automobiles, diesel engines, aircraft parts, etc., due to limitations of heat-resistant aluminum, the present invention may be applicable to the foregoing applications and, in particular, raise the limit of heat resistance of the existing automobile engine, to thereby pursue improvement in fuel efficiency.

[0150] Moreover, it is possible to prevent a homogeneous solid solution reinforcing phase formed using a proper amount of alloy elements from coarsening or segregation thereof.

[0151] Although the preferred embodiments of the present invention have been disclosed for illustrative purposes, those skilled in the art will appreciate that various modifications, additions and substitutions are possible, without departing from the scope and spirit of the invention as disclosed in the accompanying claims.

Claims

1. A heat-resistant aluminum alloy, comprising aluminum and two types of alloy elements which form a homogeneous solid solution and are combined to form a homogeneous solid solution reinforcing phase.

2. The alloy according to claim 1, wherein the alloy elements are contained in an amount of 0.5 to 10 wt.% relative to aluminum.

3. The alloy according to claim 2, wherein, one of the two alloy elements is contained in an amount of 10 to 90 wt.% while the other is contained in an amount of 90 to 10 wt.%.

4. The alloy according to claim 3, wherein the two alloy elements are chromium (Cr) and tungsten (W).

5. The alloy according to claim 4, wherein, in the case where the homogeneous solid solution reinforcing phase is composed of Cr and W, it maintains a stable single phase at a temperature up to 1800°C and has a size of 1 to 200μm.

6. The alloy according to claim 3, wherein the two alloy elements are cupper (Cu) and nickel (Ni).

7. The alloy according to claim 6, wherein, in the case where the homogeneous solid solution reinforcing phase is composed of Cu and Ni, it is stable at a temperature up to 873°C and has a crystal interface shape with a size of 1 to 50μm.

8. The alloy according to claim 3, wherein the two alloy elements are iron (Fe) and chromium (Cr).

9. The alloy according to claim 8, wherein, in the case where the homogeneous solid solution reinforcing phase is composed of Fe and Cr, it maintains a stable single phase at a temperature up to 1500°C and has a facet shape with a size of 1 to 60μm.

10. The alloy according to claim 3, wherein the two alloy elements are iron (Fe) and manganese (Mn).

11. The alloy according to claim 10, wherein the homogeneous solid solution reinforcing phase has heat resistance at a temperature up to 1245°C and is formed in a facet shape having a size of 1 to 50μm.

12. The alloy according to claim 3, wherein the two alloy elements are manganese (Mn) and vanadium (V).

13. The alloy according to claim 12, wherein the homogeneous solid solution reinforcing phase maintains a stable single phase at a temperature up to 1245°C and has a facet shape with a size of 1 to 100μm.

14. The alloy according to claim 3, wherein the two alloy elements are cobalt (Co) and nickel (Ni).

15. The alloy according to claim 14, wherein the homogeneous solid solution reinforcing phase has heat resistance at a temperature up to 1490°C and is formed in a needle-like shape having a size of 1 to 70μm.

16. The alloy according to claim 3, wherein the two alloy elements are iron (Fe) and nickel (Ni).

17. The alloy according to claim 16, wherein the homogeneous solid solution reinforcing phase maintains a stable single phase at a temperature up to 1245°C and has a granular shape with a size of 1 to 30μm.

18. The alloy according to claim 3, wherein the two alloy elements are copper (Cu) and manganese (Mn).

19. The alloy according to claim 18, wherein the homogeneous solid solution reinforcing phase maintains a stable single phase at a temperature up to 873°C and has a size of 1 to 10μm.

20. A method for manufacturing a heat-resistant aluminum alloy, comprising; adding alloy elements to an aluminum melt composed of molten aluminum, and casting the melt after the alloy elements are fused.

21. The method according to claim 20, wherein the alloy elements are Cr and W, which are directly added to the melt or, otherwise, added as a Cr-W master alloy or both of aluminum-Cr master alloy and aluminum-W master alloy to the melt.

22. The method according to claim 20, wherein the alloy elements are Cu and Ni, which are directly added to the melt or, otherwise, added as a Cu-Ni master alloy or both of aluminum-Cu master alloy and aluminum-Ni master alloy to the melt.

23. The method according to claim 20, wherein the alloy elements are Fe and Cr, which are directly added to the melt or, otherwise, added as an Fe-Cr master alloy or both of aluminum-Fe master alloy and aluminum-Cr master alloy to the melt.

24. The method according to claim 20, wherein the alloy elements are Fe and Mn, which are directly added to the melt or, otherwise, added as an Fe-Mn master

alloy or both of aluminum-Fe master alloy and aluminum-Mn master alloy to the melt.

25. The method according to claim 20, wherein the alloy elements are Mn and V, which are directly added to the melt or, otherwise, added as an Mn-V master alloy or both of aluminum-Mn master alloy and aluminum-V master alloy to the melt.

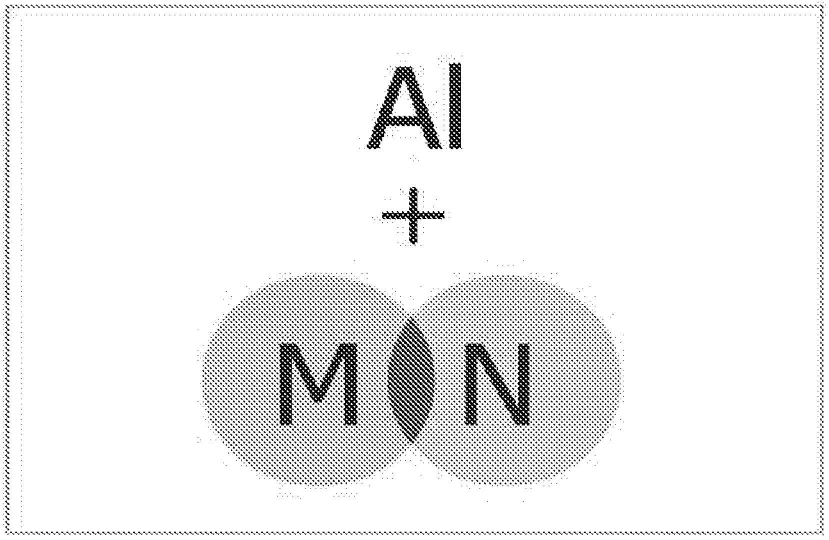
26. The method according to claim 20, wherein the alloy elements are Co and Ni, which are directly added to the melt or, otherwise, added as a Co-Ni master alloy or both of aluminum-Co master alloy and aluminum-Ni master alloy to the melt.

27. The method according to claim 20, wherein the alloy elements are Fe and Ni, which are directly added to the melt or, otherwise, added as an Fe-Ni master alloy or both of aluminum-Fe master alloy and aluminum-Ni master alloy to the melt.

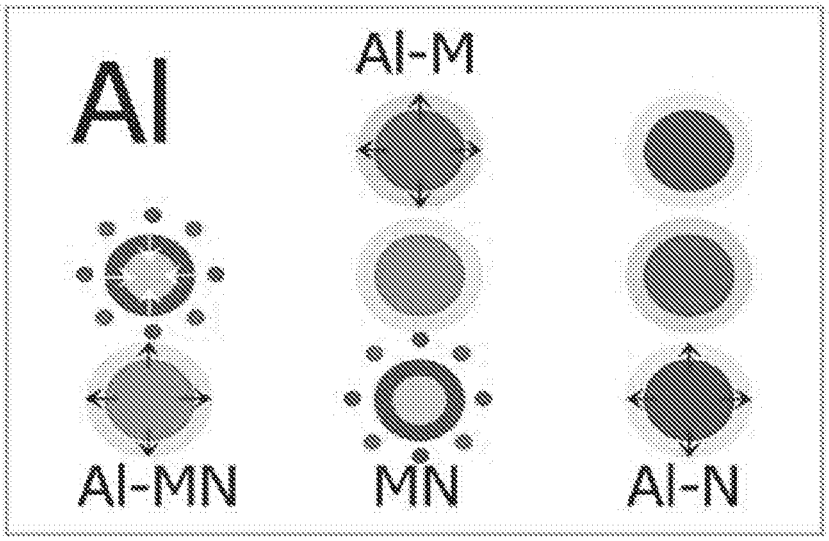
28. The method according to claim 20, wherein the alloy elements are Cu and Mn, which are directly added to the melt or, otherwise, added as a Cu-Mn master alloy or both of aluminum-Cu master alloy and aluminum-Mn master alloy to the melt.

29. The method according to claim 20, wherein the alloy elements are added in an amount of 0.5 to 10 wt.% relative to aluminum.

Fig.1



ADD M AND N TO ALUMINUM MATRIX



HIGH TEMPERATURE BEHAVIOR OF EXISTING HEAT-RESISTANT ALLOY

Fig.2

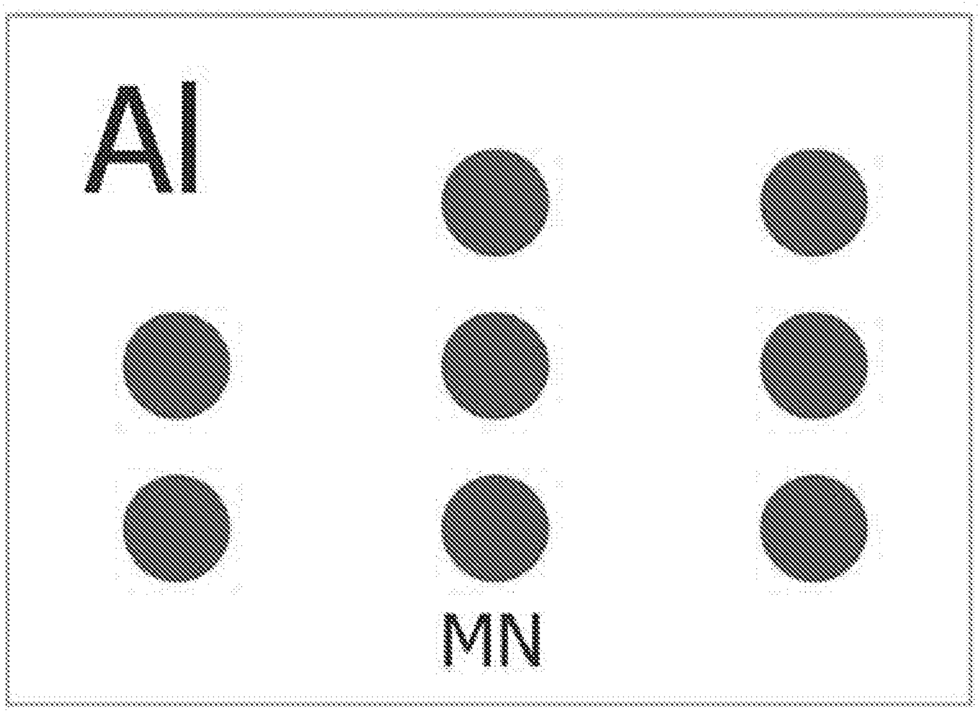
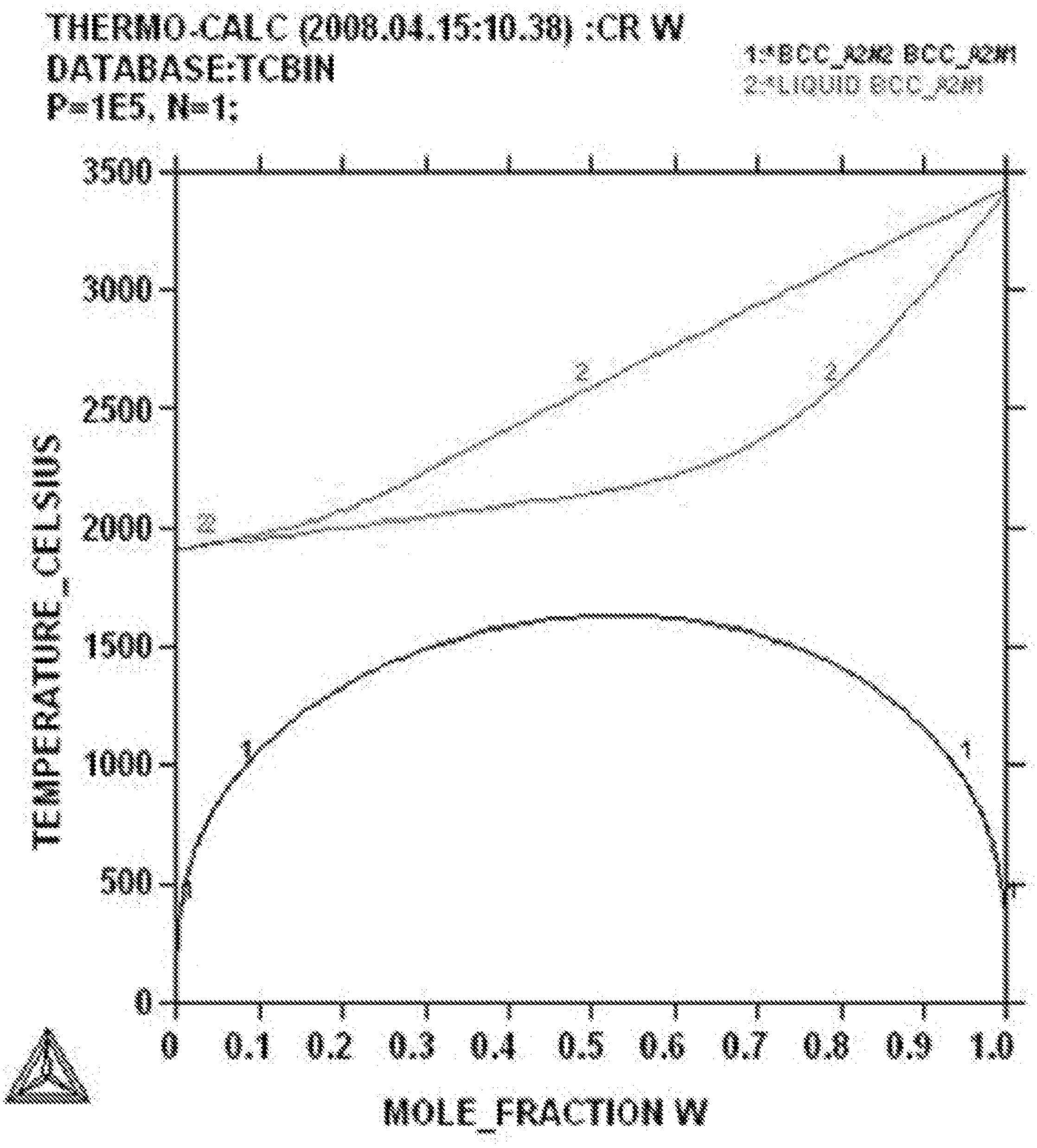


Fig.3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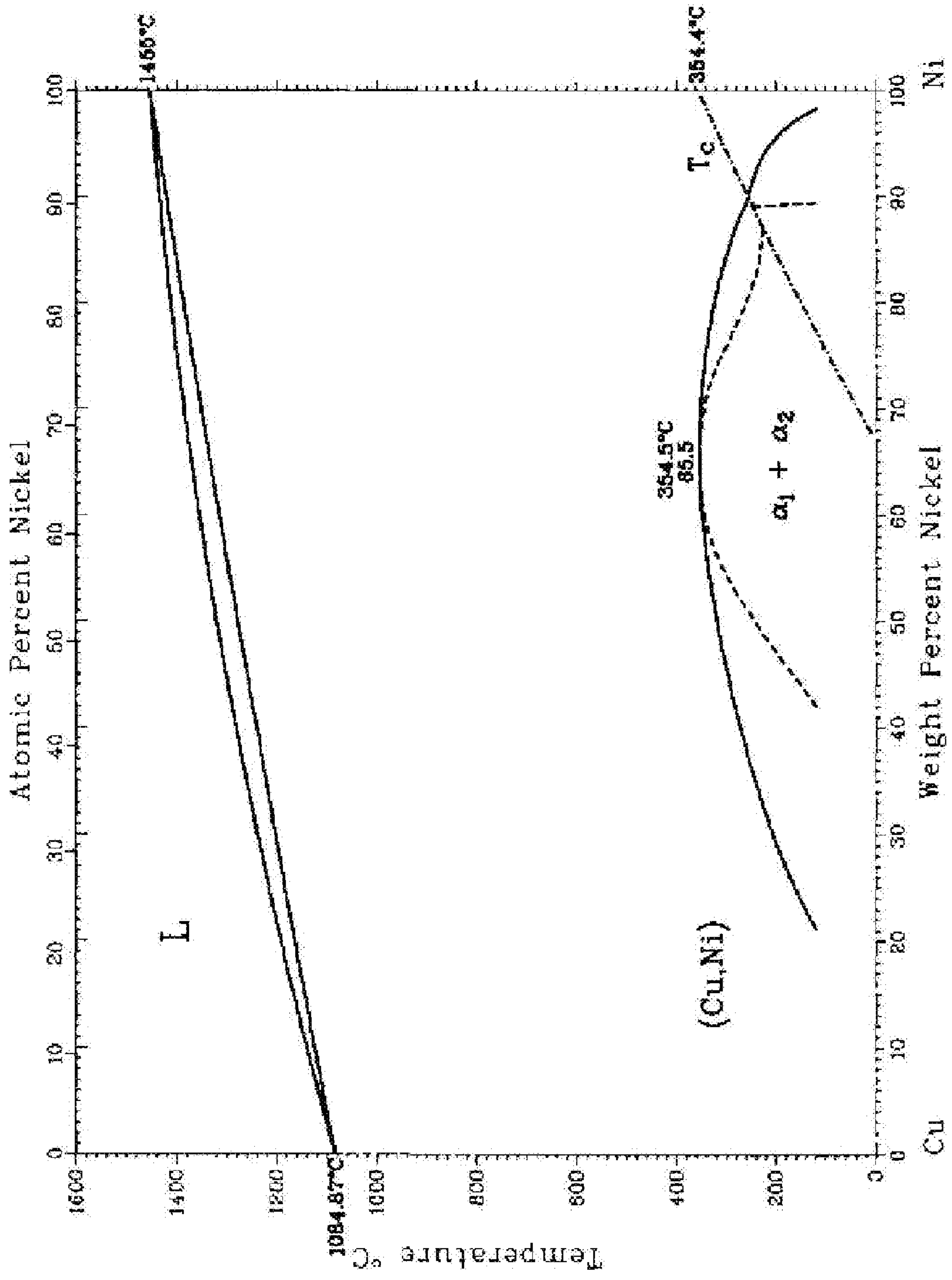
2:*LIQUID BCC_A2#1
TEMPERATURE_CELSIUS
3500
3000
2500
2000
1500
1000
500
0
MOLE_FRACTION W
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1
1
1
1
2
2
2
2

Fig.4


Atomic Percent Nickel
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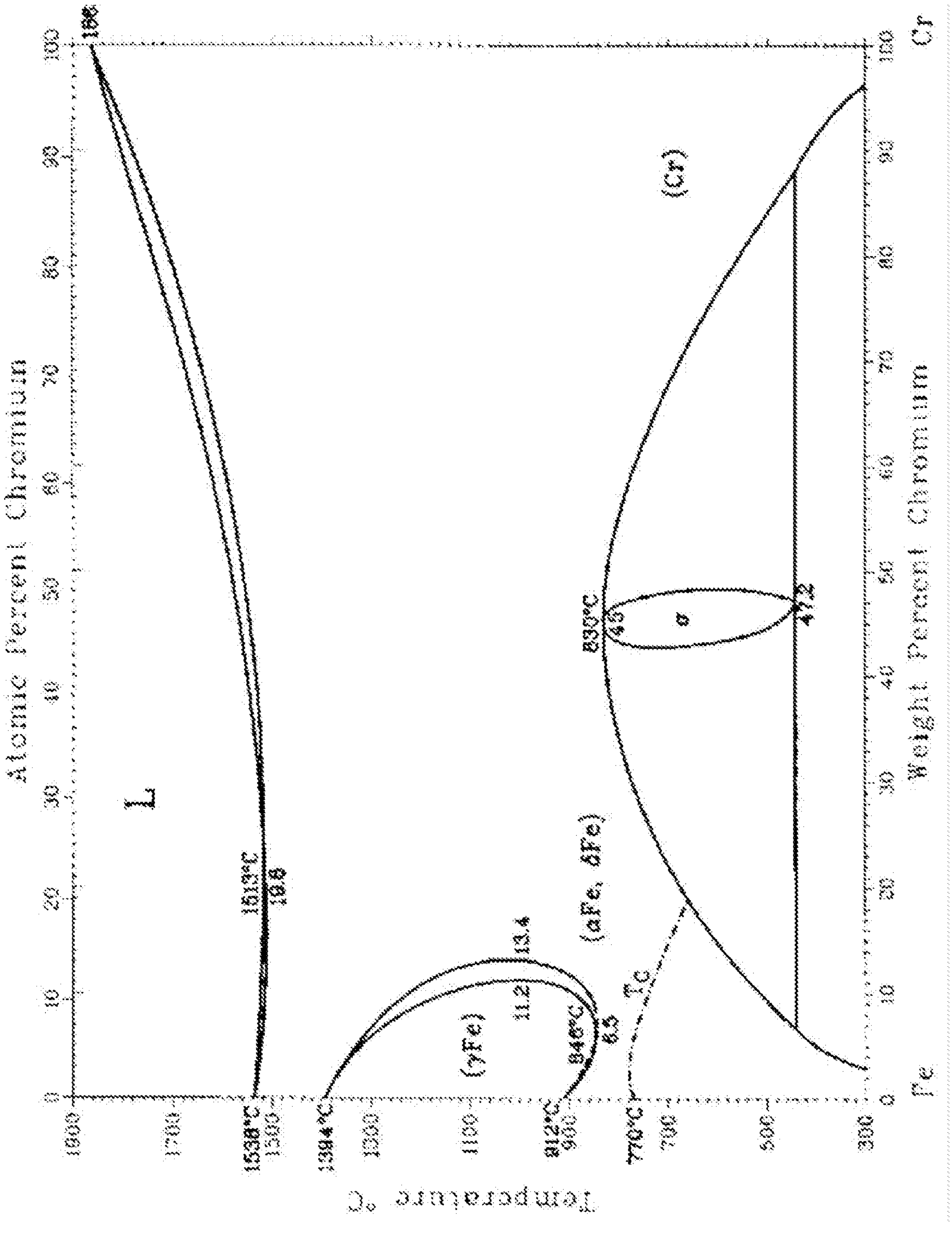
10
20
30
40
50
60
70
80
90
100
1455°C
354.4°C
L
T$_c$
354.5°C
65.5
$\alpha_1 + \alpha_2$
(Cu,Ni)
1084.87°C
Temperature °C
1600
1400
1200
1000
800
600
400
200
0
Cu
Ni
Weight Percent Nickel
0
10
20
30
40
50
60
70
80
90
100

