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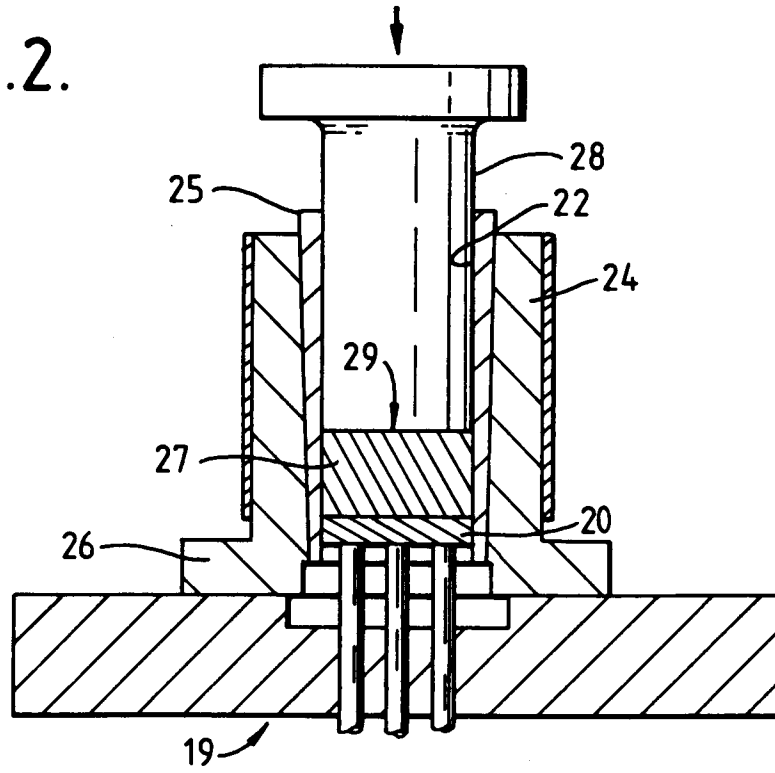
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Luton, Bedfordshire LU1 2SE(GB)(54) **Metal matrix composite composition and method.**

(57) A method of making a new metal matrix composite material formed from an aluminium-based alloy and a silicon carbide ceramic material is disclosed, in which preferably a porous pre-form (20) of the silicon carbide ceramic material having SiO₂ on the surfaces thereof is placed in an open-top die (24), heated to an elevated temperature in the range of 399°C and 1093°C, and impregnated under pressure with a molten alloy (27) comprising, by weight about 3 to 6 percent copper, about 0.5 to 5 percent magnesium and the balance essentially aluminium. The silicon carbide pre-form (20) impregnated with molten alloy is then cooled at a rate sufficient to sustain supersaturation of the copper and magnesium in the aluminium down to a predetermined temperature. The predetermined temperature is selected so as to permit precipitation in the alloy of a strengthening copper-rich secondary metallic phase containing copper, magnesium and aluminium and consisting essentially of about 40 to 80 percent by weight copper, magnesium in an amount between about 5 and 30 percent by weight, and the balance essentially aluminium. This results in the formation of a metal matrix composite material having a silicon carbide phase, an aluminium-rich primary metallic phase and a copper-rich secondary metallic phase which has the desired composition. The primary metallic phase can contain up to 10 percent of eutectic phase which is generally present as a coarse network or as isolated islands within the primary phase.

Preferably, cooling occurs immediately after the impregnating step and relatively rapidly to a temperature below about 288°C, where precipitation of the secondary metallic phase occurs. Preferably, the secondary metallic phase comprises a cubically-shaped crystal structure which measures about 40 nanometres on a side.

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Fig.2.



This invention relates to a metal matrix composite which has a ceramic phase and an aluminium alloy phase and a method of making it, as specified in the preamble of claim 1, for example as disclosed in EP-A-0 236 729.

There is a continuing need to lighten and strengthen motor vehicles and aircraft. As a result, structural members and other parts are being constructed from lighter materials such as aluminium and magnesium. Despite the advantage of light weight possessed by these materials, they have relatively inferior mechanical characteristics, such as lower yield strength, wear resistance and tensile strength. Further, aluminium, magnesium and alloys thereof are known to be relatively notch-sensitive and subject to crack propagation. These deficiencies limit the application of aluminium, magnesium and their alloys. Therefore, it is desirable for such parts to be formed from composite materials having a metal phase and a re-reinforcement phase.

A composite structure is one which comprises heterogeneous material, that is, two or more different materials which are intimately combined in order to attain desired properties of the composite material. For example, two different materials may be intimately combined by embedding one in a matrix of the other or impregnating the one with the other.

Metal matrix composite materials comprise a metal phase and a strengthening, re-reinforcing phase, such as ceramic particulates, whiskers and/or fibres. In a metal matrix material, the re-reinforcing phase is typically dispersed, distributed and/or embedded in the metal phase. Generally, a metal matrix composite material will show an improvement in such properties as strength, stiffness, contact wear resistance, and elevated temperature strength retention as compared to the metal material alone. Metal matrix composite materials show great promise for a variety of applications because they combine the strength and hardness of the strengthening phase with the ductility of the metal phase.