Fig.5


Atomic Percent Chromium
Weight Percent Chromium
Temperature °C
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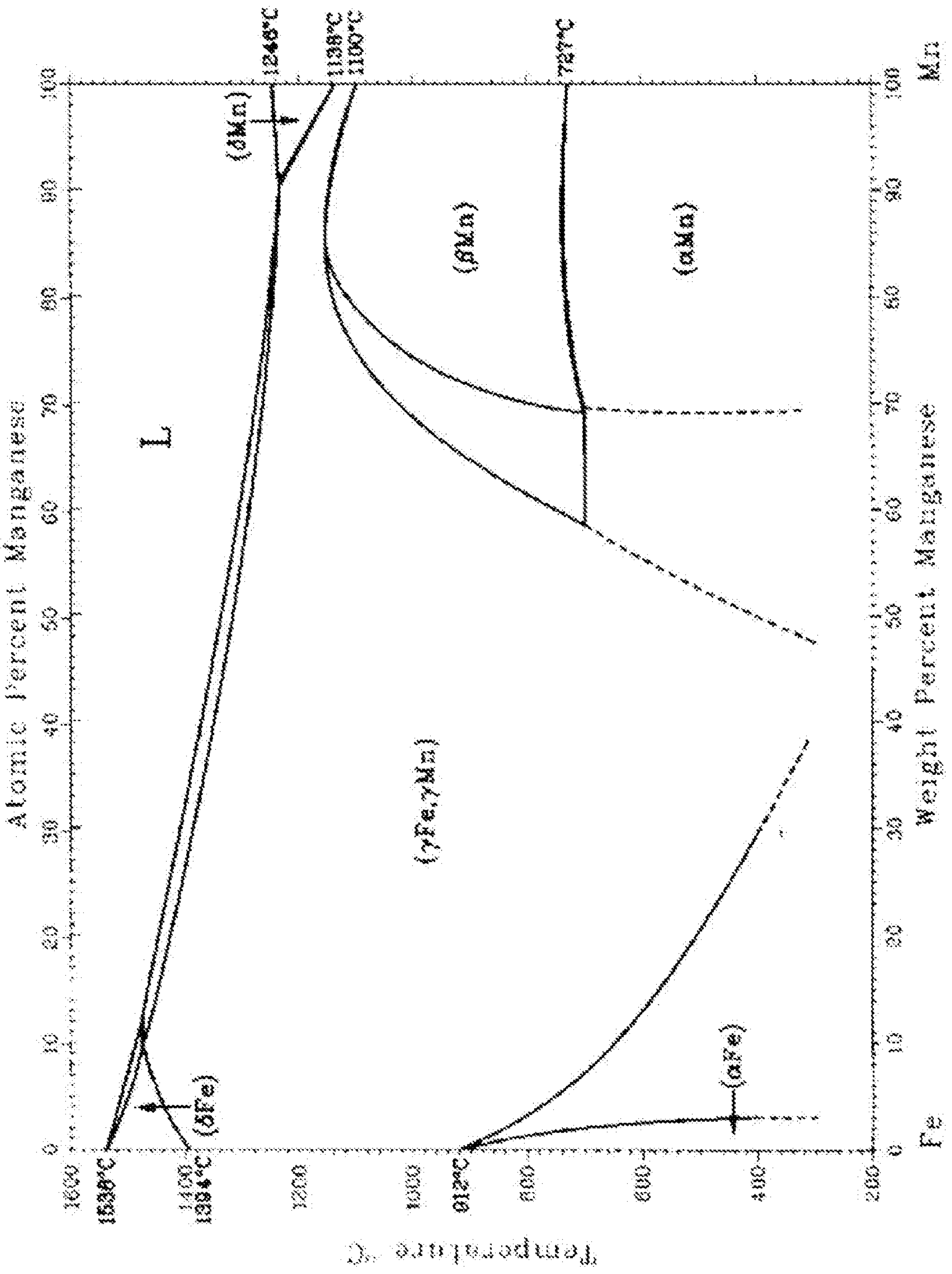
1700
1538°C
1500
1394°C
1300
1100
912°C
900
770°C
700
500
300
0
10
20
30
40
50
60
70
80
90
100
Fe
Cr
186
L
1513°C
18.8
(γFe)
13.4
11.2
846°C
6.5
(αFe, δFe)
Tc
(Cr)
830°C
45
σ
47.2

Fig.6


Atomic Percent Manganese
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20
30
40
50
60
70
80
90
100
Weight Percent Manganese
Fe
Mn
Temperature °C
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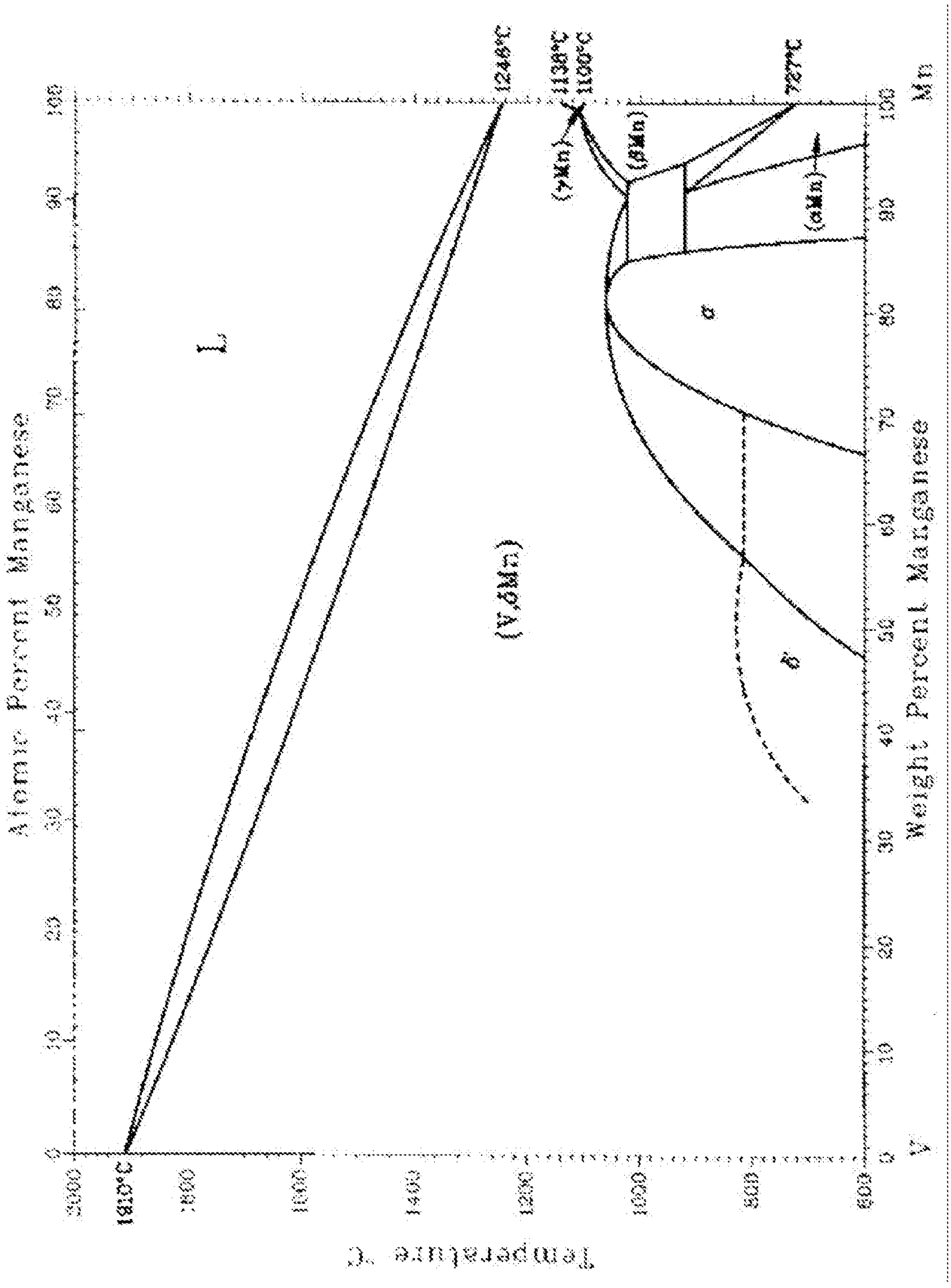
1400
1200
1000
800
600
400
200
1538°C
1394°C
912°C
1246°C
1138°C
1100°C
727°C
L
(δFe)
(γFe,γMn)
(αFe)
(δMn)
(βMn)
(αMn)

Fig.7


Atomic Percent Manganese
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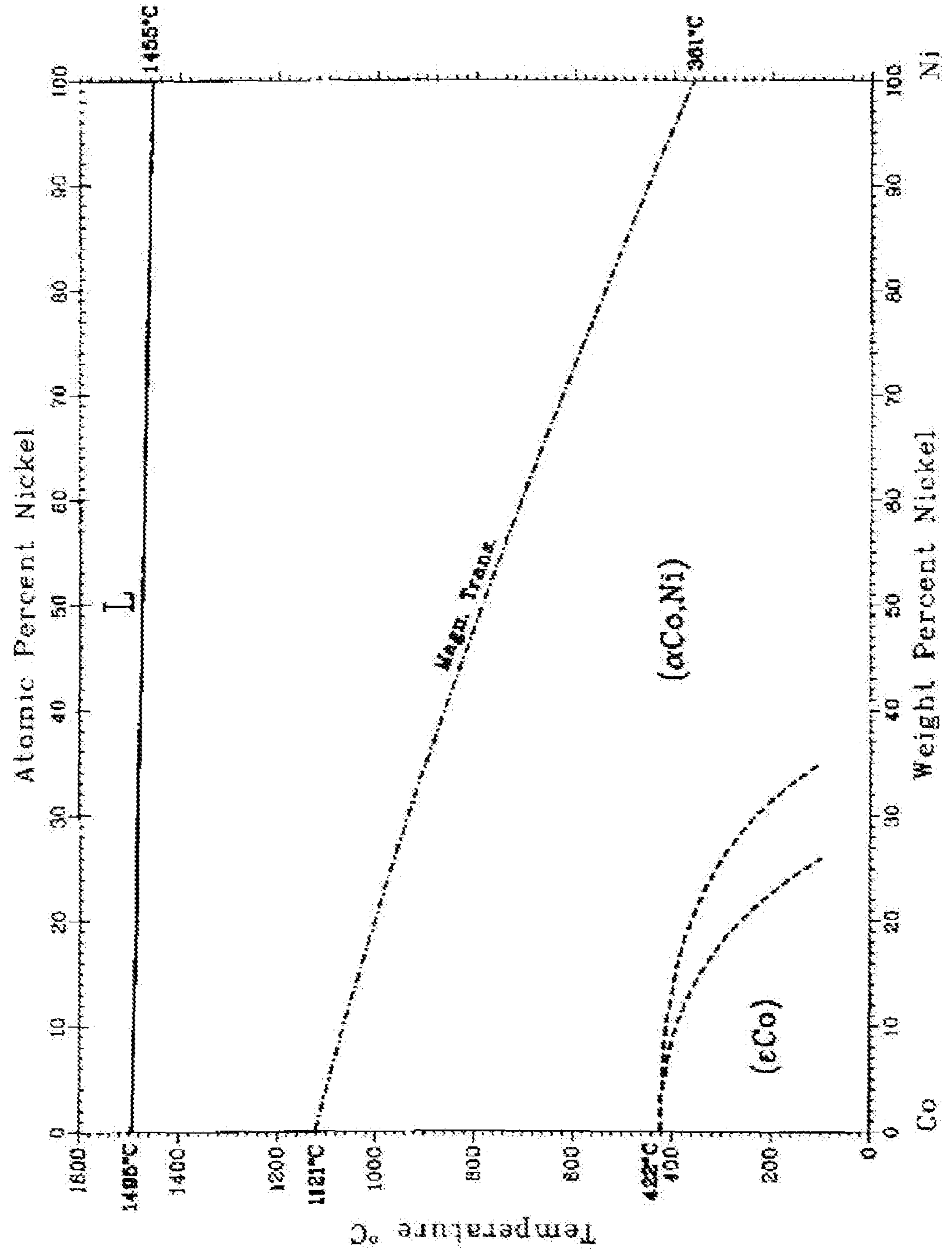
20
30
40
50
60
70
80
90
100
Temperature °C
2000
1800
1600
1400
1200
1000
800
600
1910°C
1246°C
1138°C
1100°C
727°C
L
(V,δMn)
(γMn)
(βMn)
(αMn)
σ
δ'
V
Mn
Weight Percent Manganese

Fig.8


Atomic Percent Nickel
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20
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40
50
60
70
80
90
100
1455°C
361°C
L
Magn. Trans.
(αCo,Ni)
(εCo)
Temperature °C
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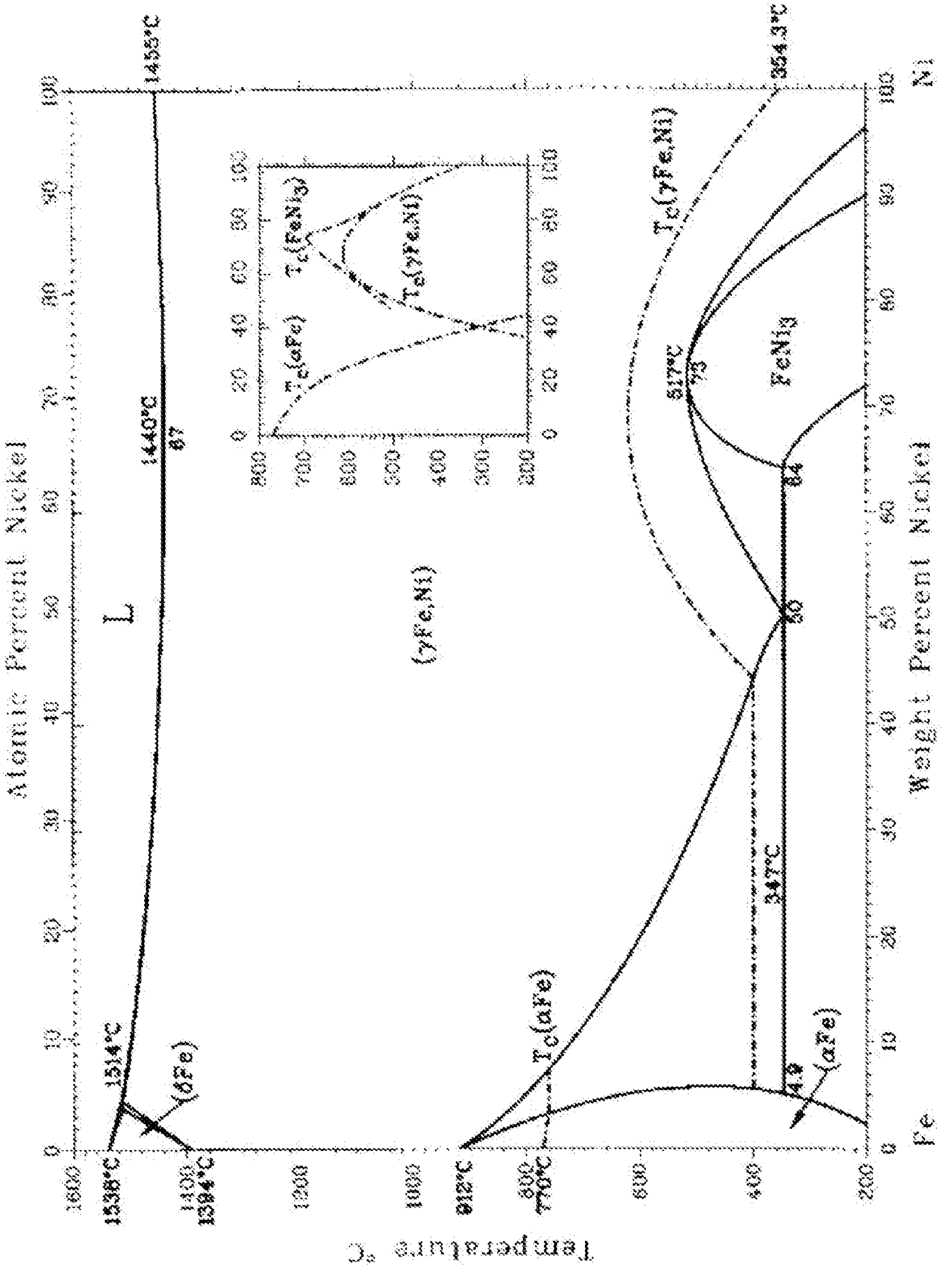
1495°C
1400
1200
1121°C
1000
800
600
422°C
400
200
0
Co
Ni
Weight Percent Nickel

Fig.9


Atomic Percent Nickel
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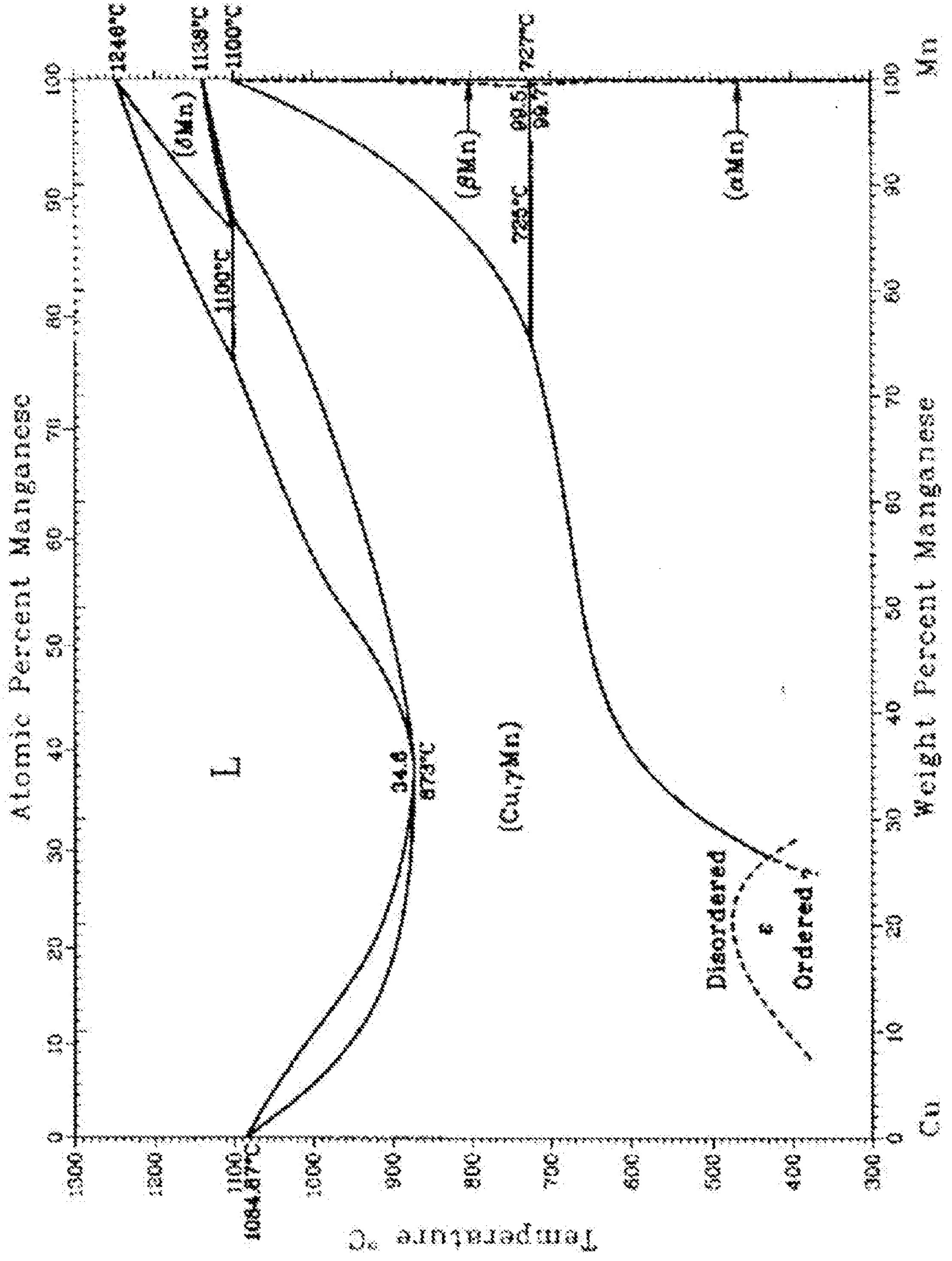
10
20
30
40
50
60
70
80
90
100
1455°C
1440°C
67
L
(γFe,Ni)
1514°C
(δFe)
1538°C
1394°C
912°C
770°C
T_c(αFe)
T_c(γFe,Ni)
354.3°C
517°C
73
FeNi$_3$
64
50
347°C
4.9
(αFe)
Temperature °C
1600
1400
1200
1000
800
600
400
200
Weight Percent Nickel
Fe
Ni
T_c(αFe)
T_c(FeNi$_3$)
T_c(γFe,Ni)
800
700
600
500
400
300
200

Fig.10


Atomic Percent Manganese
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10
20
30
40
50
60
70
80
90
100
1246°C
1138°C
1100°C
727°C
(δMn)
1100°C
(βMn)
725°C
99.5
99.7
(αMn)
L
34.6
873°C
(Cu,γMn)
Disordered
ε
Ordered
γ
Temperature °C
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1200
1100
1000
900
800
700
600
500
400
300
1084.87°C
Weight Percent Manganese
Cu
Mn