Aluminium matrix composite materials re-reinforced with a ceramic material such as alumina (Al_2O_3) or silicon carbide (SiC) are of particular interest. Such metal matrix composite materials potentially may provide the advantages of the matrix alloy workability (i.e. aluminium is known for its weight and workability advantages) whilst avoiding disadvantages with regard to low strength and crack propagation. The strength of a properly formulated composite material is relatively high compared to the same aluminium alloy without the re-reinforcing phase. Moreover, the re-reinforcing ceramic material should prevent the propagation of cracks through the composite material. However, enhanced properties and an efficient, economical method to form the composite material are needed.

It has been suggested that metal matrix composite materials may be formed by a number of methods which intermingle the ceramic material and metal alloy together so that the ceramic phase is distributed throughout the composite material. In one proposed method, the alloy is first melted and then stirred whilst ceramic fibres are added. The stirred mixture is then permitted to cool. Another proposed method includes powder metallurgy techniques, where the metal, in the form of a powder, and the ceramic re-reinforcing material, in the form of particles, whiskers or fibres are mixed and then either hot-pressed or extruded. Still other proposed methods for intermingling the materials include high-pressure casting or infiltration processes. In an infiltration method, the ceramic material is formed into a structure and molten metal is injected under the force of pressure into voids or interstices in the structure.

It has been suggested that a bonding interface exists between the metal matrix and the ceramic re-reinforcement. It also has been suggested that the strength of the interface is related to the composition of the metal and good wetting of the ceramic material by the metal during formation of the composite material.

There is a need for an improved composition for the metal phase which provides a metal matrix composite product having desired enhanced mechanical properties and good bonding at the interface between the ceramic and metal phases. There is also a need for a new method for forming metal matrix composite materials which produces such an improved composition and the desired enhanced properties.

A method of forming a metal matrix composite material according to the present invention is characterised by the features specified in the characterising portion of claim 1.

A new metal matrix composite of an aluminium based alloy and a ceramic material, and a method of making it are provided.

In the preferred method, silicon carbide ceramic material is heated to an elevated temperature, generally in the range of between about 399°C and 1093°C (750°F and 2000°F). An alloy, comprising by weight about 3 to 6 percent copper, about 0.5 to 5 percent magnesium and the balance essentially aluminium, is heated to melt the alloy. The heated ceramic material and molten alloy are mixed or intermingled with one another. The intermingled ceramic material and molten alloy are then cooled at a rate sufficient to sustain supersaturation of the copper and magnesium in the aluminium down to a predetermined temperature. The predetermined temperature is selected so as to permit precipitation of a secondary metallic phase containing the three elements copper, magnesium and aluminium. The secondary metallic phase essentially consists of between about 40 to 80 percent by weight copper, magnesium in an amount

between about 5 and 30 percent by weight, and the balance essentially aluminium. This forms a metal matrix composite material having an aluminium-rich primary metallic phase and a magnesium-containing copper-rich secondary metallic phase which has the desired composition. The primary metallic phase can contain up to 10 percent of eutectic phase which is generally present as a coarse network or as isolated islands in the phase.

Preferably, cooling occurs immediately after the step of intermingling and proceeds sufficiently rapidly to a temperature below about 288° C (550° F) before precipitation occurs. Hence, essentially all of the precipitation occurs at a temperature below about 288° C (550° F) and the precise composition of the precipitate will depend on the temperature(s) selected. During fabrication of components it is often not practically possible to conduct a controlled, rapid cooling or quench immediately after intermingling. Therefore, the constraints of the manufacturing process may require that the step of controlled cooling be deferred. If such a deferral causes the composite material to cool at an uncontrolled rate, the composite material must then be re-heated to a sufficiently high temperature as to dissolve or solubilize the copper and magnesium in the aluminium including that present in the eutectic phase. This can readily be accomplished by heating the composite material to between about 482° C and 538° C (900° F and 1000° F) preferably for between about 8 and 36 hours. Longer times or mechanical working could be used to ensure that the eutectic phase is completely dissolved. After re-heating, the cooling step immediately follows, where the composite material cools at a rate sufficient to sustain supersaturation of the copper and the magnesium in the aluminium preferably to a temperature below about 288° C (550° F) to produce the desired precipitate below about 288° C (550° F).

Preferably, the aluminium alloy melt consists by weight of at least 85 percent aluminium, about 4 to 5 percent copper, and about 1.5 to 2.5 percent magnesium, and the method includes the step of forming a self-supporting heated pre-form of a ceramic material. Preferably, the pre-form is of a silicon carbide ceramic material which is intermingled with melted alloy in an infiltration-type intermingling or mixing process, by applying about 79290 kPa (11,500 PSI) of pressure to a surface of the molten aluminium alloy remote from the silicon carbide pre-form so as to force the molten alloy into the interstices of the pre-form (i.e. impregnate the pre-form).

In a preferred embodiment, a metal matrix composite product is formed in accordance with the invention, having a silicon carbide ceramic phase distributed substantially uniformly throughout the metal phase. Although silicon carbide ceramic material is preferred, other ceramic material, such as crystalline alumina, crystalline alumina-silica and glass, may also be selected. The metal phase comprises the aluminium-based primary metallic phase and the secondary metallic phase distributed essentially uniformly throughout the primary metallic phase wherein the secondary metallic phase contains the three elements copper, magnesium and aluminium and consists essentially of about 40 to 80 percent by weight copper, magnesium in an amount between about 5 and 30 percent by weight, and the balance essentially aluminium.

Desirably, the secondary metallic phase has cubically-shaped crystal structures which are between about 30 to 50 nm (300 to 500 angstroms) on a side, and preferably 40 nm (400 angstroms) on a side and comprises at least about 50 percent by weight copper.

Preferably, the secondary metallic phase has a volume fraction which is up to about 5 percent of the volume fraction of the metal phase; and the primary metallic phase includes alpha-aluminium with a volume fraction of at least 95 percent of the volume fraction of the metal phase. The primary metallic phase can contain up to 10 percent of eutectic phase which is generally present as a coarse network or as isolated islands in the phase.

Desirably, the ceramic phase comprises silicon carbide particles and an oxide. The oxide may be present in the form of an oxygen-containing binder, (i.e. SiO₂) admixed with silicon carbide particles. Preferably, the ceramic phase comprises silicon carbide (SiC) particles and oxides thereof, (i.e. SiO₂) formed by surface oxidation of the SiC.

Objects, features and advantages of this invention are to provide a unique metal matrix composite material with enhanced mechanical properties and a process of making it, which is efficient and economical, and which facilitates the manufacture of composite components.

It is also an object to provide a unique metal matrix composite material having a metal phase comprising an alloy: which enhances the mechanical properties of the composite material; which provides the advantages of relatively high strength and low weight as compared to other materials commonly used to form articles, such as automotive, boat, airplane and other parts; which provides high strength and low weight advantages needed to increase fuel economy and reduce fuel consumption; and which is readily adaptable to the process of casting parts.

These and other objects, features and advantages of this invention will be apparent from the following

detailed description, appended claims and accompanying drawings in which:

Figure 1 is a transmission electron micrograph of a metal matrix composite material embodying the invention.

Figure 2 is an apparatus used in a method of the invention.

5 Figure 3 is a diagram of oxide layer formation as a function of temperature.

Figure 4 is a diagram of atom percent of magnesium as a function of distance from an interface.

Figure 5 is a diagram of uniaxial tensile strength as a function of weight percent magnesium.

Figure 6 is a diagram of composite strength compared to matrix strength.

Figure 7 is a phase diagram of a Mg-Cu-Al system.

10 In a preferred embodiment of the invention, a metal matrix composite material 10, as shown in Figure 1, comprises a ceramic phase 11 distributed substantially uniformly throughout the composite material 10, and a metal phase 13 which comprises an aluminium-based primary metallic phase 14 and a secondary metallic phase 15 distributed throughout the primary metallic phase 14. The secondary metallic phase 15 contains copper, magnesium and aluminium and consists essentially of about 40 to about 80 percent by weight
15 copper, magnesium in an amount between about 5 and 30 percent by weight and the balance essentially aluminium. Preferably, the secondary metallic phase 15 comprises cubically-shaped structures which are about 40 nm (400 angstroms) on a side. The ceramic phase 11 comprises particles preferably in the form of fibres or single crystal whiskers having an aspect ratio (i.e. length to diameter ratio), greater than 3 to 1 and preferably greater than 10 to 1. Preferably, the ceramic phase 11 is of a silicon carbide material, however,
20 other ceramic materials, such as alumina, alumina-silicate glasses, and crystalline alumina-silica may be used.

The preferred method of making the metal matrix composite of the invention 10 includes the steps of:

- a) heating the ceramic material to a temperature between about 399°C and 1093°C (750°F and 2000°F) to preclude chilling of the melt upon contact with the ceramic material and to promote better
25 wetting of the ceramic material by the melt;
- b) melting an alloy comprising, by weight, about 3 to about 6 percent copper, about 0.5 to about 5 percent magnesium and the balance essentially aluminium;
- c) intermingling the heated ceramic material with the melted alloy; and
- d) cooling the intermingled ceramic material and alloy at a rate sufficient to sustain supersaturation of the
30 copper and magnesium until a predetermined temperature is reached, the predetermined temperature being selected so as to permit precipitation of a secondary metallic phase containing copper, magnesium and aluminium and consisting essentially of about 40 to 80 percent by weight of copper, magnesium in an amount between about 5 to 30 percent by weight, and the balance essentially aluminium, thereby forming a metal matrix composite having an aluminium-based primary metallic phase
35 and the secondary metallic phase distributed throughout the primary metallic phase. The primary metallic phase can contain up to 10 percent of eutectic phase which is generally present as a coarse network or as isolated islands in the phase.

The intermingling step is accomplished by a number of methods, such as mixing and heating powdered metal and ceramic material; melting a metal and adding ceramic material whilst stirring; or infiltrating a
40 ceramic pre-form with a melted metal. In essence, any method which achieves intermingling or dispersion of ceramic material in the metal alloy may be used.