Fig.11

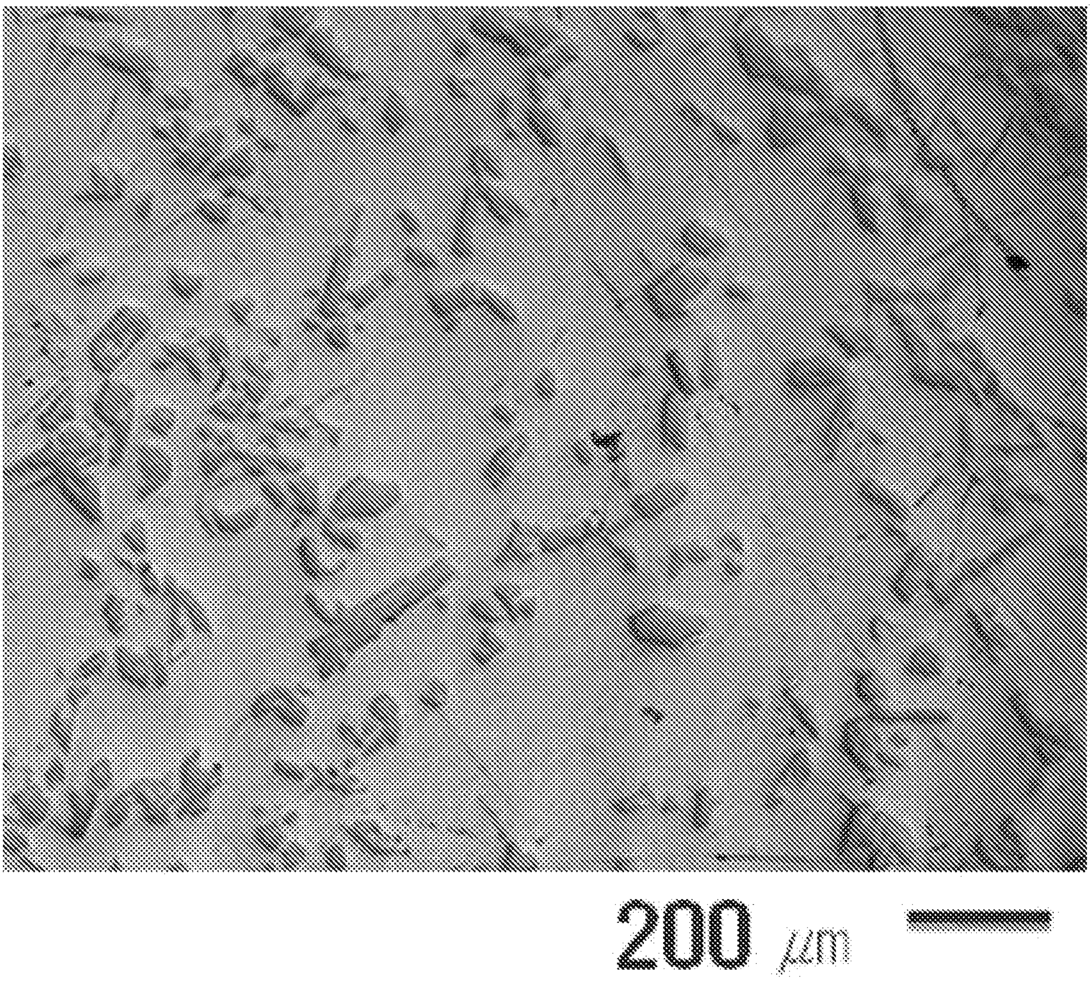


Fig.12

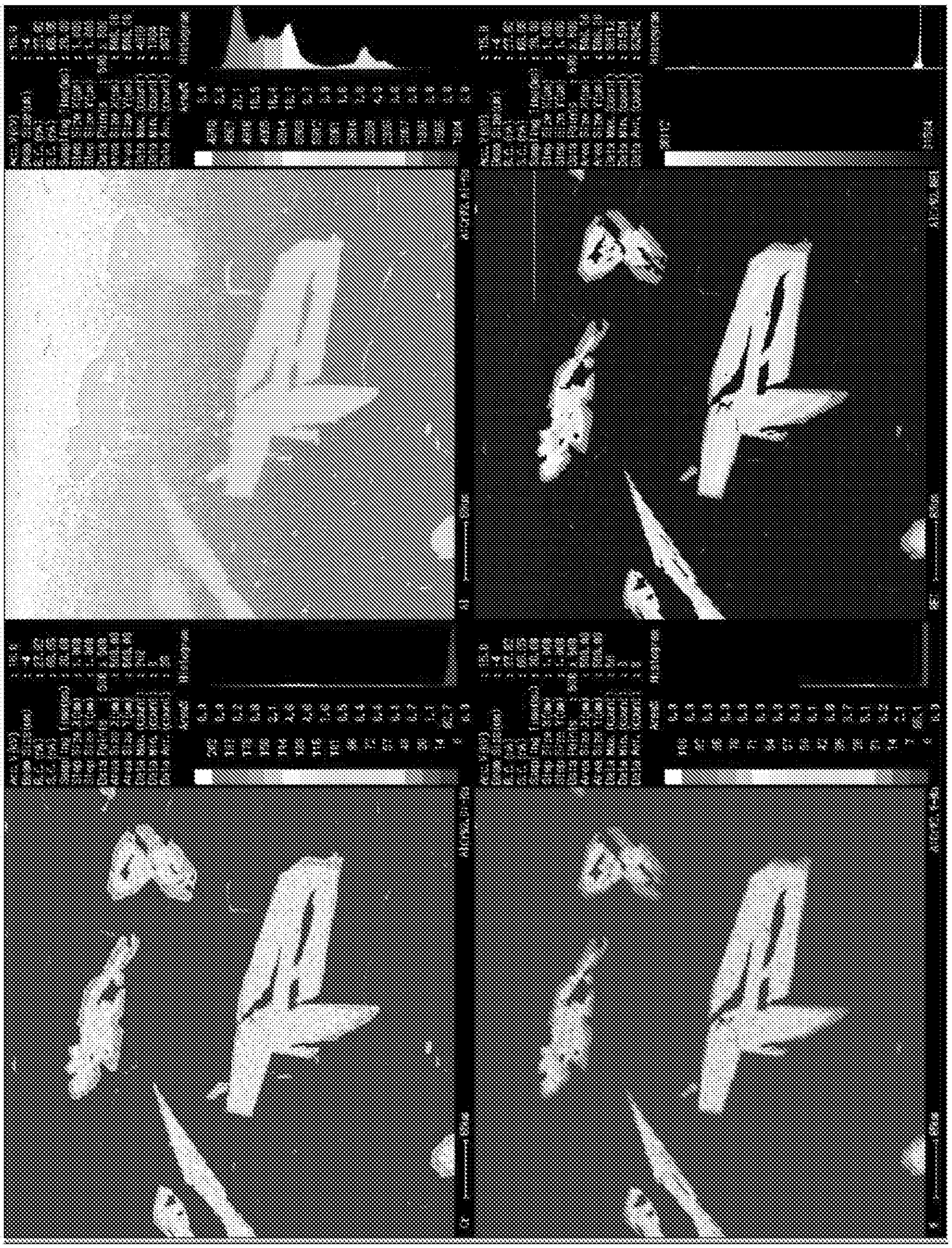


Fig.13

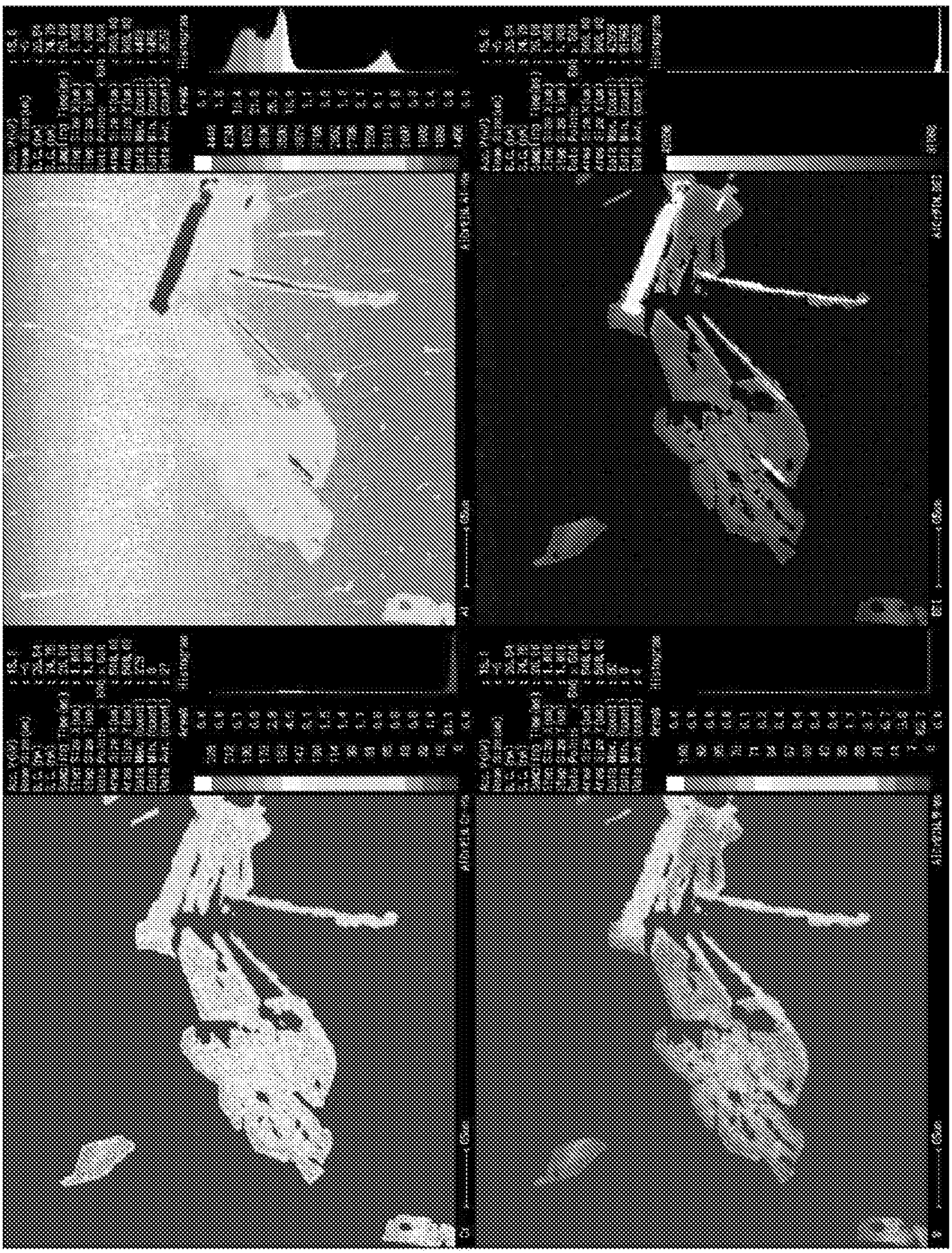


Fig.14

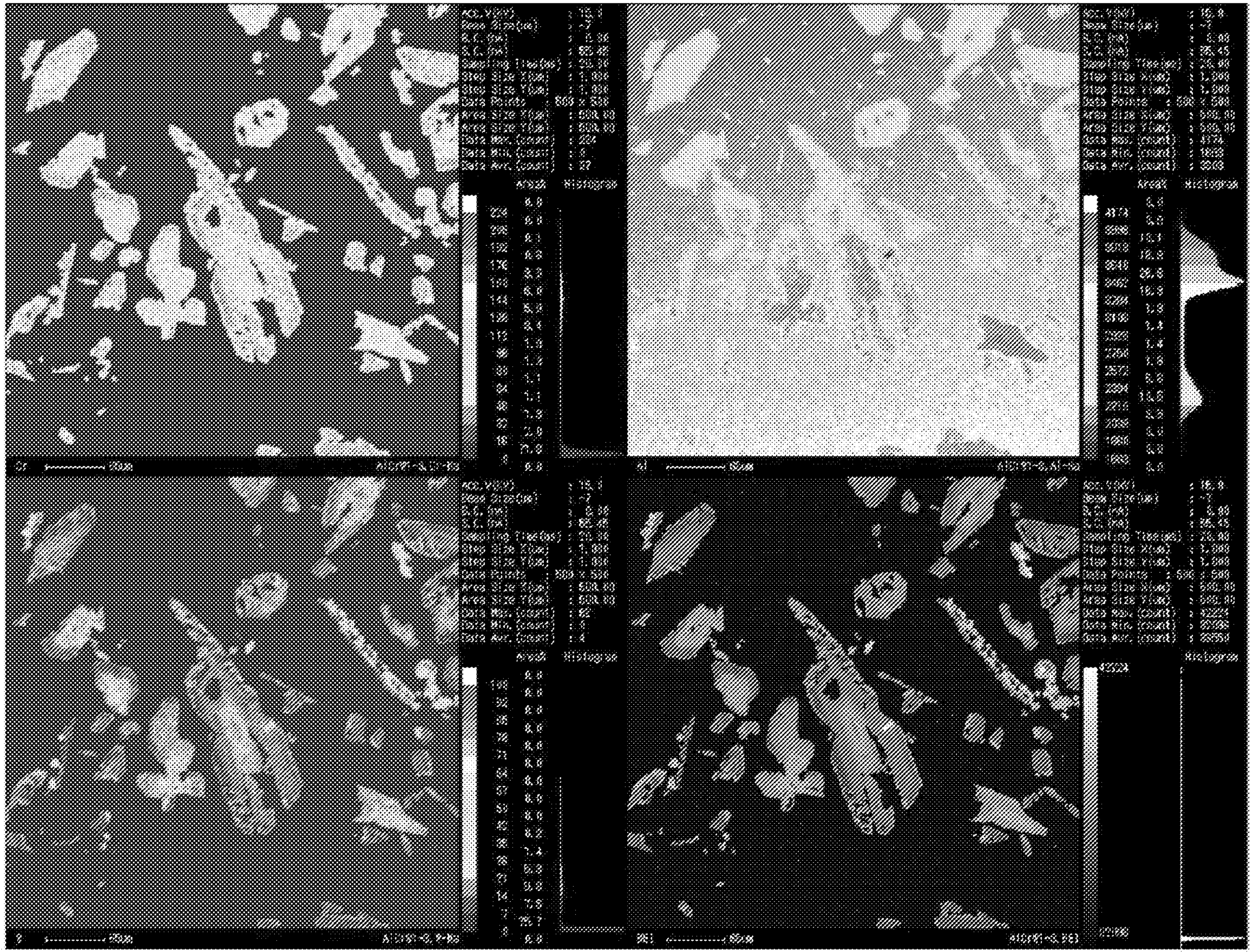


Fig.15

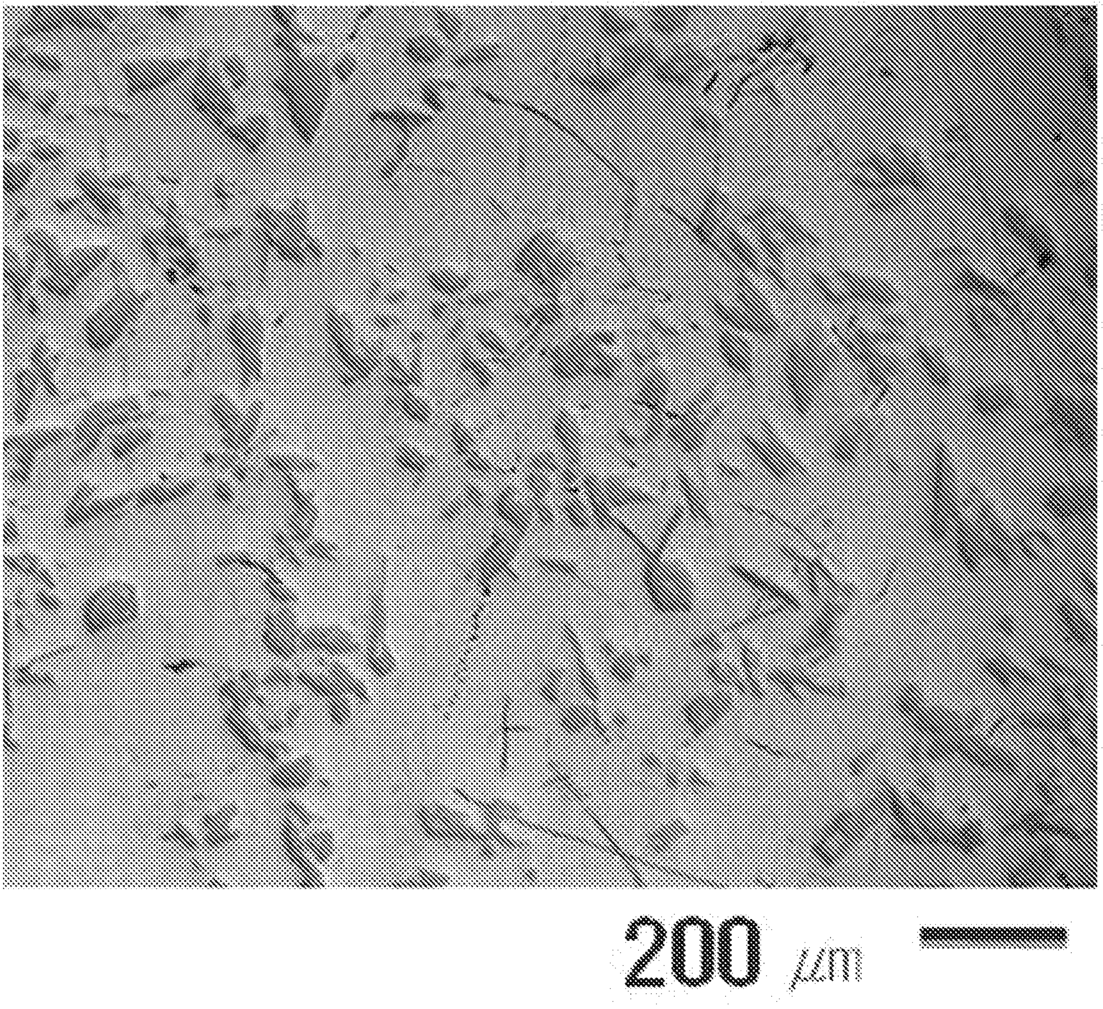


Fig.16

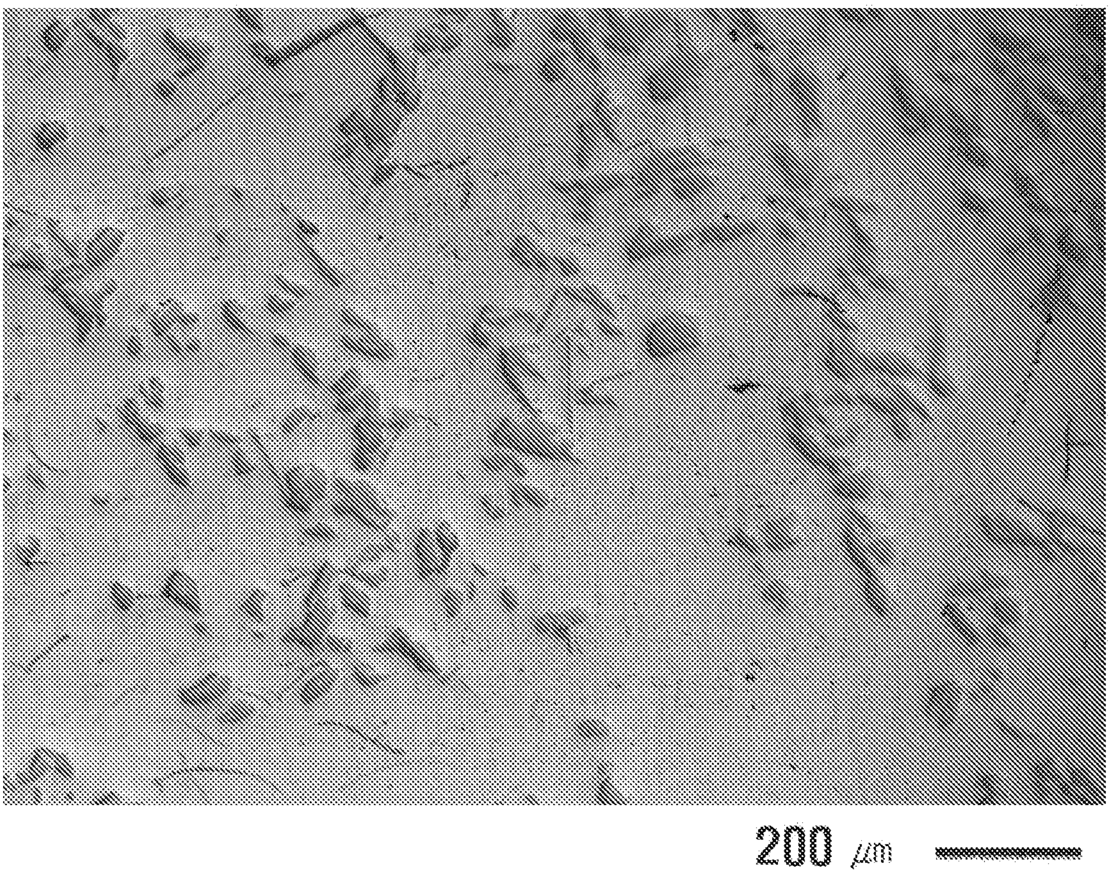
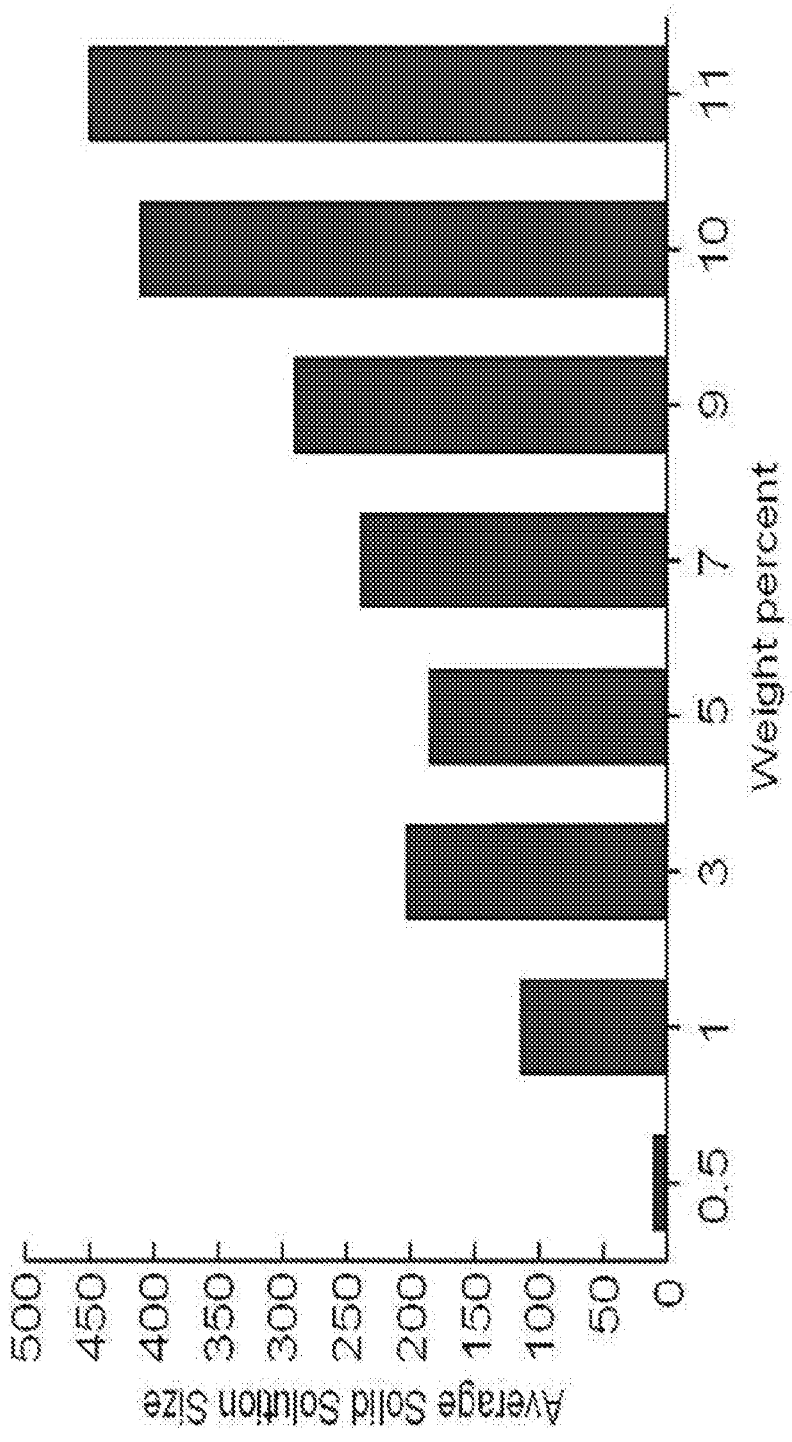