The intermingled alloy and ceramic material (i.e. the composite material) must be hot enough to achieve a relatively homogeneous metal alloy solution. Then the cooling step is conducted to cool the composite material from an elevated temperature to a predetermined temperature at or below which the precipitation of
45 the secondary metallic phase occurs. The cooling step is sufficiently rapid as to preclude any substantial precipitation from occurring before the predetermined temperature is reached.

Preferably, the aforesaid rapid cooling occurs immediately after the step of intermingling to achieve a temperature below about 288°C (550°F) thereby causing precipitation to occur below about 288°C (550°F). Due to the configuration of many components it is often not practically possible to conduct a
50 controlled, rapid cooling or to quench immediately after intermingling as different portions of the component cool at different rates. Therefore, the constraints of the manufacturing process may require that the step of controlled cooling be deferred. If such a deferral causes the composite material to cool at an uncontrolled rate, the composite material must then be re-heated to a temperature sufficient to re-dissolve or re-solubilize the copper and magnesium in the aluminium including that present in the eutectic phase. Heating
55 to a temperature between about 482°C and 538°C (900°F and 1000°F) preferably for between about 8 and about 36 hours is adequate for this purpose though any temperature above about 482°C (900°F) would be effective. Longer times or mechanical working could be used to ensure that the eutectic phase is completely dissolved. After re-heating, the cooling step immediately follows, where the composite material

cools at a rate sufficient to sustain supersaturation (i.e. of the copper and magnesium in the aluminium) preferably to a temperature below about 288° C (550° F) to produce the desired precipitate below about 288° C (550° F).

The rapid cooling is desirably conducted by quenching in a liquid, preferably water, at a temperature between about 26.7° C and 93° C (80° F and 200° F). Then, if desired, an aging step may follow the quench. The aging step desirably occurs at about 66° C to 288° C (150° F to 550° F) for about 4 to about 48 hours, and preferably at 149° C to 204° C (300° F to 400° F) for 4 to 8 hours. A natural aging step may be conducted at about room temperature for up to a few days. It is well known in the art that aluminium alloys generally exhibit an increase in strength over time, sometimes for years after quenching. Thus, the aging step will simply depend on the temper condition desired at the time the part is placed in use. In order to efficiently and economically produce cast components, preferably the infiltration method is used to achieve mixing or intermingling. In this preferred method, a ceramic pre-form is contoured to the shape of the final part desired; heated; impregnated with molten alloy metal under pressure; and then cooled at a relatively rapid, controlled rate. The resultant composite part will be in the shape of the final product desired, with little or no subsequent machining being required. Importantly, no subsequent treatment such as mechanical work or heat treatment is required to impart enhanced mechanical properties, as further discussed below.

The metal matrix composite process and the physical properties of the composite material will be further described by reference to the following examples.

Example 1

The preferred infiltration method was used to cast a component part from a pre-form of the preferred silicon carbide material, which was contoured to the final shape desired for the part. In this method:

- a) a porous (i.e. 80% porosity) pre-form was formed of a ceramic material which included silicon carbide whiskers bound together by a layer of oxides of silicon (i.e. SiO₂) on the surface of the whiskers;
- b) the pre-form was placed in a mould and was heated to a temperature between about 788° C and 816° C (1450° F and 1500° F);
- c) an alloy comprising by weight, about 4.5 percent copper, about 0.45 percent magnesium, the balance essentially aluminium, was melted at a temperature between about 788° C and 816° C (1450° F and 1500° F);
- d) the heated ceramic pre-form was impregnated with the melted alloy by applying about 79290 kPa (11,500 PSI) of pressure to a free surface of the molten aluminium alloy remote from the pre-form;
- e) the pressure was maintained for about 4 minutes to enable the metal to solidify, after which the infiltrated pre-form and excess solidified metal was ejected from the mould;
- f) the impregnated pre-form was naturally cooled from an ejection temperature of about 454° C (850° F) to room temperature at an uncontrolled rate;
- g) the impregnated pre-form was solution-treated by re-heating to 525° C (977° F) by placing in a furnace heated to 399° C (750° F) and ramping the temperatures up to 525° C (977° F) at a rate not exceeding more than 22° C (40° F) per hour, and holding for 16 hours followed by water quenching into 68° C (155° F) water at a rate of about 220° C (400° F) per second; and
- h) the solution-treated impregnated pre-form was aged for 5 hours at 188° C (370° F) and air-cooled. At this temperature a secondary metallic phase formed which contained the three elements, copper, magnesium and aluminium. The metallic phase essentially consisted of about 40 to about 80 percent by weight copper, magnesium in an amount between about 5 and 30 percent by weight and the balance essentially aluminium. By this infiltration method, a metal matrix composite material was formed having an aluminium-based primary metallic phase comprising about 95 percent by volume alpha aluminium and the secondary metallic phase distributed throughout the primary metallic phase. The primary metallic phase can contain up to 10 percent of eutectic phase which is generally present as a coarse network or as isolated islands. The resultant metal matrix composite product had a silicon carbide content of about 20 percent by volume, a yield strength of 317 megapascals (MPa), a tensile strength of 317 MPa and exhibited elongation of zero percent.