Fig.17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3
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7
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10
11
Weight percent

Fig.18

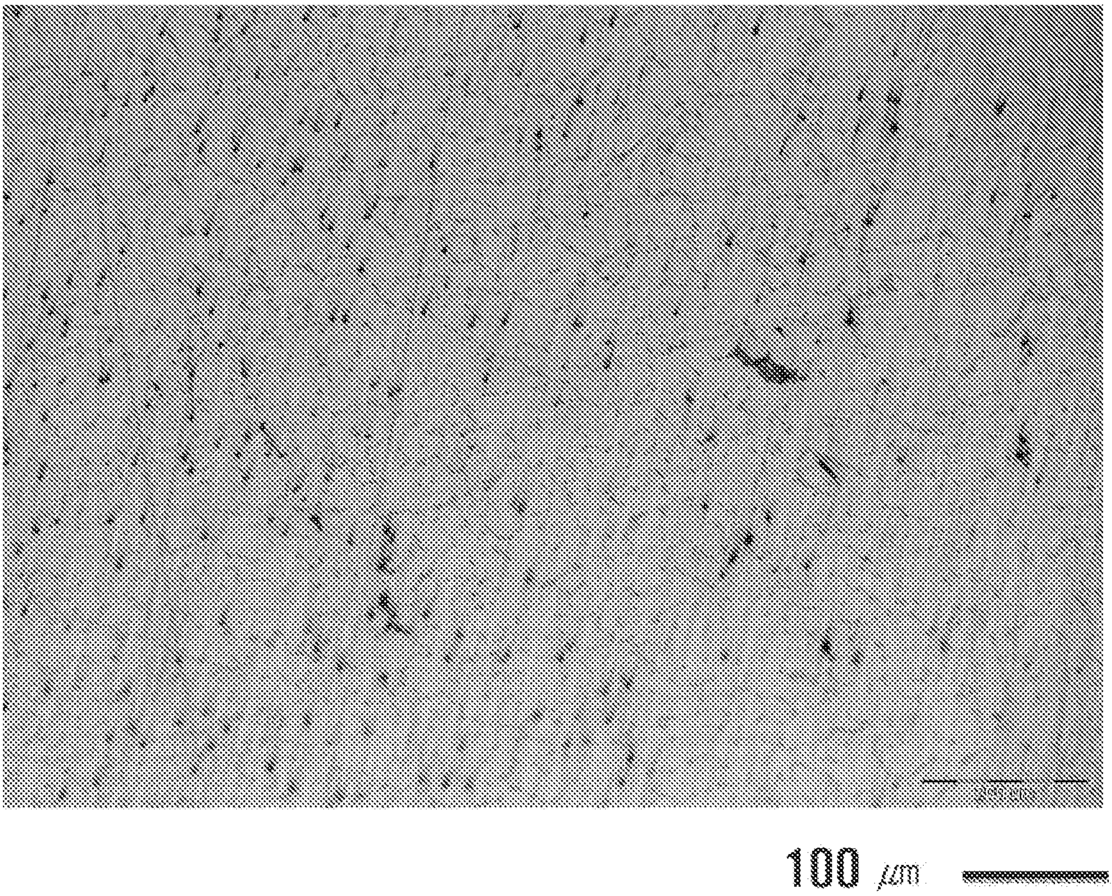


Fig.19

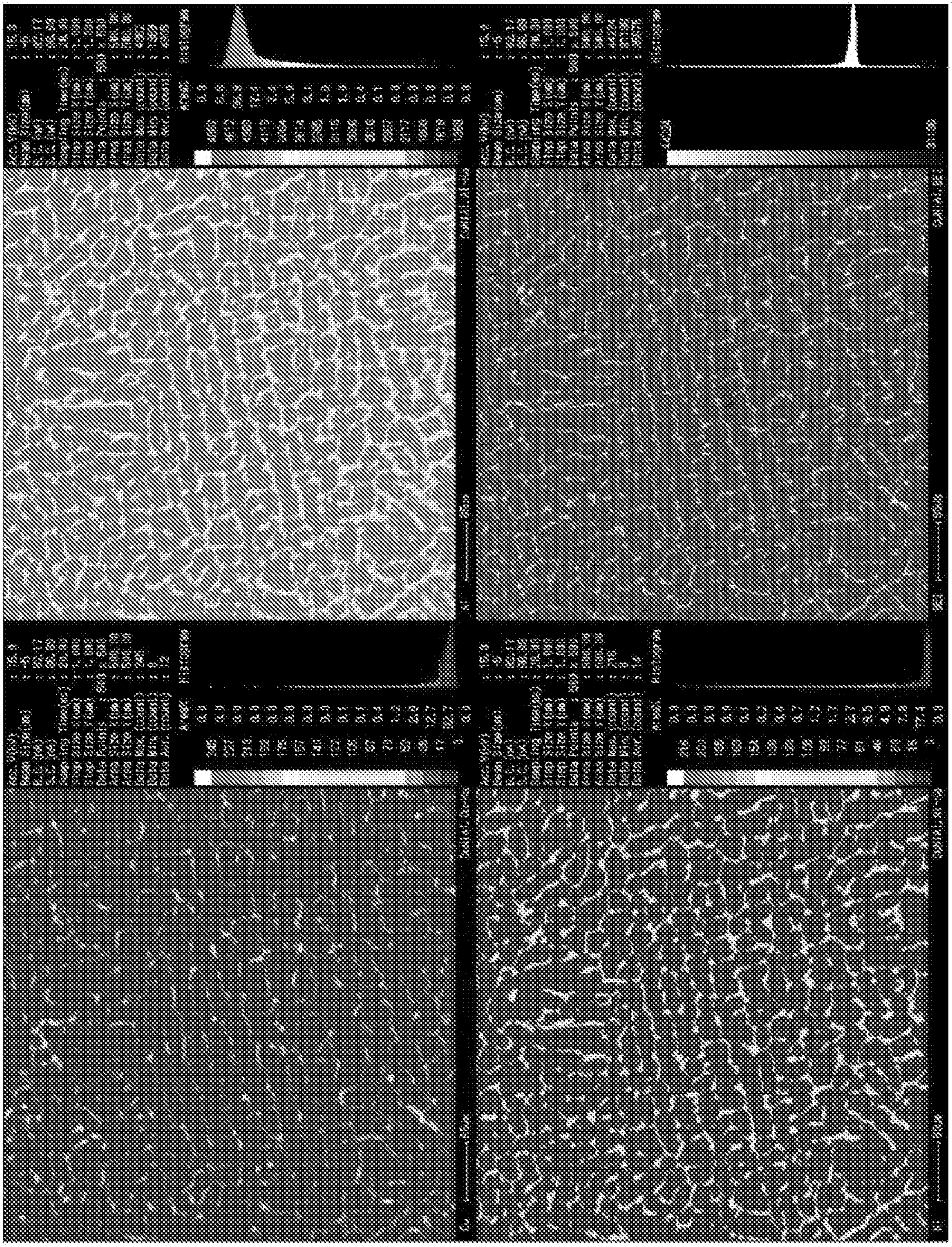


Fig.20

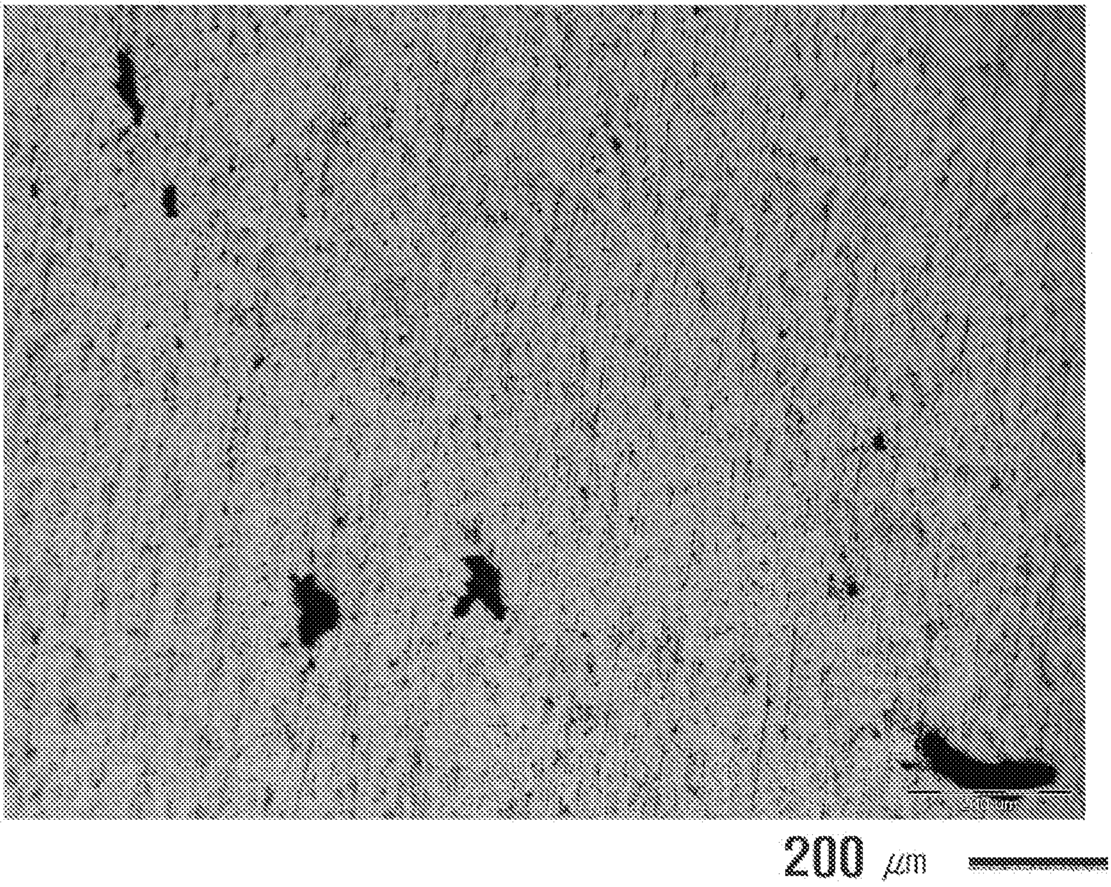


Fig.21

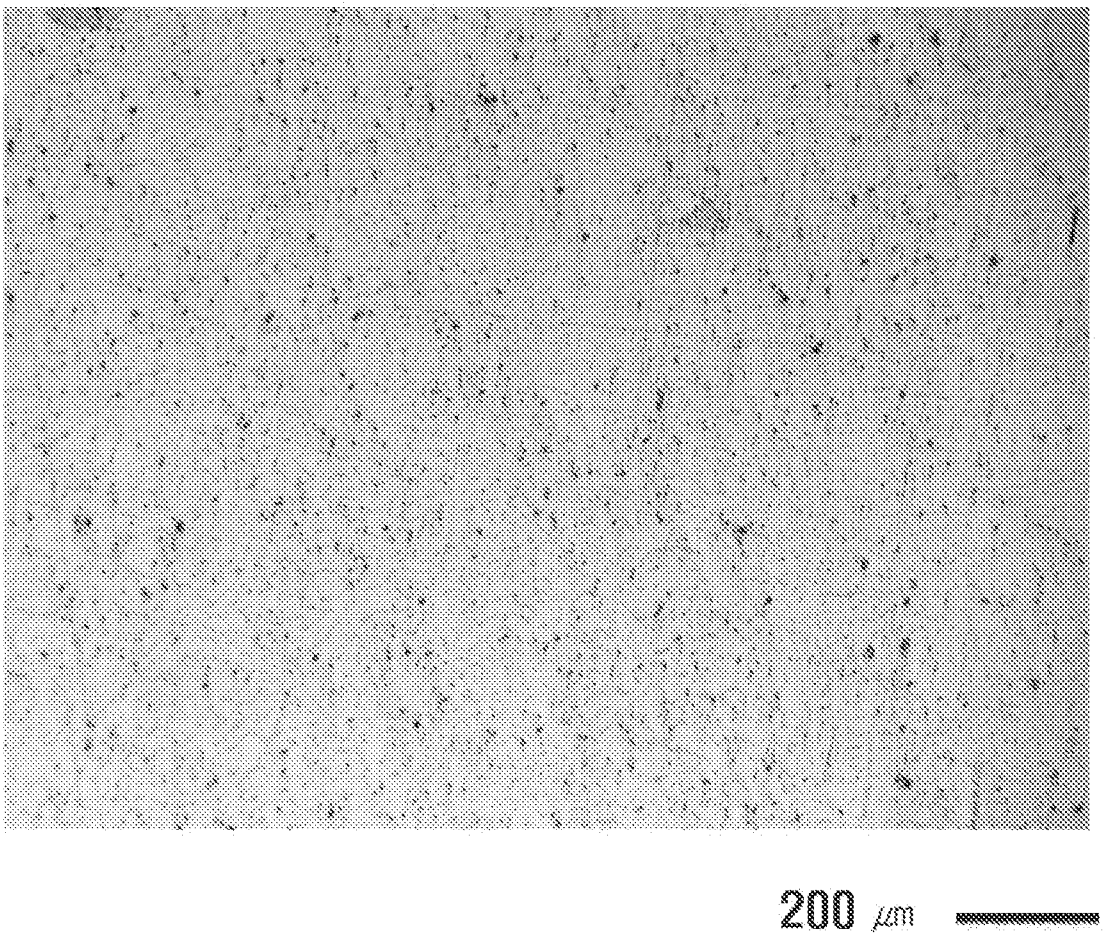
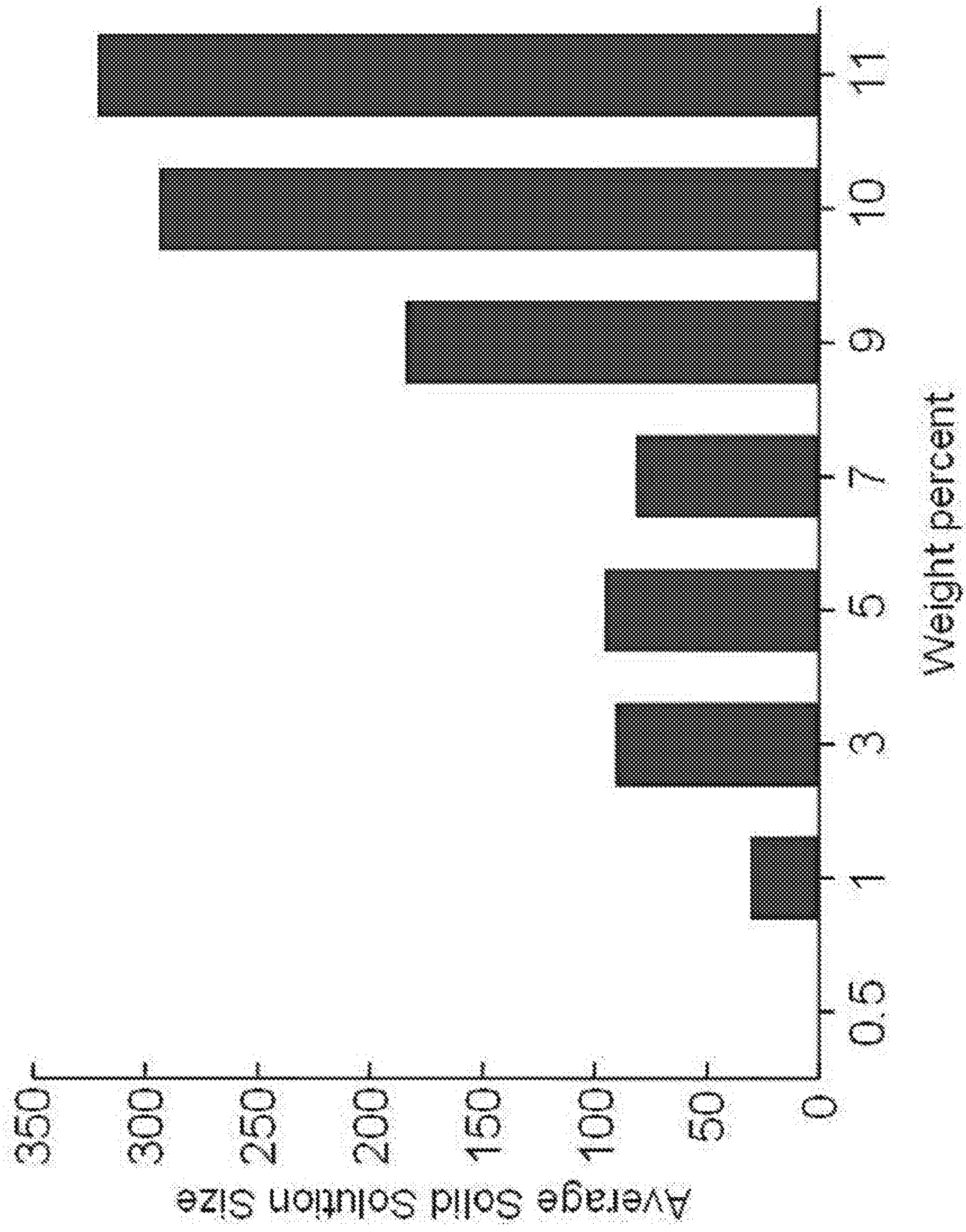


Fig.22


Average Solid Solution Size
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Weight percent
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1
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10
11