Examples 2, 3, 4 and 5

In Examples 2, 3, 4 and 5 the method of Example 1 was followed except that the weight percent of magnesium was increased to 0.9 percent, 1.1 percent, 1.58 percent, and 1.9 percent, respectively. The yield strength was, respectively, 459 MPa, 476 MPa, 478 MPa and 512 MPa; the tensile strength was, respectively, 562 MPa, 546 MPa, 543 MPa and 596 MPa; and the total elongation was, respectively, 2%,

0.9%, 0.5% and 1.3%. Table 1 is a summary of the properties obtained from the examples.

TABLE 1

Example No.	Mg %	Yield Strength (MPa)	Tensile Strength		Total Elongation (%)
			(MPa)	(KSI)	
1	0.45	317	317	46	0.0
2	0.90	459	562	81	2.0
3	1.10	476	546	79	0.9
4	1.58	478	543	79	0.5
5	1.90	512	596	86	1.3
MPa = Megapascals					
KSI = Thousands of Pounds per Square Inch					

In Examples 1-5, infiltration was accomplished using a casting mould 19, (Fig. 2). The pre-form 20 was made of the preferred silicon carbide particles, with an oxide layer grown on the silicon carbide particles by heating the particles in air at an elevated temperature. The oxide layer had a thickness of approximately 0.2 micrometres. The pre-form 20 was placed in a cylindrical cavity 22 of an open-top die 24 having a sleeve 25 resting on a base element 26 and heated to the temperature specified. A charge of molten aluminium alloy 27 was then ladled into cavity 22 and onto the pre-form 20. A hydraulically-driven punch 28 was advanced into cavity 22 to apply a pressure of about 79290 kPa (11,500 PSI) to a free surface 29 of the molten alloy charge 27 remote from the pre-form 20, to inject the alloy 27 by force of pressure into the voids of the pre-form 20 in about 15 to 30 seconds.

Although silicon carbide particles were used in Examples 1-5, composite materials were also formed with either crystalline alumina-silica, or alumina-silicate glass in place of silicon carbide. The silicon carbide particles used in the examples were of the preferred whisker type, having diameters less than two micrometres and elongated with an aspect ratio generally greater than about 3 to 1 and preferably significantly greater than 10 to 1.

An oxide layer seemed to facilitate the wetting of the ceramic material by the metal alloy. An oxide layer may be present in the form of a binder added to the ceramic material, or grown "in situ" by surface oxidation of the ceramic material. One such binder is colloidal silica (SiO_2) or colloidal alumina (Al_2O_3).

Preferably, the oxide layer is grown in situ by surface oxidation of the ceramic material. It has been found that the thickness of the oxide layer on the silicon carbide may be controlled. Various thicknesses of silicon oxides (i.e. SiO_2) were formed by heating in air to temperatures in the range of 800 °C to 1400 °C. At the lower end of the range, an oxide thickness of about 0.2 micrometres was achieved, at the higher end of the range, an oxide thickness of about 0.5 micrometres was achieved in about 10 to 16 hours. The thickness of the oxide film in micrometres, is shown as a function of temperature in Figure 3.

In Examples 1-5, the alloy used was 206 aluminium available from any casting alloy supplier in the U.S.A. The 206 aluminium is essentially a binary Al-4.5% Cu alloy with trace amounts of other elements. Various amounts of magnesium were added to the 206 Al-4.5% Cu alloy to form the Al-Cu-Mg alloy melts with Mg in the range of 0.45% to 1.9% by weight.

It has been found that a range of about 0.5 to about 5 percent Mg and a range of about 3 to 6 percent Cu are each satisfactory ranges, the balance being essentially aluminium. Preferably, magnesium is present in the alloy in a range of about 1.5 to 2.5 weight percent and copper is present in the alloy in a range of about 4 to 5 weight percent. Other elements typically found in alloys may also be present in low concentrations. Such typical elements include manganese (Mn), chromium (Cr), zinc (Zn), titanium (Ti), iron (Fe), vanadium (V), zirconium (Zr), nickel (Ni), bismuth (Bi), palladium (Pd), tin (Sn), beryllium (Be), silver (Ag), antimony (Sb), cobalt (Co) and silicon (Si). These typical elements may be present in concentrations up to about 3 percent but preferably are present in smaller quantities. Silicon, up to about 20 weight percent, may be tolerated.

It has been found that the pre-form should be heated, prior to impregnation, to a temperature of between about 399 °C and 1093 °C (750 °F and 2000 °F) and preferably to a temperature between about 649 °C and 954 °C (1200 °F and 1750 °F). Pre-heating of the pre-form will facilitate impregnation thereof and will prevent the occurrence, for example, of premature solidification of the molten alloy.

The pressure at which impregnation occurs in an infiltration technique is not critical. Preferably, the pressure is of the order of 34474 kPa (5,000 pounds per square inch) or greater. Generally, the selection of the pressure is determined by the desired length of the infiltration step, so long as premature cooling does not occur. Higher pressures cause infiltration to occur more rapidly and lower pressures cause infiltration to occur more slowly.