Fig.23

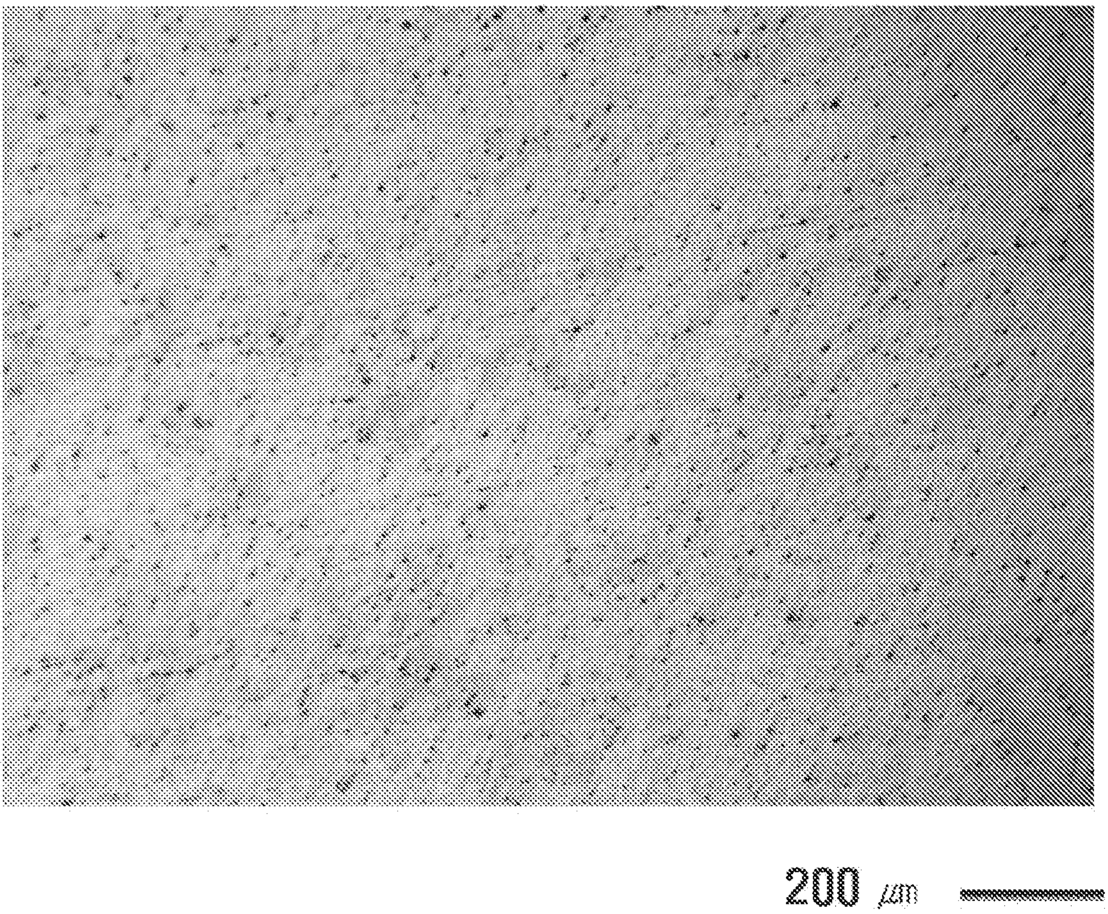


Fig.24

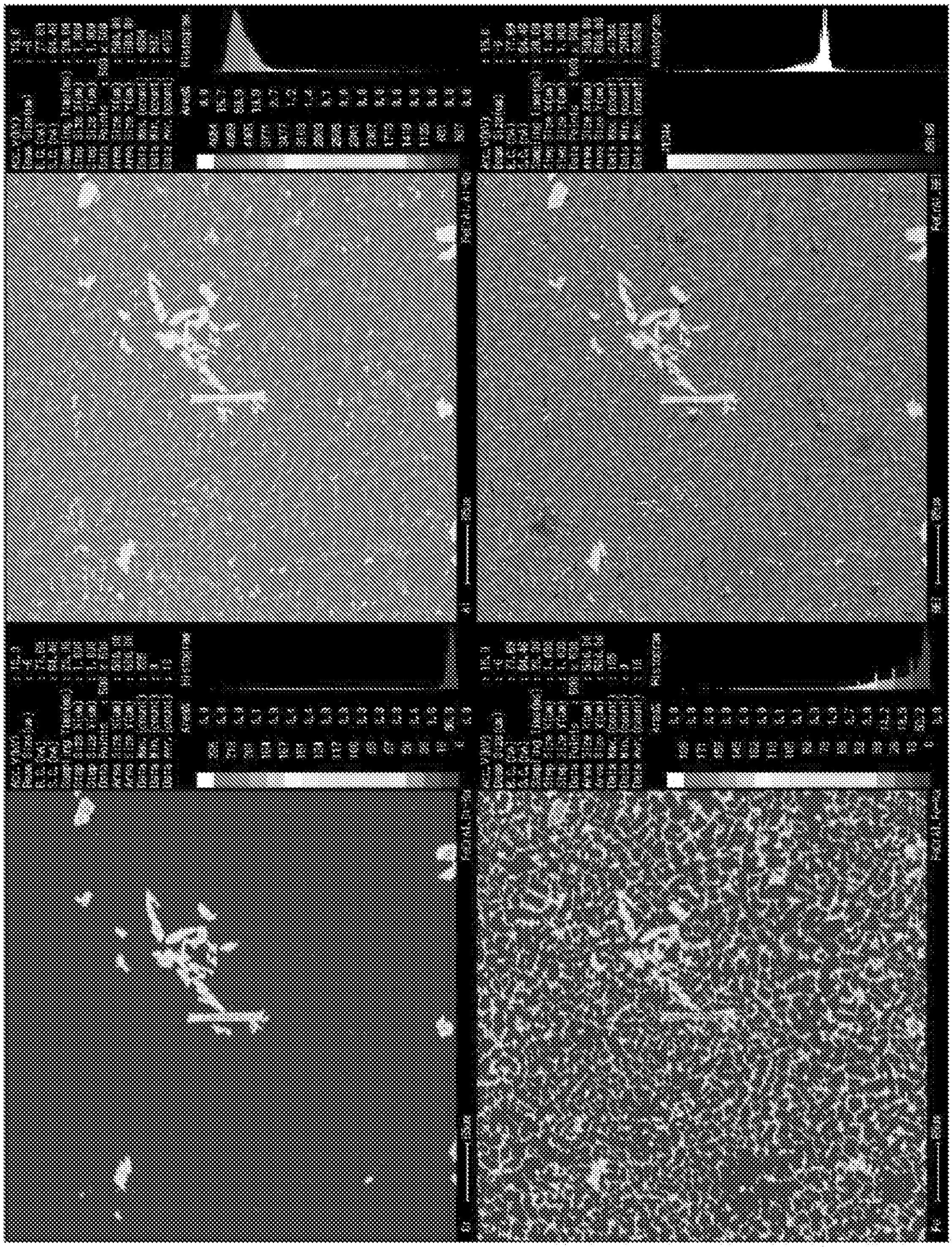


Fig.25

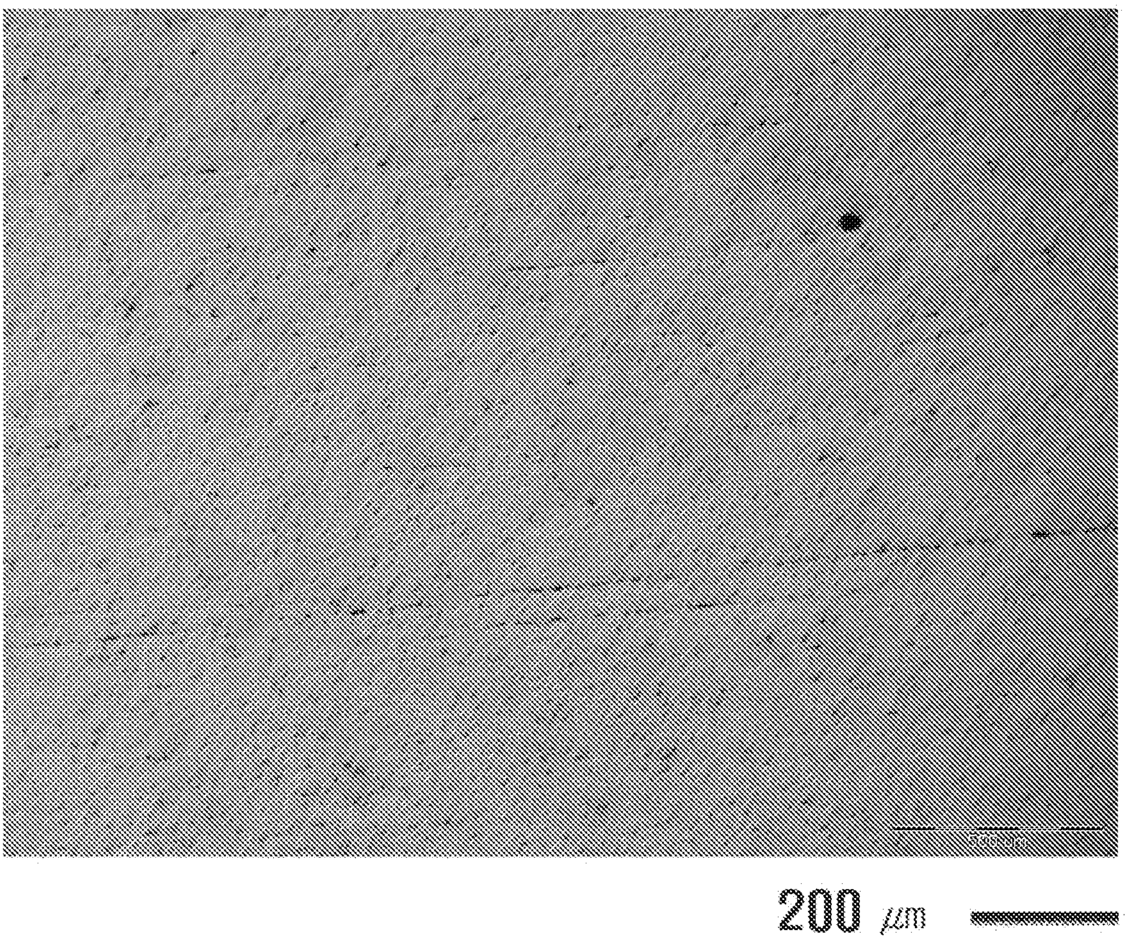


Fig.26

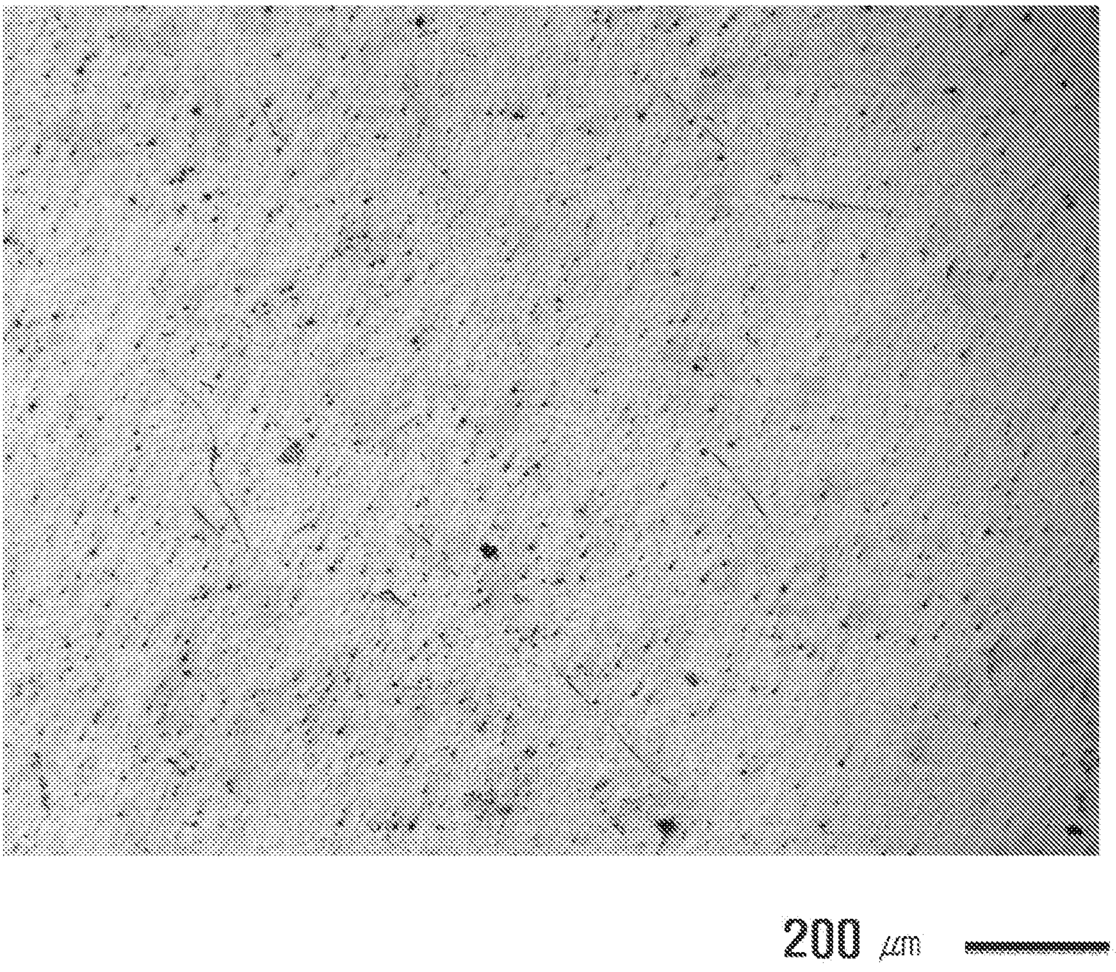


Fig.27

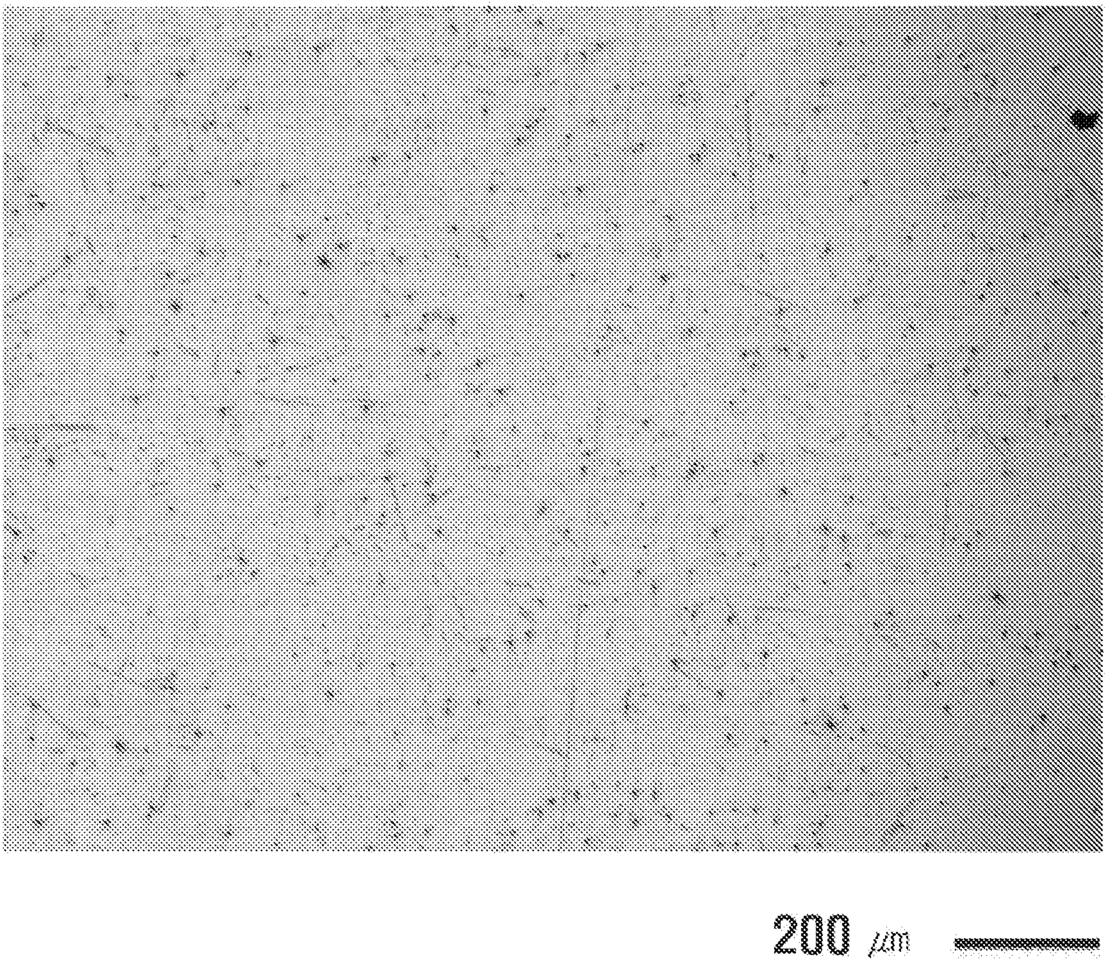


Fig.28

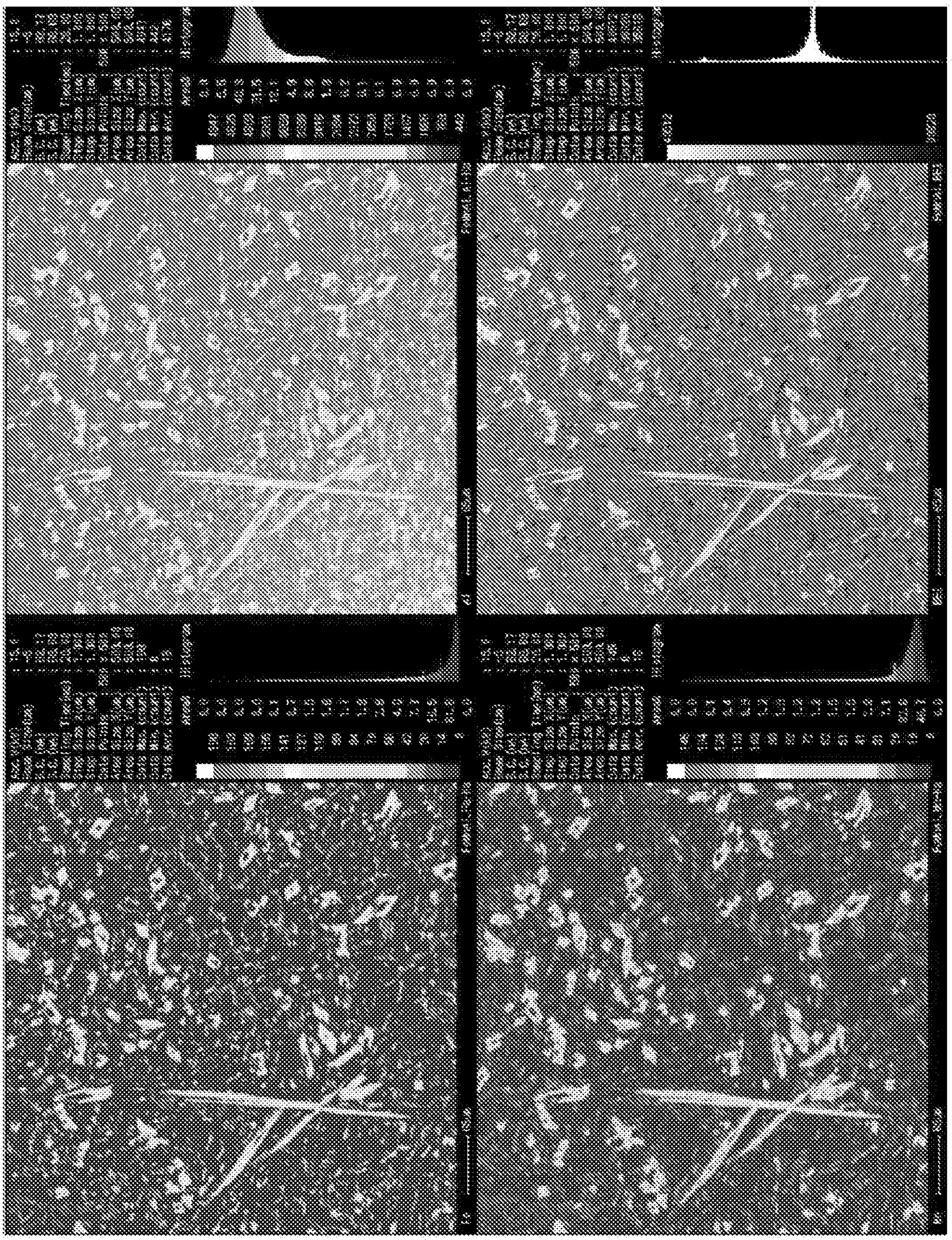


Fig.29

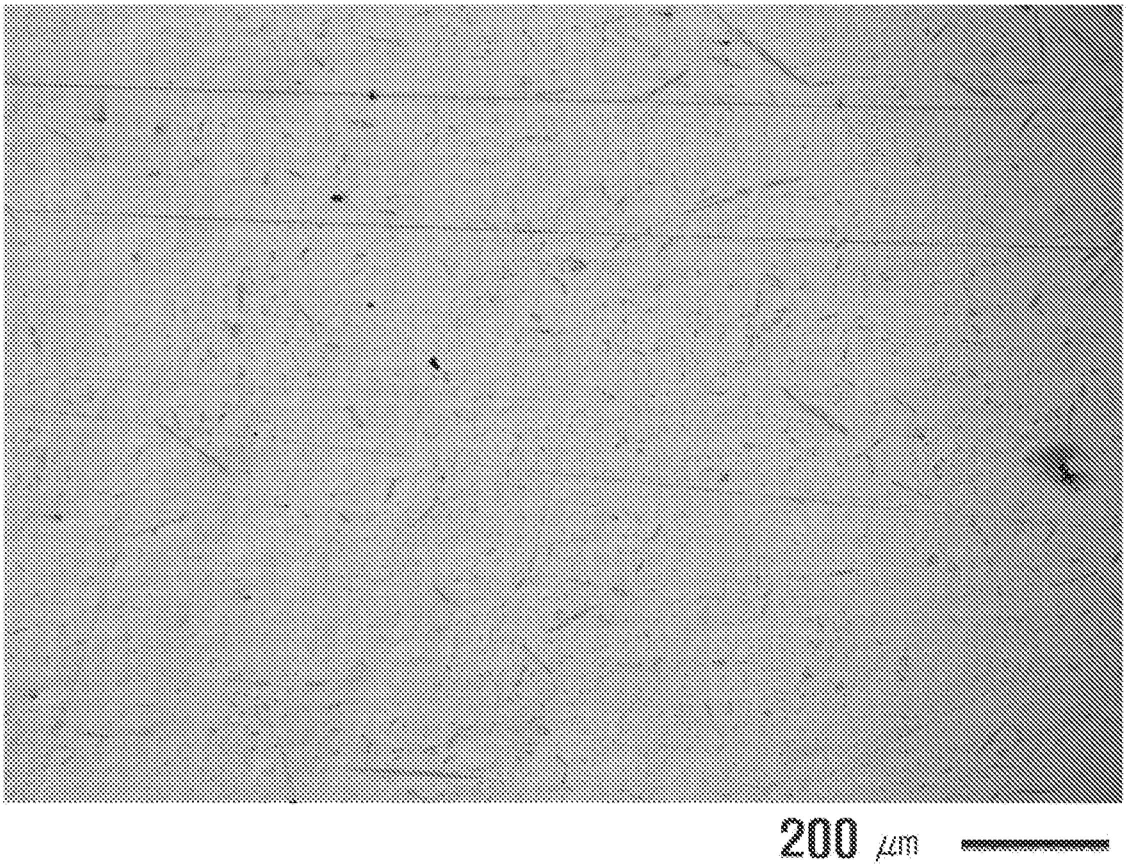


Fig.30

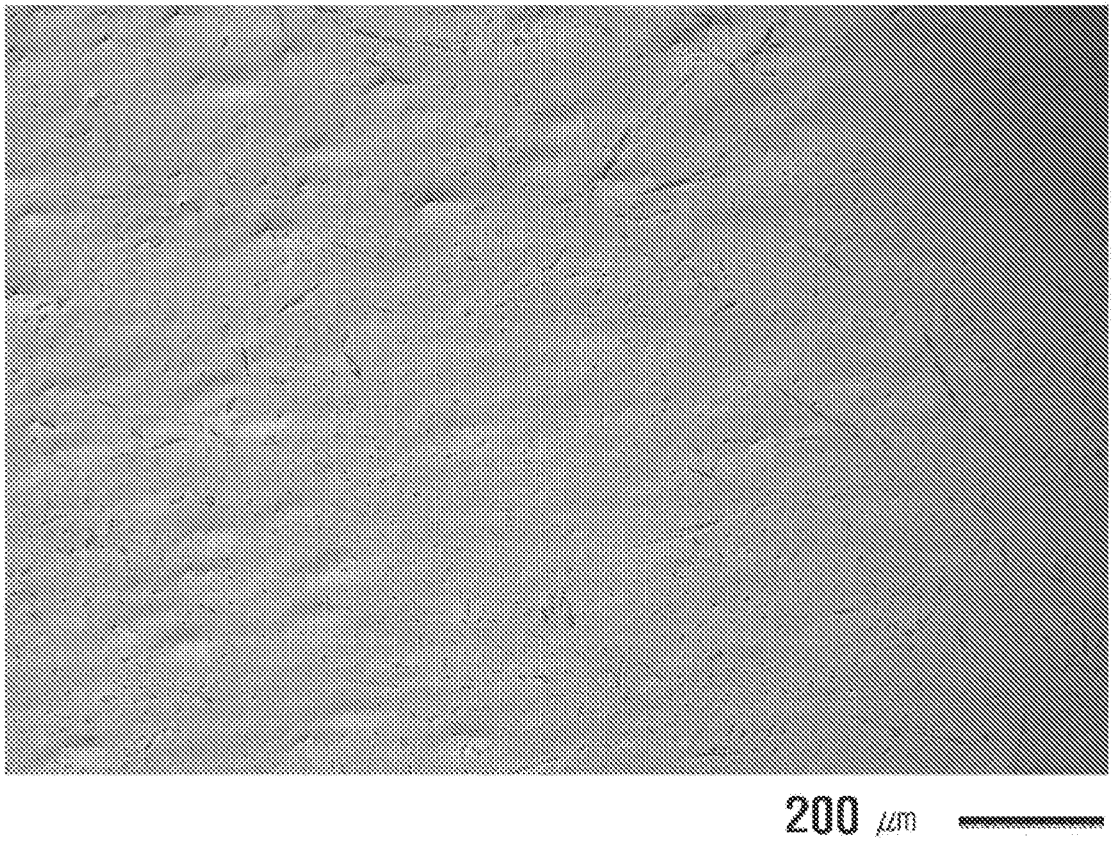
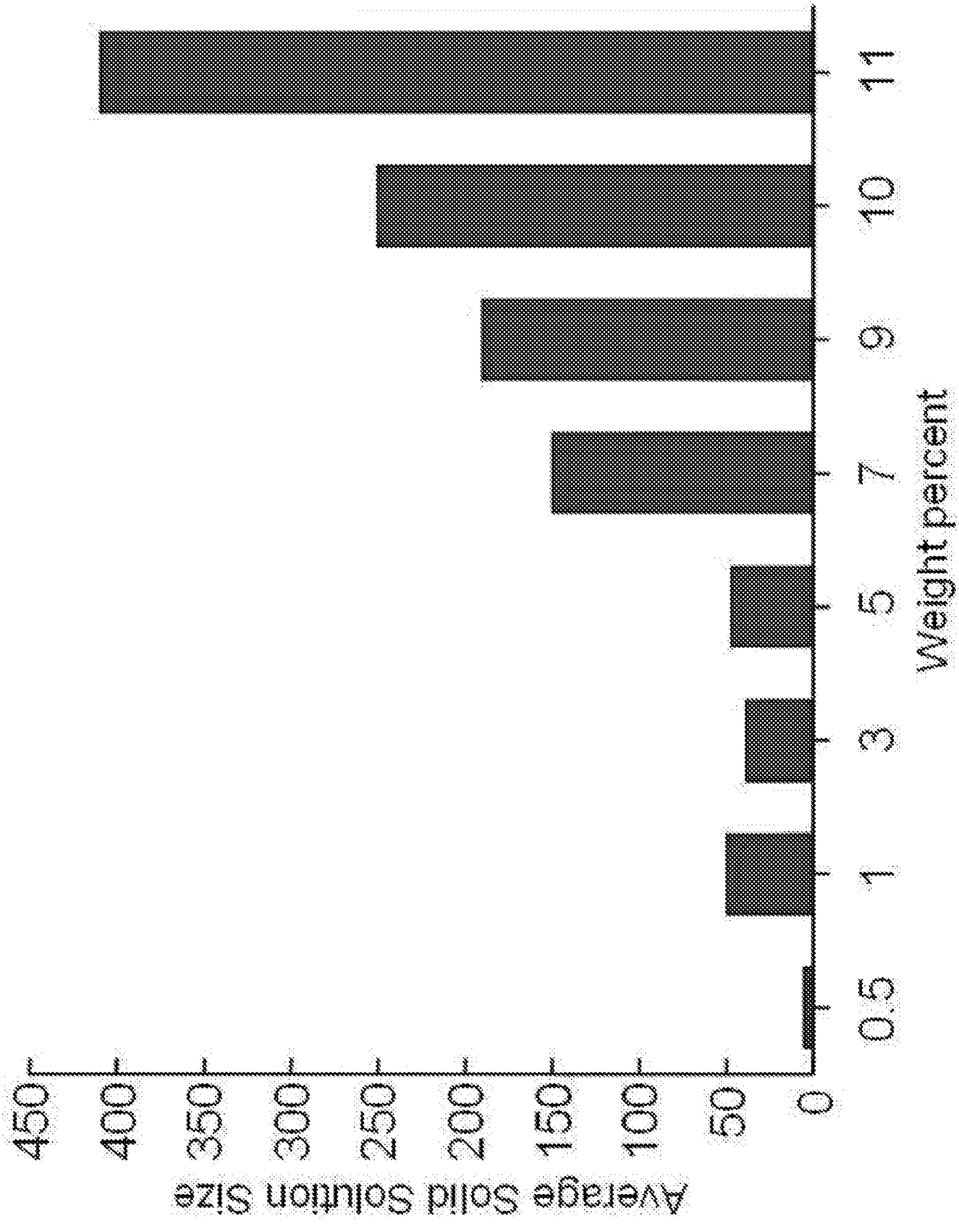


Fig.31


Average Solid Solution Size
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50
100
150
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250
300
350
400
450
Weight percent
0.5
1
3
5
7
9
10
11

Fig.32

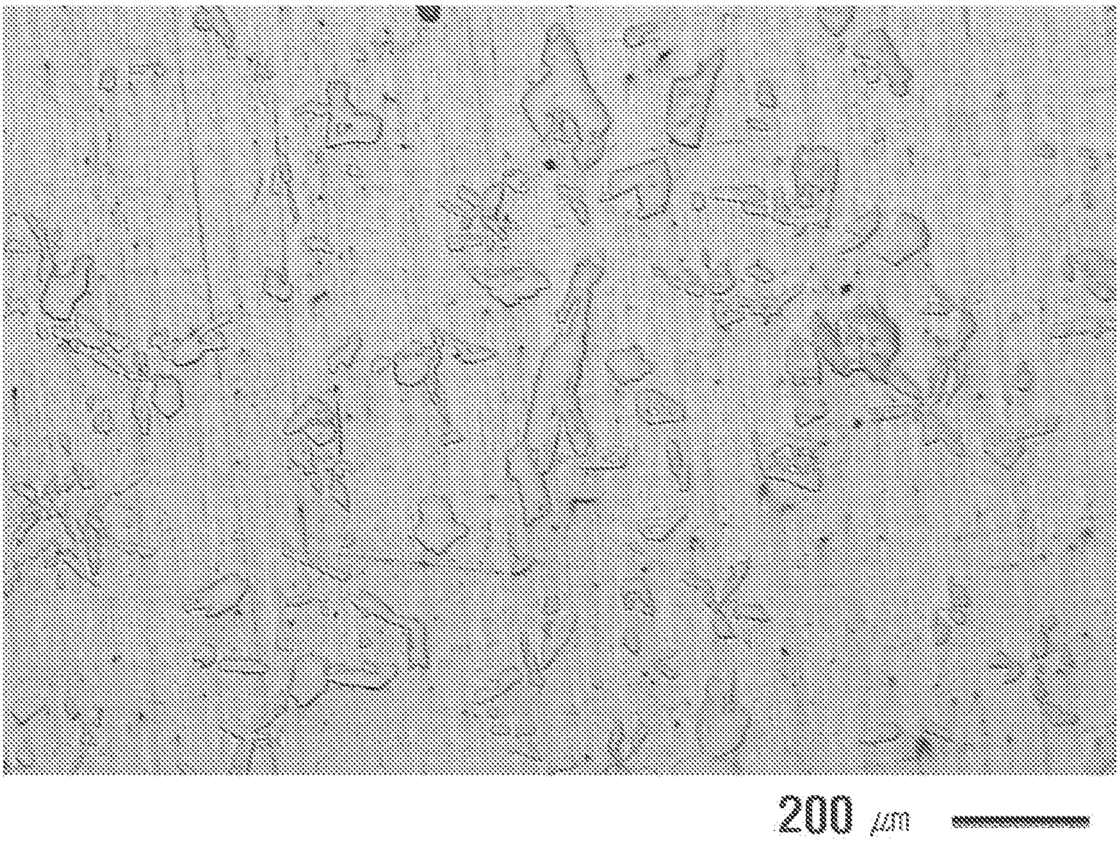


Fig.33

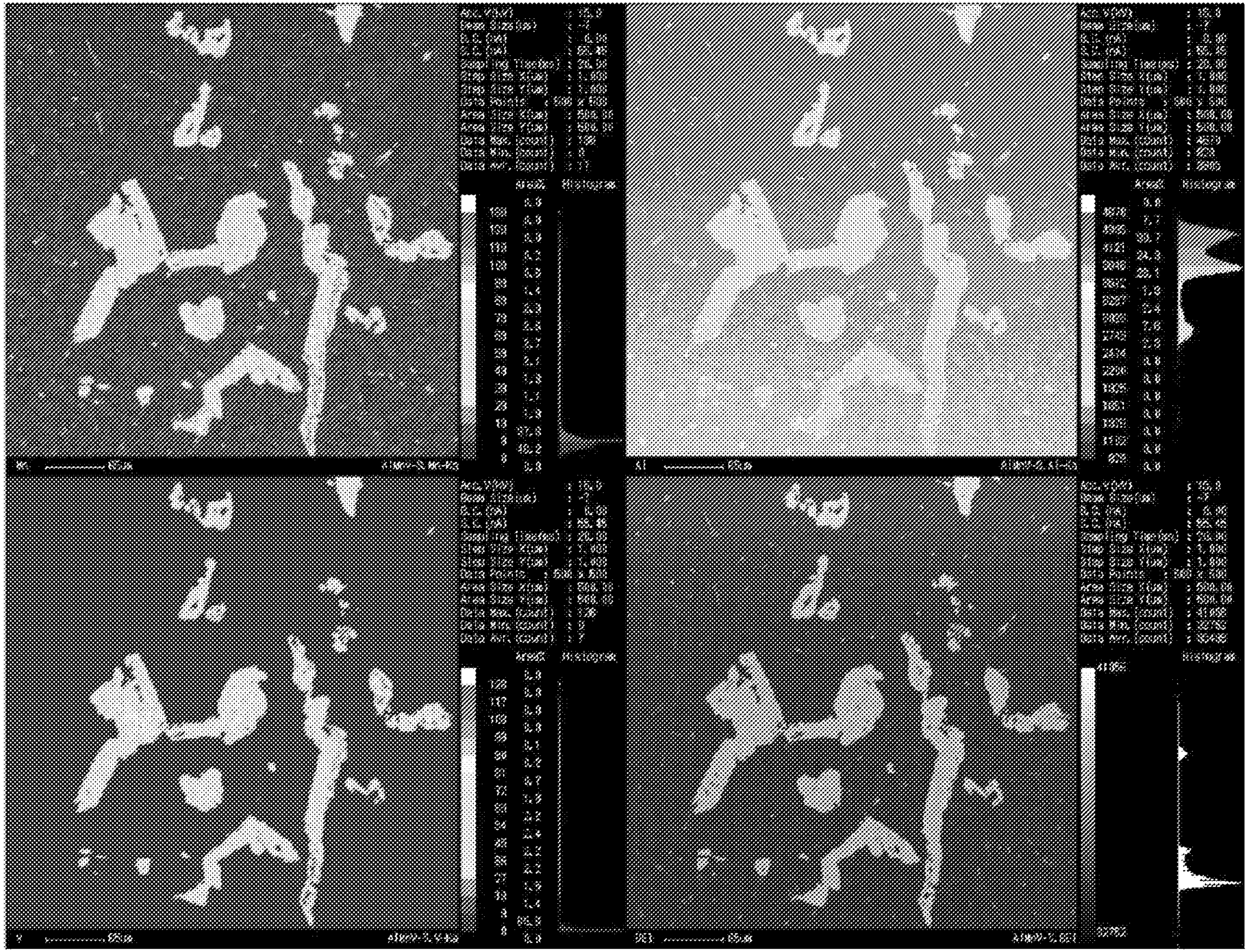


Fig.34

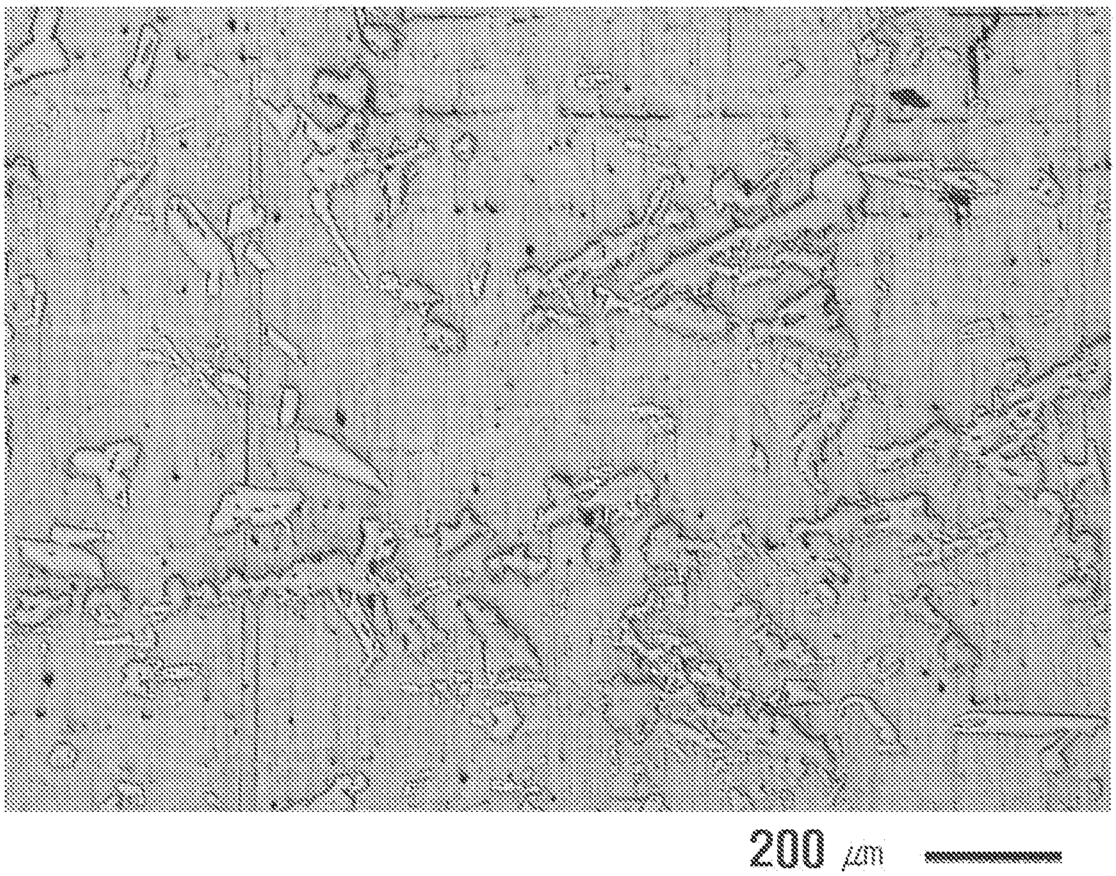


Fig.35

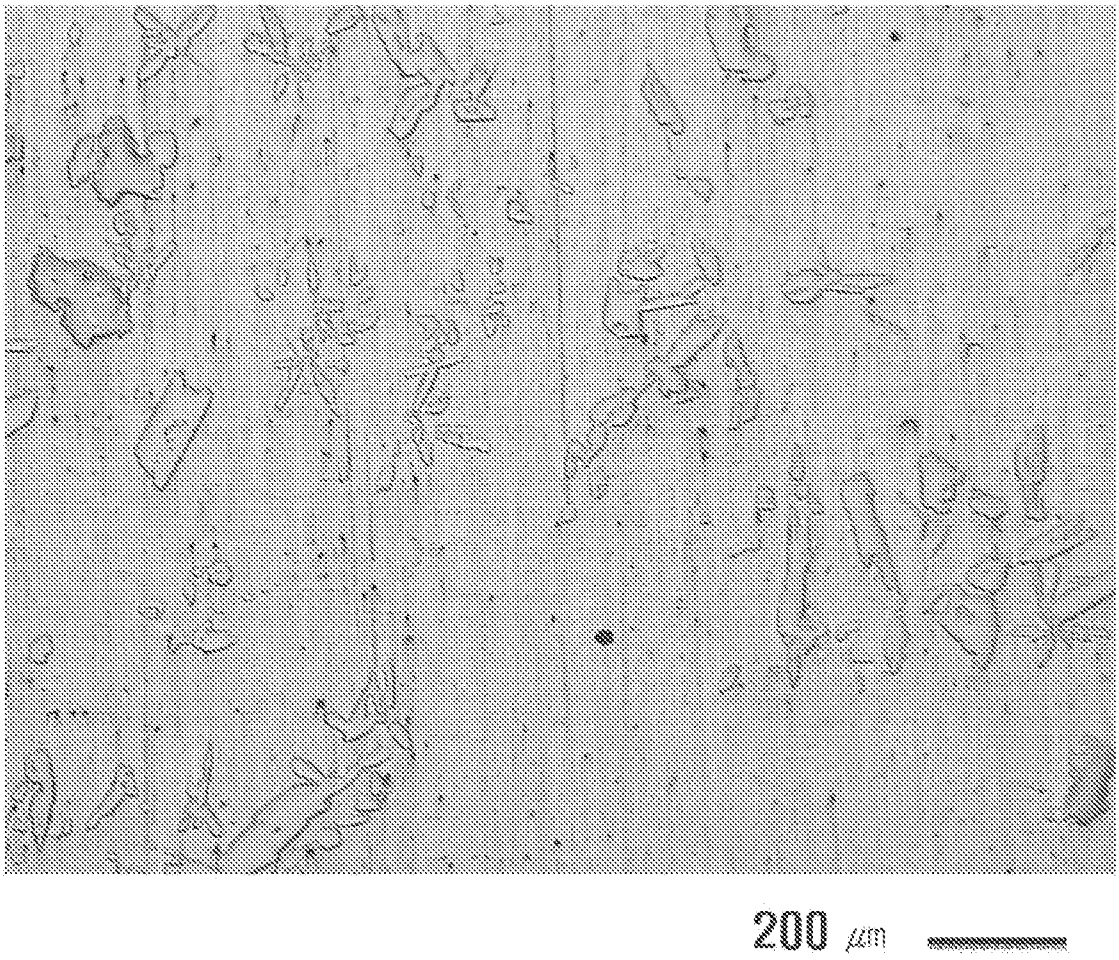
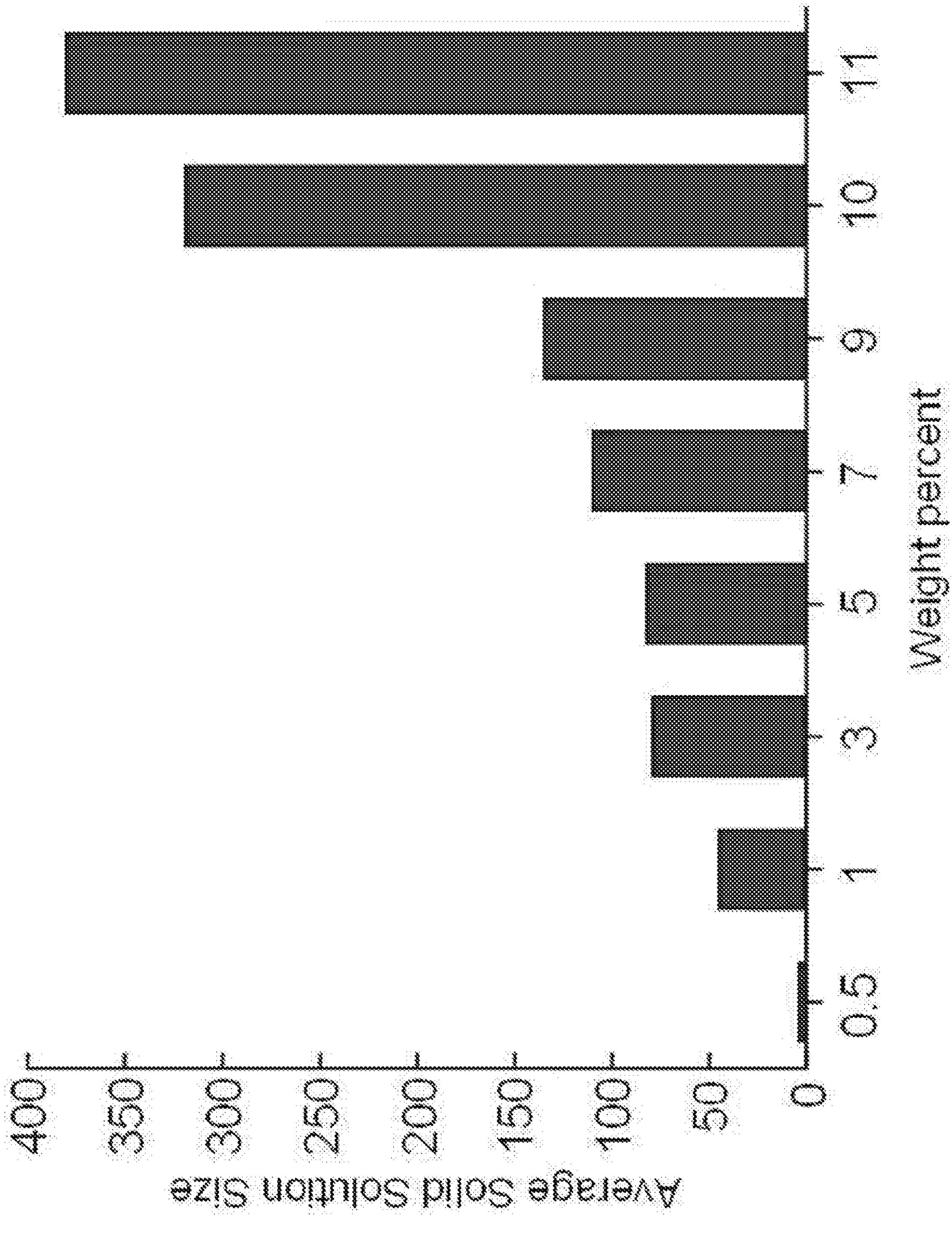


Fig.36


Average Solid Solution Size
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350
400
Weight percent
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1
3
5
7
9
10
11