The cooling rate of about 220 °C (400 °F) per second after completion of solidification was found to be satisfactory. Other rates of cooling may be used so long as cooling proceeds sufficiently rapidly to a temperature below about 288 °C (550 °F), so that essentially all of the precipitation will occur at a temperature below about 288 °C (550 °F).

The metal matrix composite materials of the invention comprising the preferred silicon carbide ceramic material and the new second metal phase composition, as shown in Figure 1, have the strengths as shown in Table 1. The new secondary metallic phase is in the form of cubically-shaped structures, about 30 nm to 50 nm (300 to about 500 angstroms) on a side and preferably about 40 nm (400 angstroms) on a side. The structures are clearly visible on the transmission electron micrograph of Figure 1. Although the secondary metallic phase consists of about 40 to 80 percent by weight copper, magnesium in an amount between about 5 and 30 percent by weight, and the balance essentially aluminium, it has been found that the atom percent of magnesium, at the interface between the metal and the ceramic material, in the "as cast" material, is relatively high and drops off significantly with distance from the interface (Figure 4).

The metal matrix composite material of the invention clearly exhibits improved strength compared to the unre-inforced metal. As shown in Figure 5, the re-inforced matrix (i.e. the composite material) has a uniaxial tensile strength (UTS) in the range of 482633 kPa (70 to 90 thousands of pounds per square inch (KSI)), as magnesium is increased from about 0.5 percent to about 2 percent. In contrast, the unre-inforced matrix metal alone has a UTS which decreases from a high of about 448159 kPa (65 KSI) down to about 103421 kPa (15 KSI) as the percentage of magnesium increases from about 0.5 percent to about 2 percent.

The metal matrix composites 10 were compared to prior-art wrought composite materials obtained by repeated working and/or heat-treating. Figure 6 is a graph having matrix tensile strength on the X axis and composite strength on the Y axis. Sigma C represents the composite strength and Sigma M represents the matrix strength. The diagonal line is formed by points where Sigma C and Sigma M are equal. Thus, if the strength of a composite material is greater than the strength of the matrix metal alone, such a composite material would be represented on the graph by a point above the diagonal line. The composite materials of the invention 10, indicated on Table 1, generally exhibit strength well in excess of 500 MPa and approaching 600 MPa; and the composite materials 10 are represented by the large cross located above the diagonal line in Figure 6.

Wrought composite materials, indicated by squares in Figure 6, exhibit a wide range of strengths and in one case the strength of the wrought composite material is worse than that of the matrix metal. Such wrought composite materials required significant additional treatment to obtain their properties, as shown in Figure 6. In contrast, the metal matrix composite materials of the invention 10 in their "as cast and heat-treated condition", without subsequent mechanical working treatment, have properties comparable to or better than the wrought composite materials.

Two comparative cast composite materials are indicated on Figure 6, by small crosses. These two comparative composite materials were formed with either a 339 or 1275 aluminium alloy, each of which is different from the alloy of the invention. The comparative composite materials exhibit considerably less strength than the composite material of the invention 10. The composite materials of the invention 10 may be subjected to subsequent working and/or heat treating to further enhance their properties over and above the improved properties shown on Figure 6.

Although not wishing to be confined to any particular theory, it appears that the enhanced properties of the composite materials of the invention 10 are achieved, at least in part, because: (1) magnesium significantly improves bonding, as is well-known; (2) there is a limited amount of low-melting eutectic phase in the composite material; (3) magnesium, and particularly copper, provide a relatively large amount of the secondary metallic phase which is a strengthening precipitate; (4) the ceramic material enhances stability of the secondary metallic phase; (5) the oxide layer improves strength by improving bonding at the metal-ceramic interface; and (6) the ceramic material and oxide may each improve strength by contributing to the formation of the copper-rich second metal phase, which has not heretofore been observed in castings.

In order to produce these results the invention takes advantage of the phenomena that an alloy exists as a homogeneous solution at one temperature and decomposes into its constituents at some lower temperature. A more fundamental description of this phenomena, which occurs as cooling takes place may be helpful. When metals dissolve in one another at an elevated temperature, desired compositions and properties may be obtained by controlling the cooling of the metal solution from the elevated temperature.

For example, the solubilities of several alloying elements in solid aluminium are much greater at elevated temperatures than at room temperature. If an aluminium alloy containing, for example, 5 percent by weight copper is heated to well over 482° C (900° F), all of the copper will be in solution. If the alloy is then rapidly cooled or quenched, it becomes supersaturated, containing almost 5 percent more copper solute in solution than it can retain under equilibrium conditions, and particles of an aluminium-copper metallic phase will precipitate. The final properties will depend on the size and distribution of the precipitated particles, which in turn depend on the control of the cooling conditions. The rejection of solute to form a precipitate generally occurs in a similar manner whether the metal solution is a solid or liquid. Thus, the changes that take place when a liquid solution cools may also occur during the cooling of a solid solution. The invention takes advantage of the phenomena that an alloy exists as a homogeneous solution at one temperature and decomposes into its constituents at some lower temperature. Such decomposition leads to the formation of a metal phase, the structure of which is like that of the eutectic if cooling occurs from a liquid, or a eutectoid if the structure is the result of the decomposition of a solid solution. Whether the cooling occurs from a liquid homogeneous solution or a solid homogeneous solution is not critical. What is critical is preventing the rejection of solute until a desired (lower) temperature is reached, to form the desired precipitate. Correspondingly, if the composition of the precipitate desired is known, the cooling conditions may be controlled so as to selectively generate the desired precipitate.