Fig.37

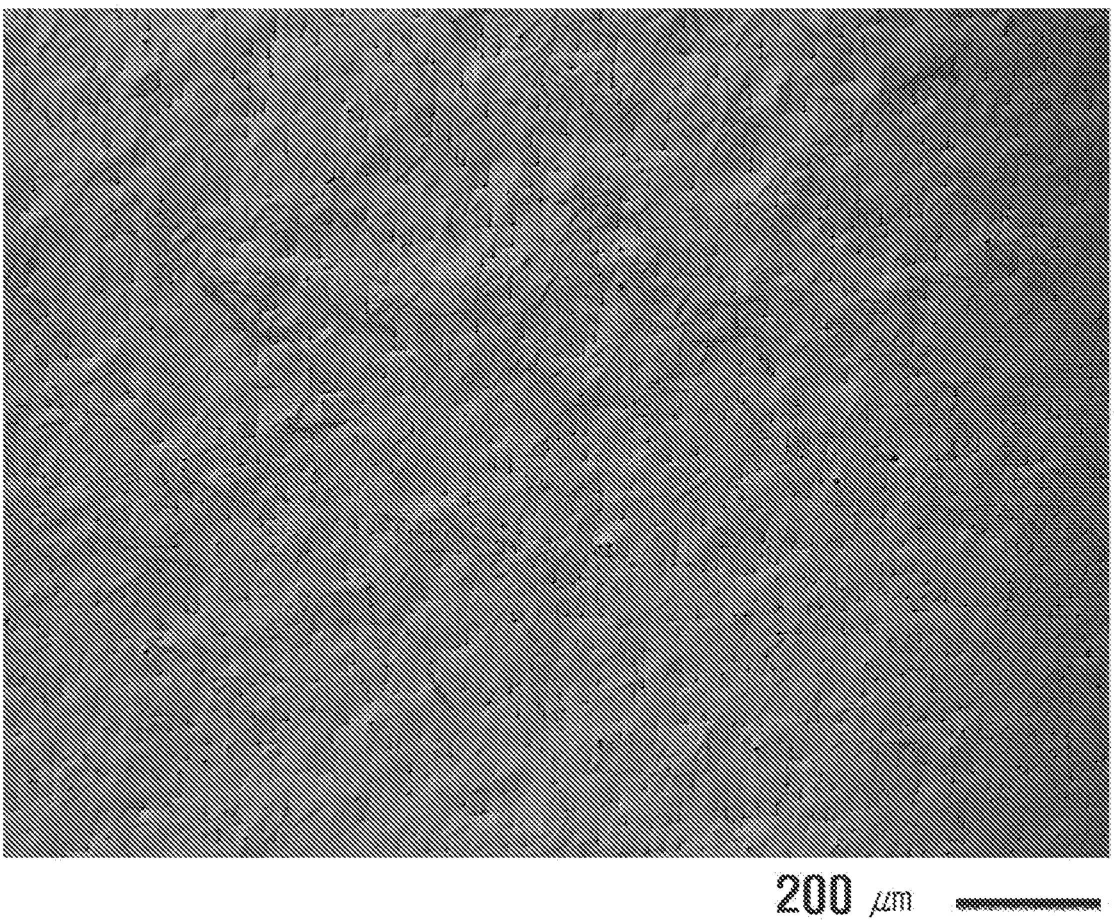
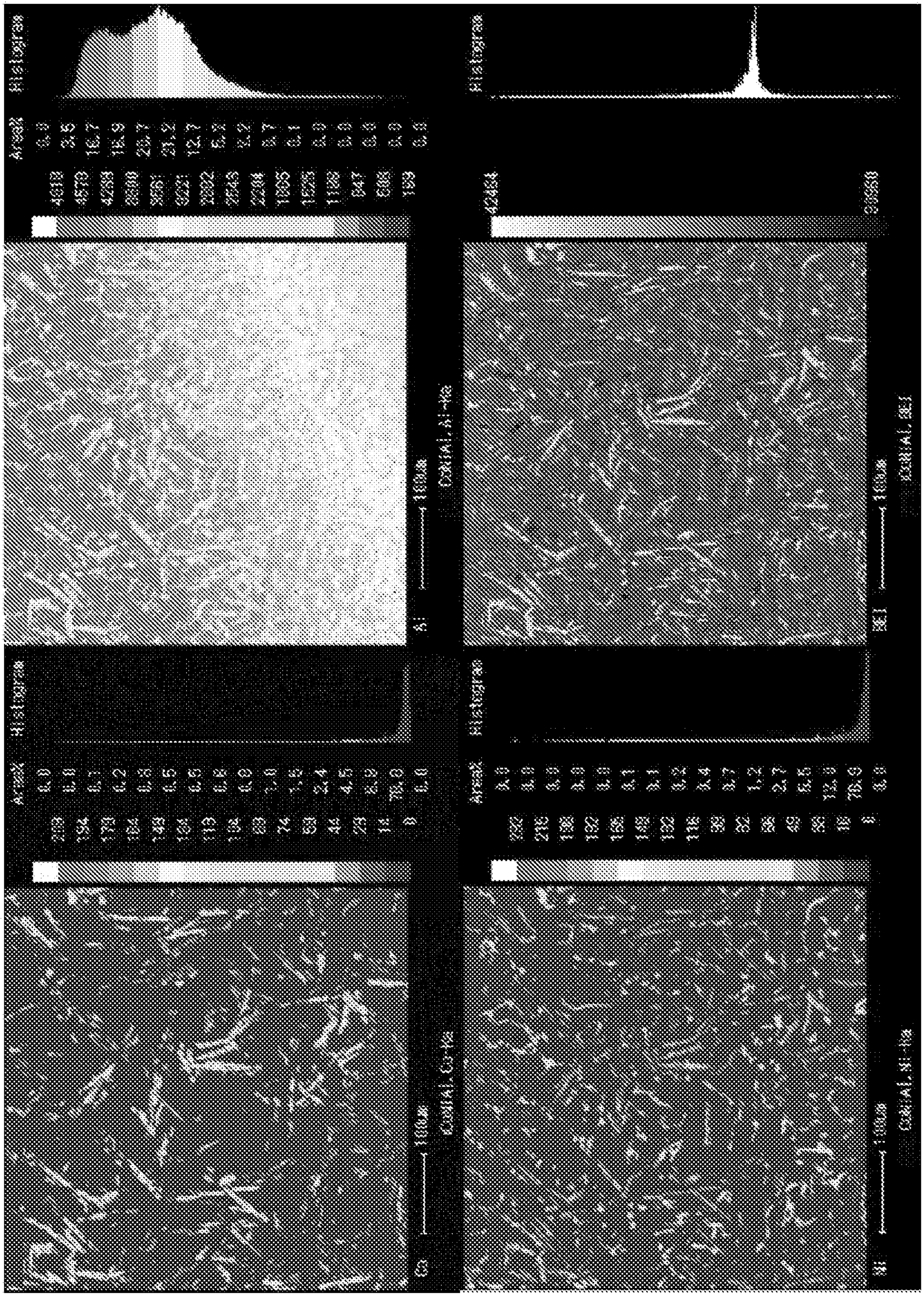


Fig.38


Histogram
Area%
Al
100μm
CoNiAl Al-Ka
Histogram
BEI
100μm
CoNiAl BEI
Histogram
Area%
Co
100μm
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Histogram
Area%
Ni
100μm
CoNiAl Ni-Ka

Fig.39

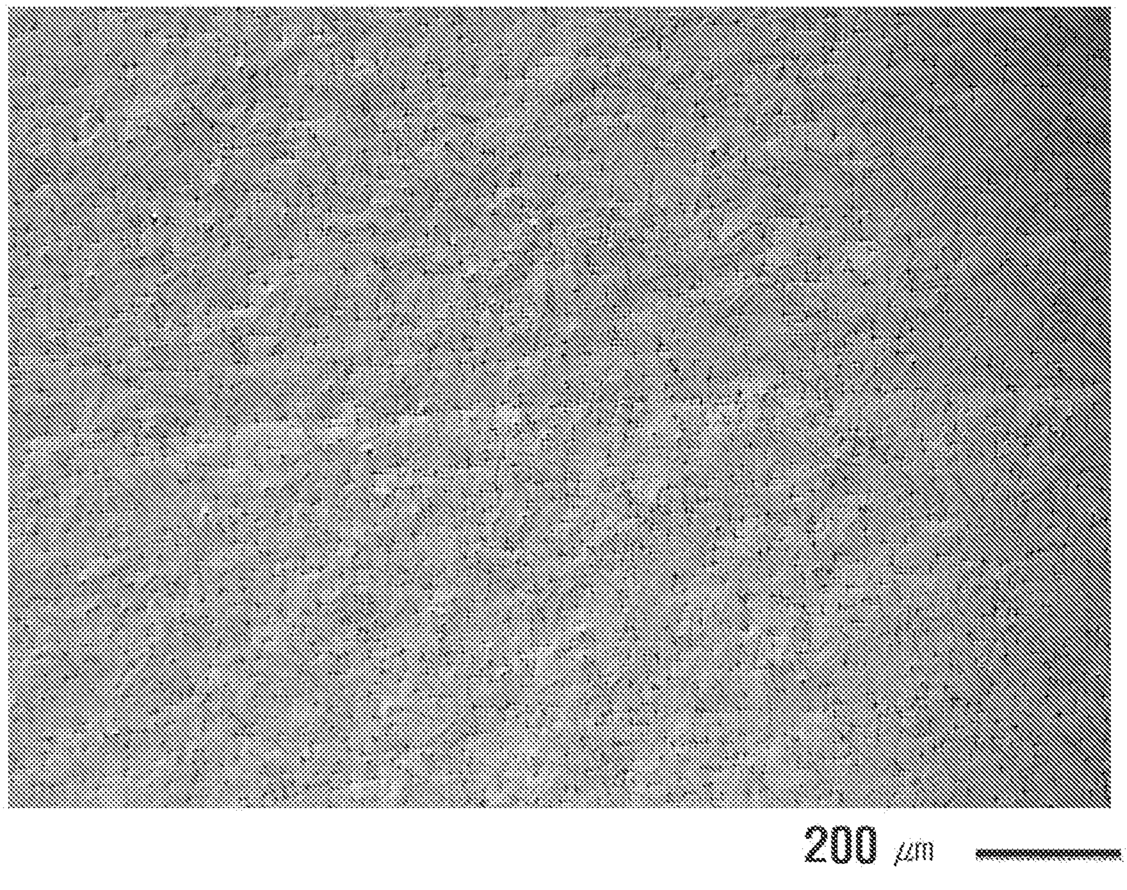


Fig.40

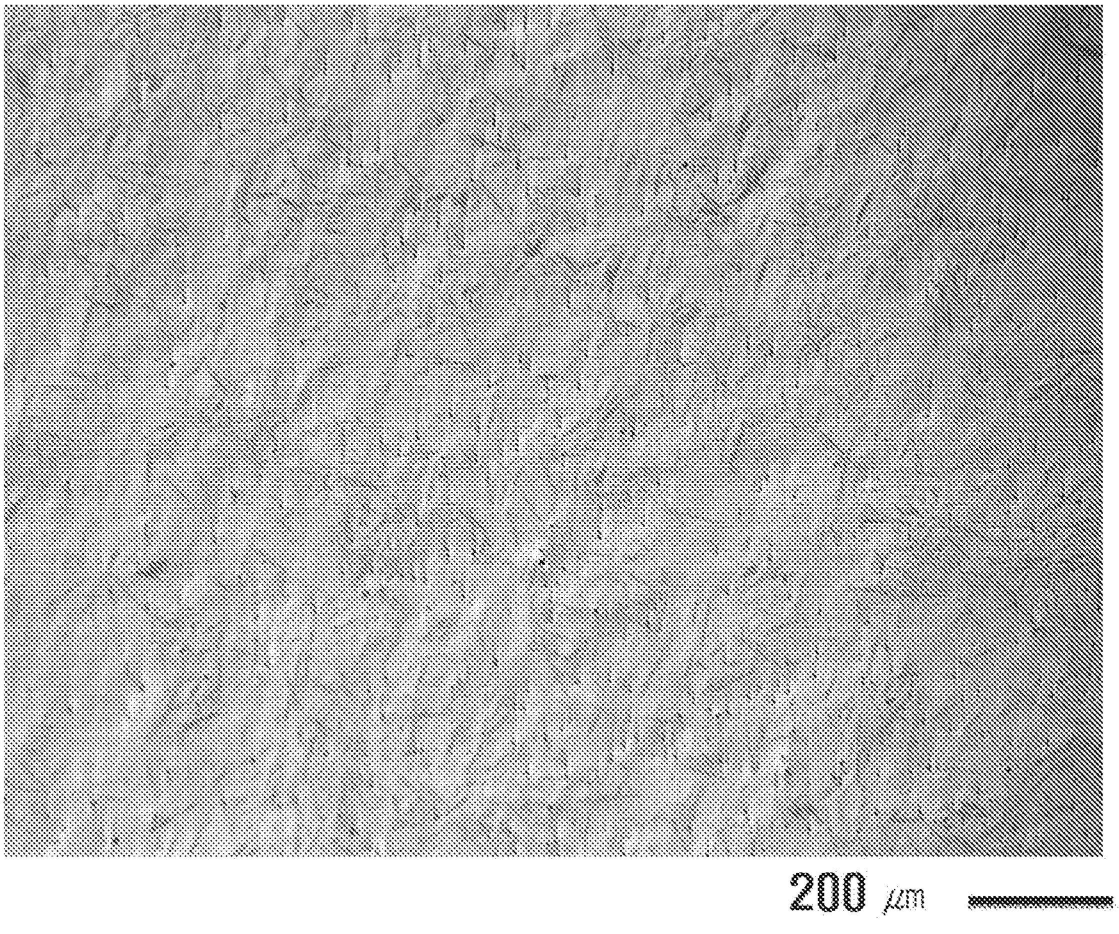


Fig.41

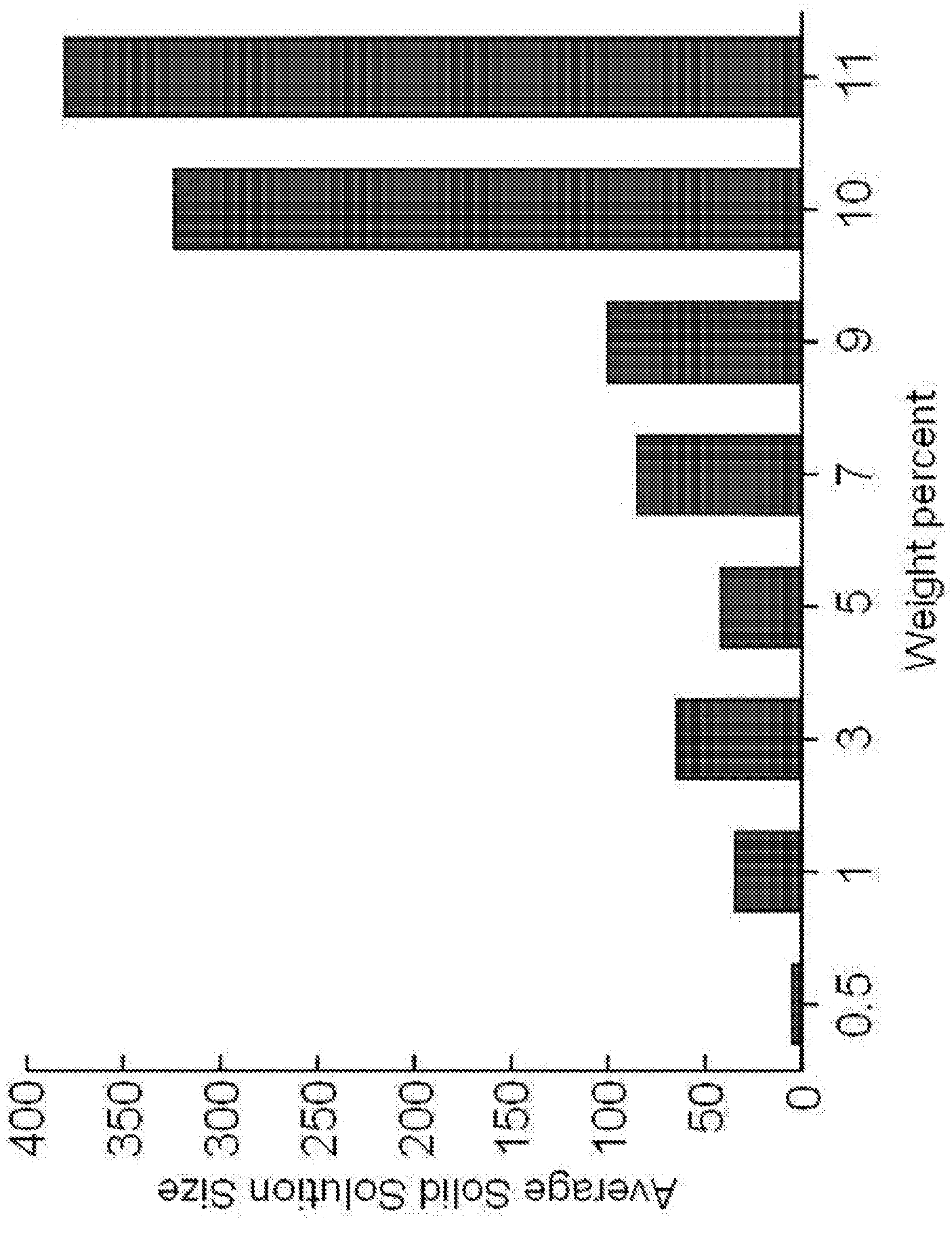

Average Solid Solution Size
0
50
100
150
200
250
300
350
400
Weight percent
0.5
1
3
5
7
9
10
11