As was described earlier, if a casting is made and controlled cooling does not immediately take place, the cast part will be permitted to cool at some random uncontrolled rate. The desired composition of the metal phase will, therefore, not be achieved. In this event, to take advantage of the precipitation hardening reaction, it is possible to produce a supersaturated solid solution by re-heating the part, and then conducting the rapid cooling step.

Transmission electron micrographs show the existence of the cubic-shaped precipitate obtained by the method of the invention. The precipitate has not been observed before in castings and was tentatively determined to include one or more of the following specific compositions: Cu₆Mg₂Al₅, CuAl₂, CuMgAl₂ and/or CuMgAl.

Relative to other systems, very little is known about the Mg-Cu-Al system. Although some phases having Mg-Cu-Al have been reported, many of those which have been reported are said: (1) to be unstable and are not in equilibrium with aluminium; and/or (2) to require the presence of zinc, thus forming an Al-Cu-Mg-Zn phase. It has been determined that the precipitate of the invention, that is the secondary metallic phase of the invention, has a composition in the range bounded by the trapezoidal-shaped area shown on the intermetallic phase diagram of Figure 7. This phase consists of the three elements copper, magnesium and aluminium and has over 40 percent copper and magnesium in an amount between about 5 and 30 percent by weight, with the balance essentially aluminium. Such a phase has never been reported in a cast metal matrix composite material.

With regard to the phenomena of enhanced bonding, Figure 4 shows that the atom percent of magnesium at the interface between the metal and the ceramic material is relatively high and drops off significantly with distance from the interface. It is believed that enhanced bonding is also achieved by the magnesium addition.

The enhanced mechanical properties of the composite material are believed to be produced by: (1) a strong, thin bond (interface) for efficient load transfer; (2) an interface which remains stable during service; and (3) a strong, tough matrix which resists crack propagation with particle and whisker re-inforcements. More specifically, the controlling of the interfacial properties and the formation of the second metal phase which leads to the enhanced mechanical characteristics is believed to be due to a combination of the composition of the matrix metal phase, the oxide layer on the re-inforcement and the controlled cooling and precipitation hardening of the metal matrix.

The invention provides enhanced metal matrix composite properties achieved by the specific constituents of the matrix, their volume or weight fraction, the method by which the metal matrix composite material is formed and the temperature conditions prevailing during formation of the metal matrix composite material.

The invention also provides optimized matrix toughness, control of the matrix/re-inforcement interaction and the ability to maintain the desired matrix composition during manufacture of a composite material and the service life of the composite material. Metal matrix composite materials of the invention achieve the advantages of relatively high strength and low weight as compared to other materials commonly used to form articles.

Finally, the invention provides metal matrix composite materials fabricated by a method which: (1) is cost-effective because it utilizes an intermingling impregnation process which provides a casting in the shape of the part desired; and (2) permits, alternatively, an immediate cooling step after infiltration, or re-heating and cooling steps to achieve the enhanced metal matrix composite properties.

While the invention has been described primarily in terms of specific examples thereof it is not intended to be limited thereto but rather only to the extent set forth hereafter in the scope of the claims which follow.