Fig.42

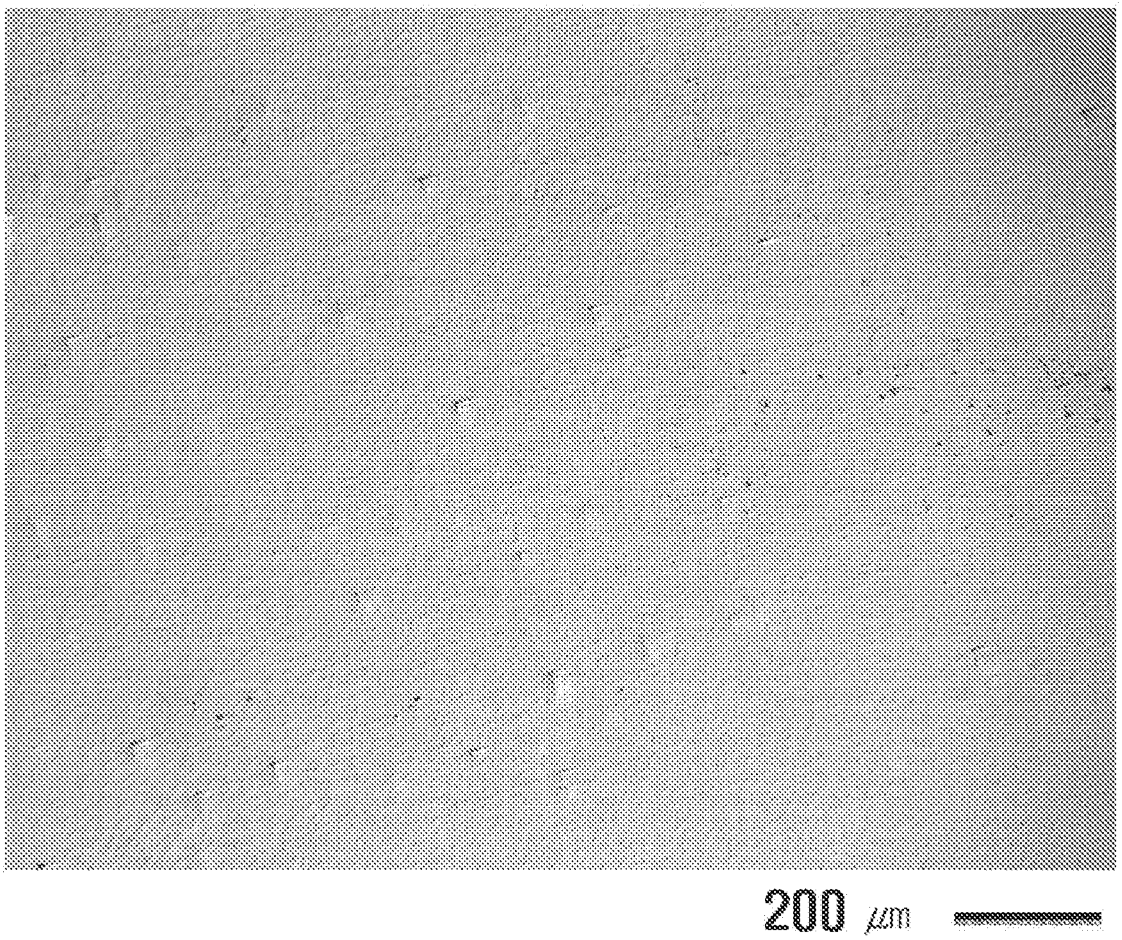


Fig.43

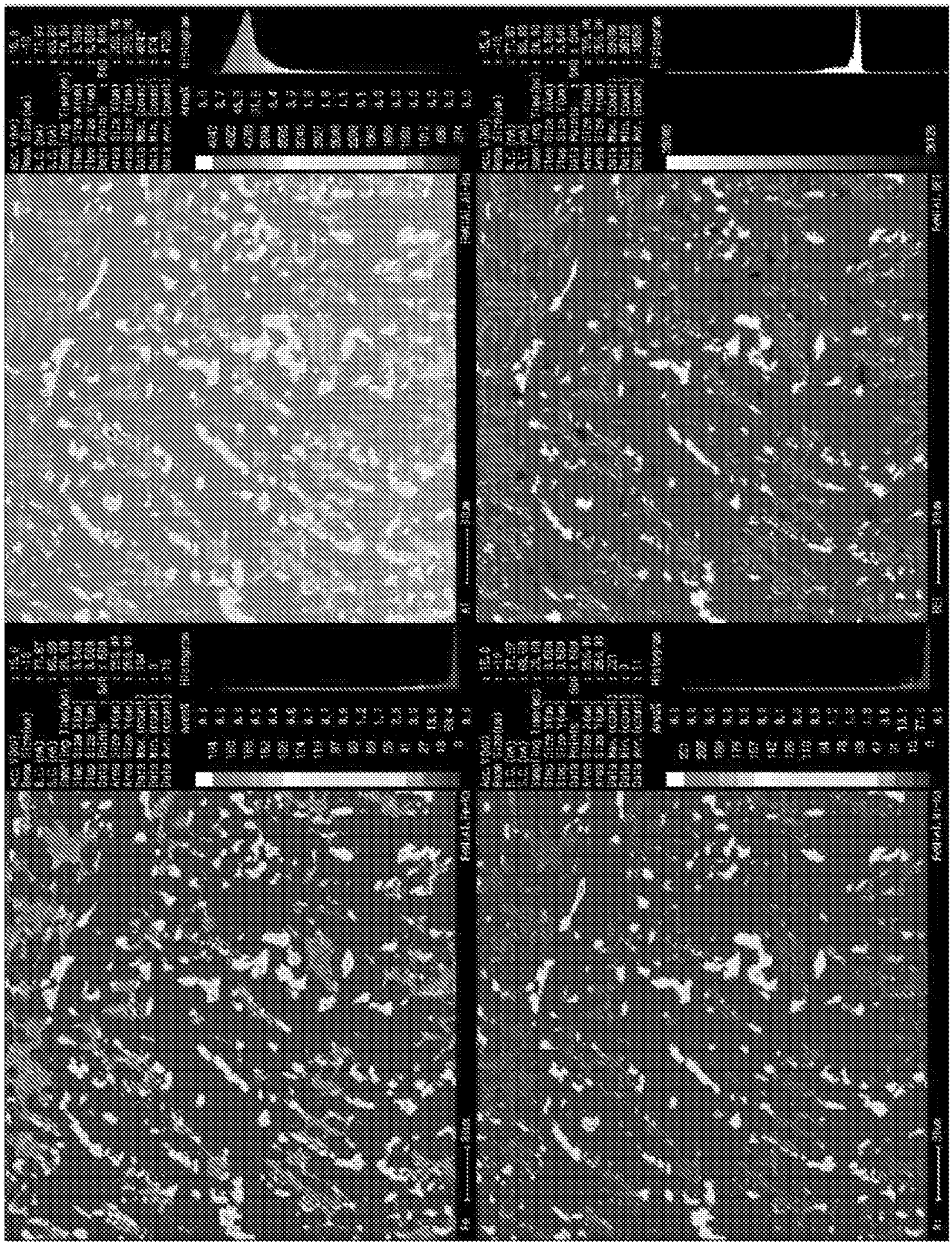


Fig.44

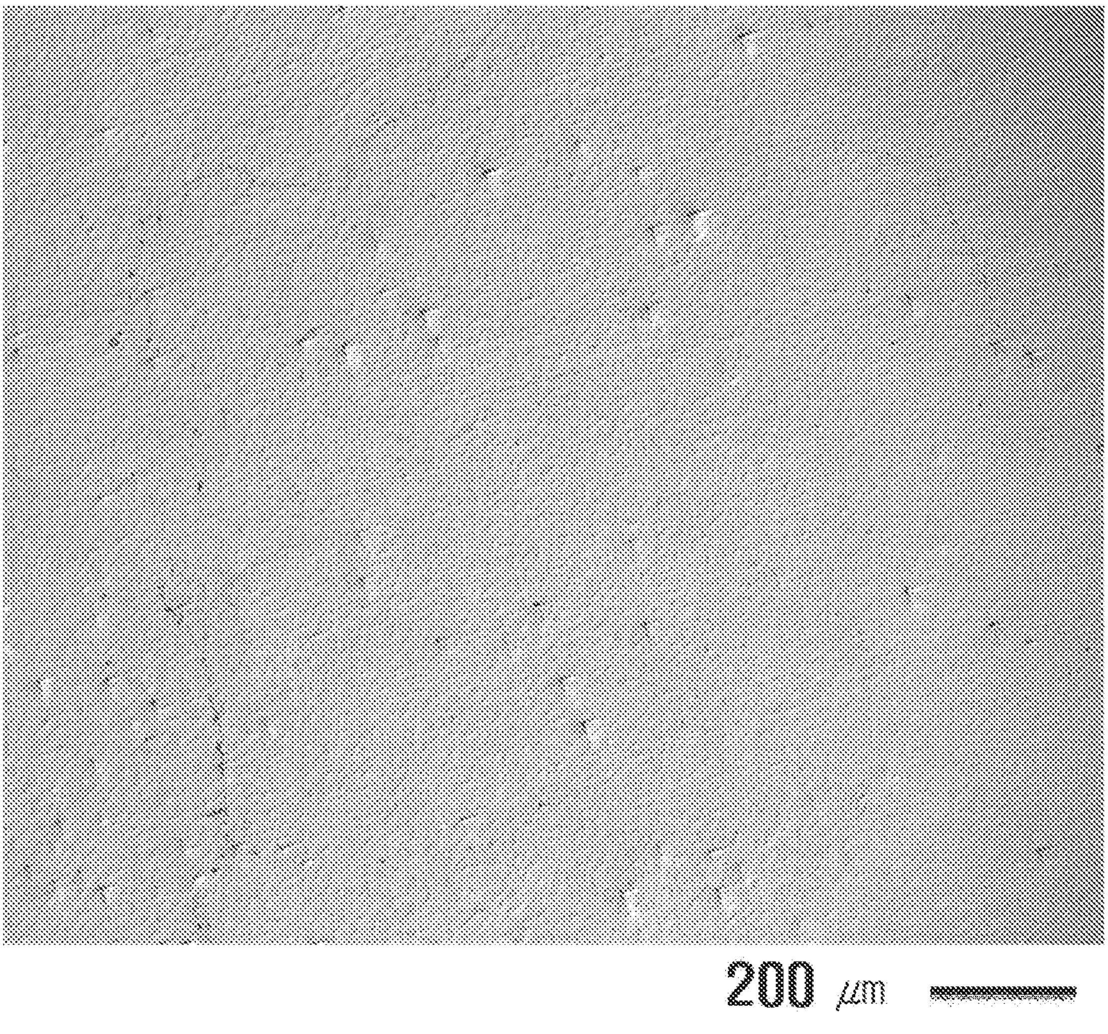


Fig.45

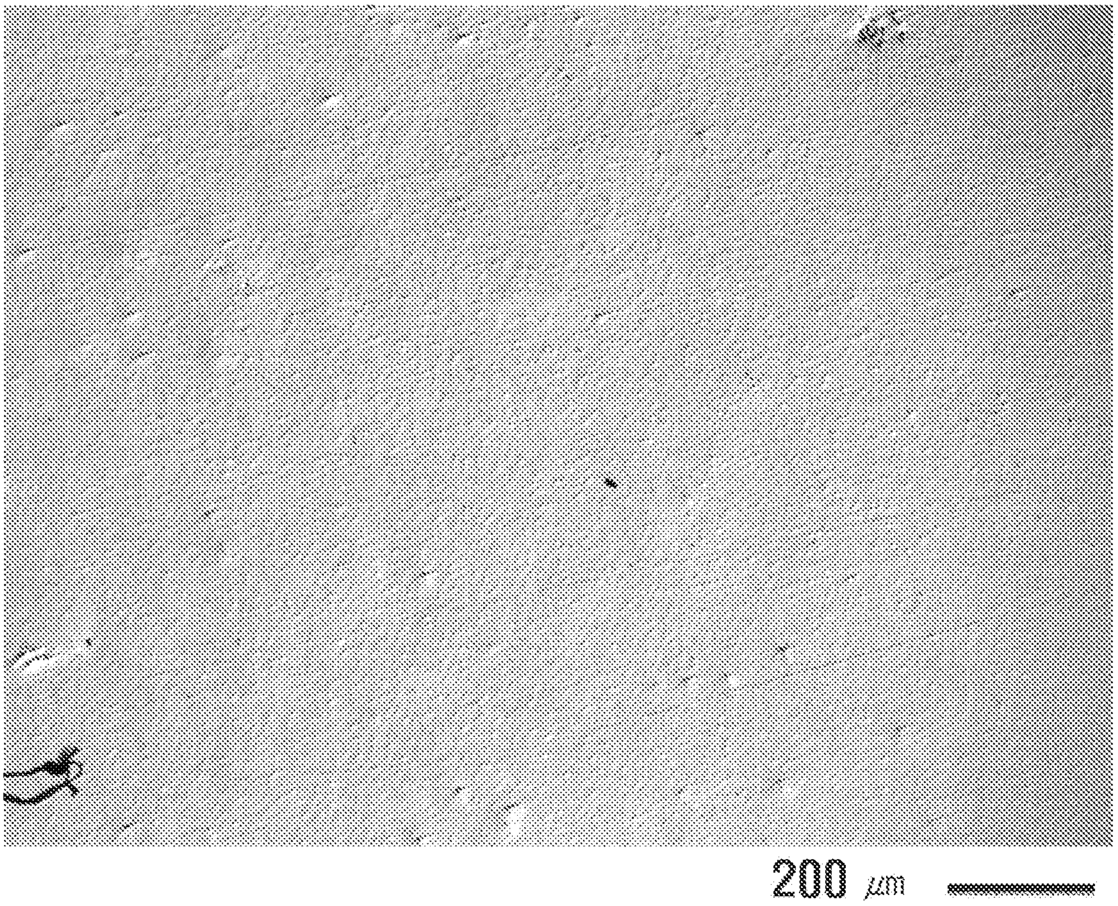


Fig.46

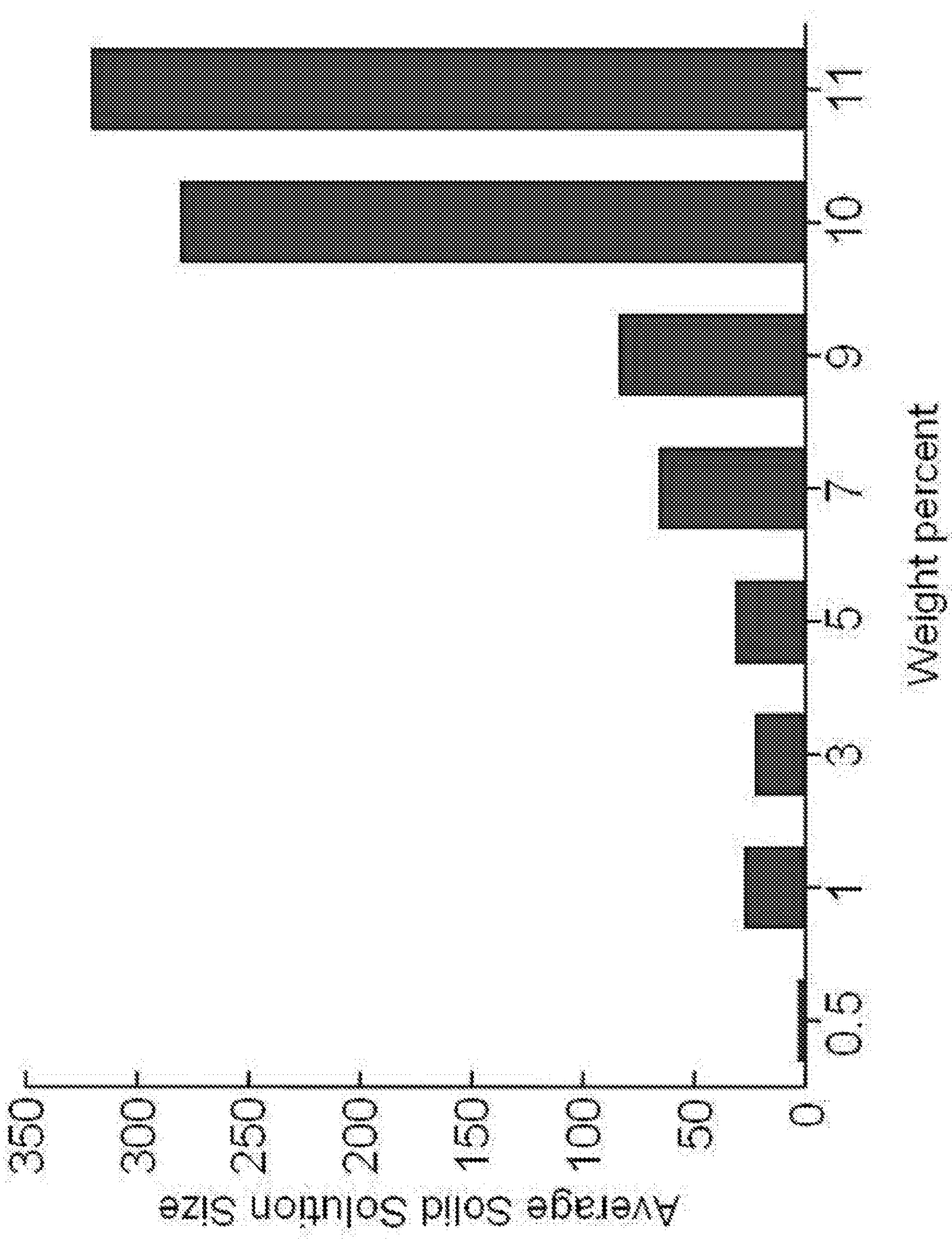

Average Solid Solution Size
350
300
250
200
150
100
50
0
0.5
1
3
5
7
9
10
11
Weight percent

Fig.47

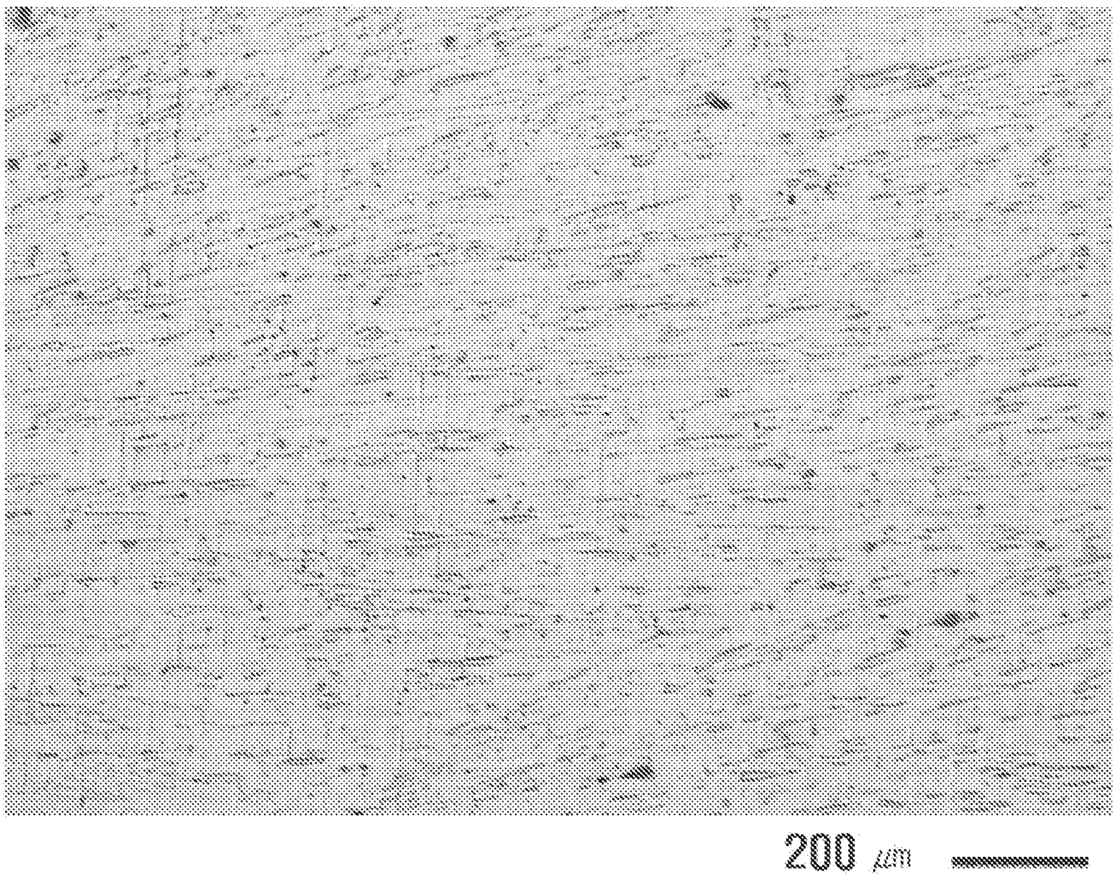


Fig.48

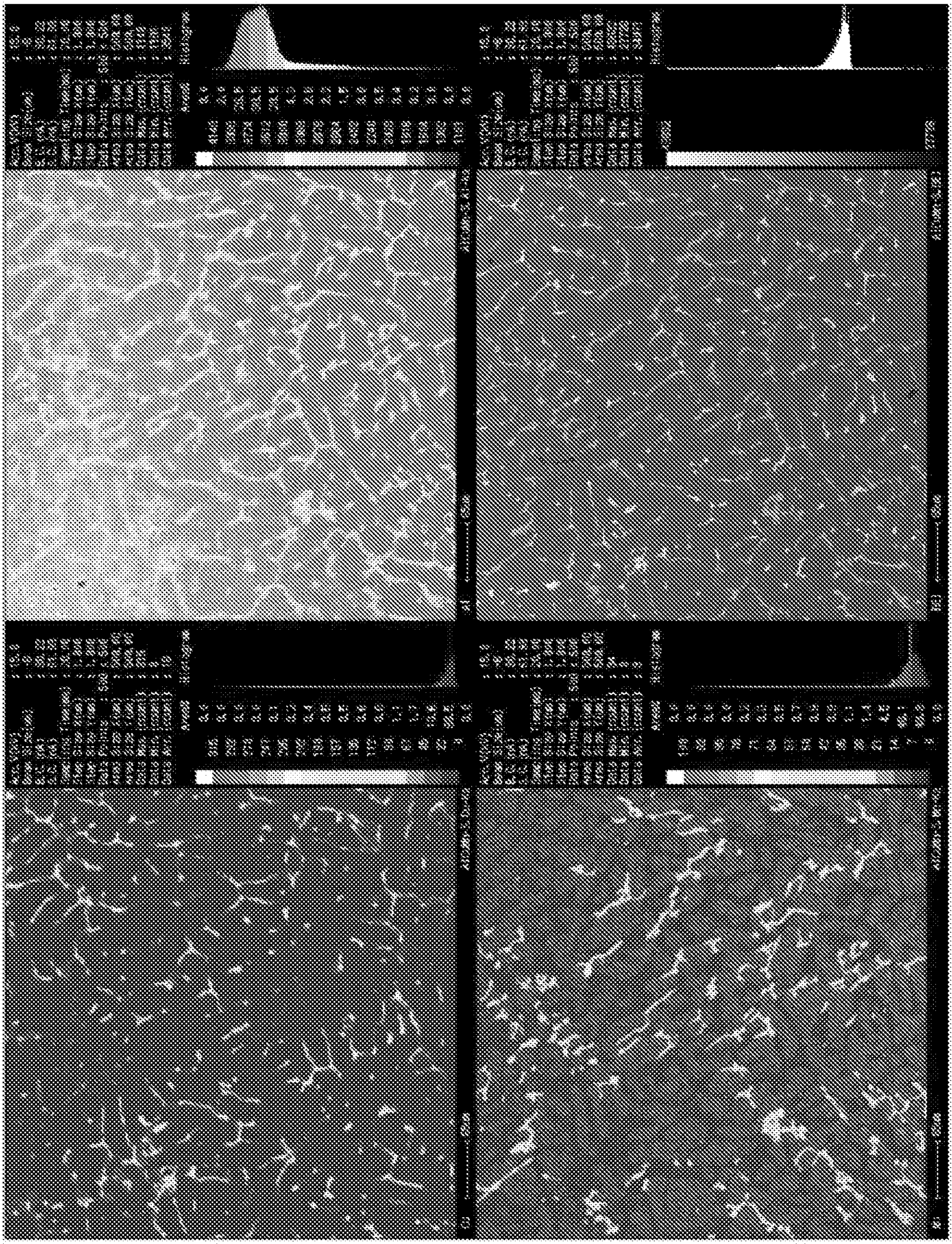


Fig.49

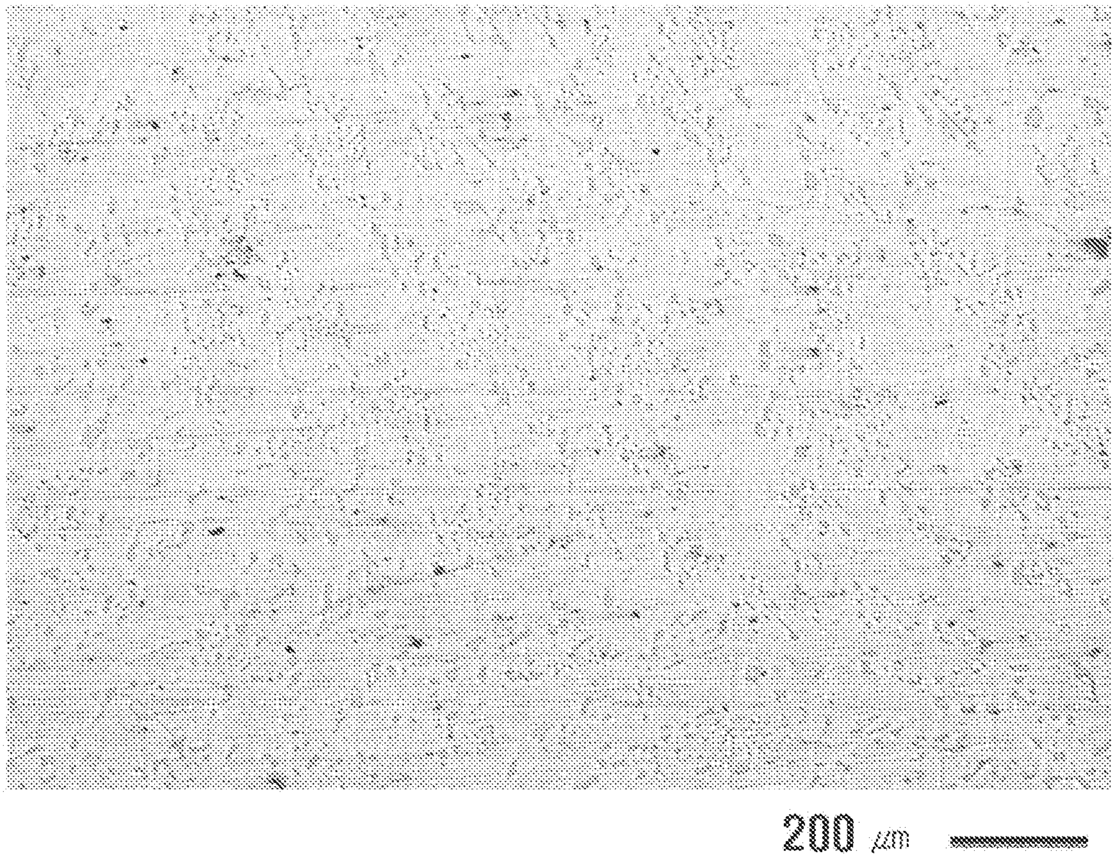
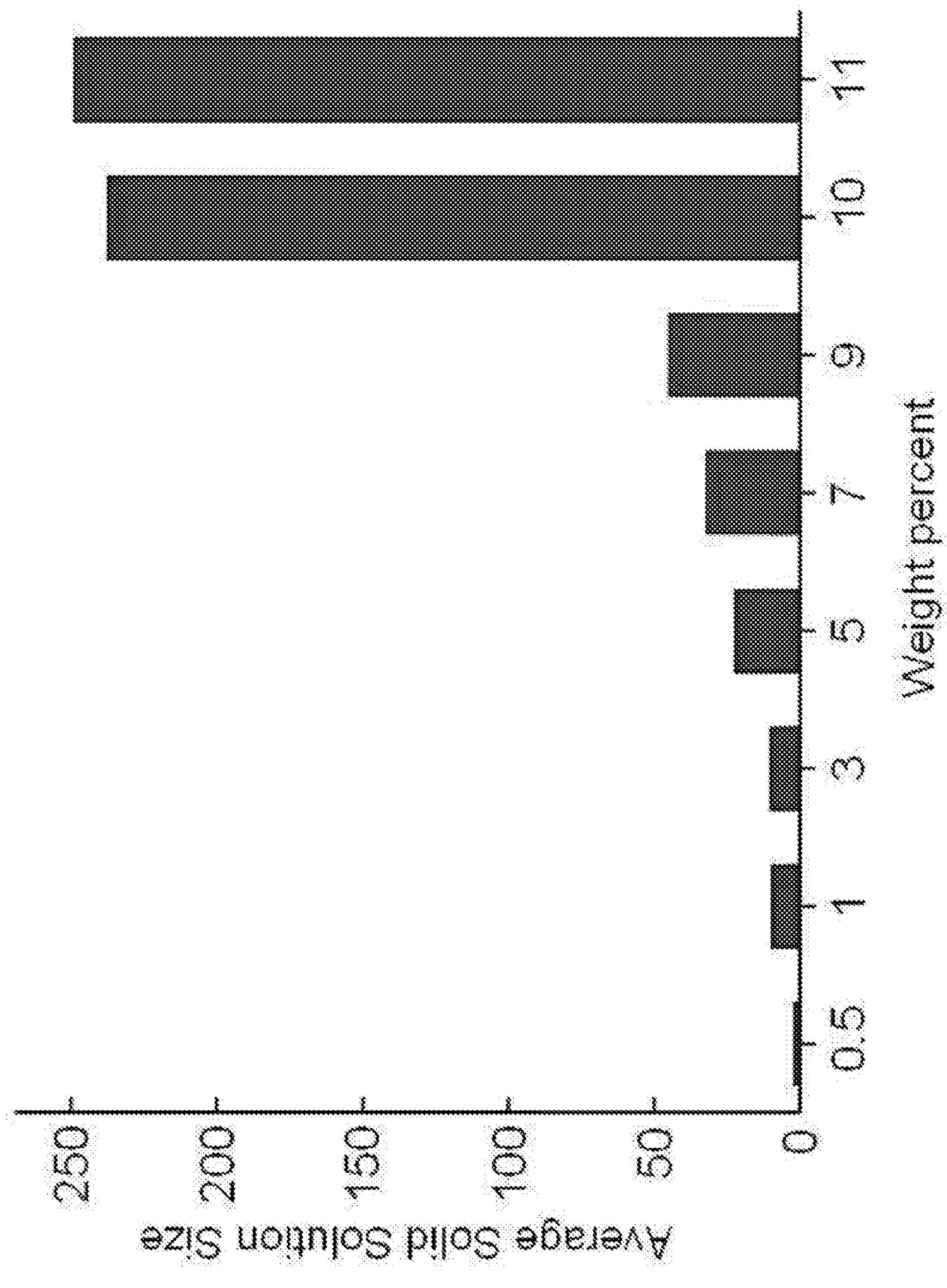


Fig.50

Fig.51


Average Solid Solution Size
0
50
100
150
200
250
Weight percent
0.5
1
3
5
7
9
10
11