Claims

1. A method of forming a metal matrix composite material (10) having a ceramic phase (11) intermingled with an aluminium alloy phase (13), characterised in that the method comprises the steps of:
 - a) heating a ceramic material having silicon dioxide (SiO_2) on the surface thereof to a temperature between about 399°C and 1093°C ;
 - b) melting an alloy comprising, by weight, about 3 to 6 percent copper, about 0.5 to 5 percent magnesium, and the balance essentially aluminium;
 - c) intermingling the heated ceramic material with the melted alloy whereby the magnesium reacts with the silicon dioxide (SiO_2) and liberates silicon (Si) into the alloy; and
 - d) cooling the intermingled ceramic material and alloy at a rate sufficient to sustain supersaturation of the copper and magnesium in the aluminium until a predetermined temperature is reached, the predetermined temperature being selected so as to permit precipitation of a secondary metallic phase (15) having a cubically-shaped crystal structure and consisting essentially of about 40 to 80 percent by weight copper, magnesium in an amount between about 5 and 30 percent by weight, and the balance essentially aluminium, thereby forming a metal matrix composite material (10) having an aluminium-based primary metallic phase (14) and the secondary metallic phase (15) distributed throughout the primary metallic phase (14).
2. A method according to claim 1, in which the predetermined temperature is below about 288°C .
3. A method according to claim 1, in which the aluminium alloy comprises at least 85 percent aluminium, about 4 to 5 percent copper and about 1.5 to 2.5 percent magnesium by weight.
4. A method according to claim 1, in which the cooling step substantially immediately succeeds the intermingling step.
5. A method according to claim 1, in which, after step (c) and immediately before step (d), the intermingled ceramic material and alloy are permitted to cool and are subsequently re-heated to a temperature above about 482°C for a time sufficient to dissolve the copper and magnesium in the aluminium.
6. A method according to claim 5, in which the temperature is less than 538°C and the time is between about 8 and 36 hours.
7. A method of forming a metal matrix composite material (10) according to any one of the preceding claims, in which the ceramic phase (11) is silicon carbide.
8. A method according to claim 7, in which the ceramic phase (11) comprises a plethora of silicon carbide particles.
9. A method according to claim 8, in which the particles are elongated particles having an aspect ratio greater than 3 to 1.
10. A method of forming a metal matrix composite material (10) having a ceramic phase (11) containing silicon intermingled with an aluminium alloy phase (13), characterised in that the silicon is present in the ceramic phase (11) as silicon carbide, and the method comprises the steps of:
 - a) forming a porous pre-form (20) of the silicon carbide ceramic material, said pre-form (20) having silicon dioxide (SiO_2) on the surfaces thereof;
 - b) heating the pre-form (20) to a temperature between about 399°C and 1093°C ;
 - c) melting an alloy comprising by weight, about 3 to 6 percent copper, about 0.5 to 5 percent magnesium, and the balance essentially aluminium;
 - d) impregnating the heated pre-form (20) with the melted alloy (27) whereby the magnesium reacts with the silicon dioxide (SiO_2) and liberates silicon (Si) into the alloy; and
 - e) cooling the impregnated pre-form at a rate sufficient to sustain supersaturation of the copper and

- 5 magnesium in the aluminium until a predetermined temperature is reached, the predetermined temperature being selected so as to permit precipitation of a secondary metallic phase (15) having a cubically-shaped crystal structure and consisting essentially of about 40 to 80 percent by weight copper, magnesium in an amount between about 5 and 30 percent by weight, and the balance essentially aluminium, thereby forming a metal matrix composite material (10) having an aluminium-based primary metallic phase (14) and the secondary metallic phase (15) distributed throughout the primary metallic phase (14).
- 10 11. A method according to claim 10, in which the pre-form (20) is impregnated by applying a force of at least 34474 kPa to a free surface (29) of the molten alloy (27) to force the molten alloy (27) into the pre-form (20).
12. A method according to claim 10, in which the predetermined temperature is below about 288 ° C.
- 15 13. A method according to claim 10, in which the aluminium alloy comprises at least about 85 percent aluminium, about 4 to 5 percent copper and about 1.5 to 2.5 percent magnesium by weight.
- 20 14. A method according to claim 10, in which, after step (d) and immediately before step (e), the impregnated pre-form (20) is permitted to cool and is subsequently re-heated to a temperature above about 482 ° C for a time sufficient to dissolve the copper and magnesium in the aluminium.
15. A method according to claim 14, in which the temperature is less than 538 ° C and the time is between about 8 and 36 hours.
- 25 16. A method according to claim 10, in which the cooling step substantially immediately succeeds said impregnating step.
17. A method according to claim 10, in which the ceramic phase (11) comprises a plethora of silicon carbide particles.
- 30 18. A method according to claim 17, in which the particles are elongated particles having an aspect ratio greater than 3 to 1.
- 35 19. A method according to claim 10, in which the ceramic phase (11) comprises a plethora of silicon carbide particles and a binder therefor containing silicon dioxide (SiO₂).
20. A metal matrix composite casting comprising:
- 40 a) a ceramic phase (11) containing a silicon compound, distributed substantially uniformly throughout the casting; and
- b) a metal phase (13) containing aluminium, copper and magnesium, characterised in that the metal phase (13) comprises, by weight, about 3 to 6 percent copper, about 0.5 to 5 percent magnesium, and the balance essentially aluminium, said metal phase (13) having an aluminium-rich primary metallic phase (14) and a copper-rich secondary metallic phase (15) distributed throughout the primary metallic phase (14), wherein said secondary metallic phase (15) has a cubically-shaped crystal structure and consists essentially of about 40 to about 80 percent by weight copper, about 5 to about 30 percent by weight magnesium, and the balance essentially aluminium.
- 45 21. A casting according to claim 20, in which said cubically-shaped crystal structure measures about 30 to 50 nanometres on a side.
- 50 22. A casting according to claim 21, in which said cubically-shaped crystal structure measures about 40 nanometres on a side.
23. A casting according to claim 20, in which the secondary metallic phase (15) is distributed substantially uniformly throughout the primary metallic phase (14).
- 55 24. A casting according to claim 20, in which the secondary metallic phase (15) forms up to about 5 percent by volume of the metal phase.

25. A casting according to claim 20, in which the primary metallic phase includes alpha-aluminium and at least 95 percent by volume of the metal phase.

26. A casting according to claim 20, in which the ceramic phase comprises elongated silicon carbide particles having an aspect ratio greater than 3 to 1.

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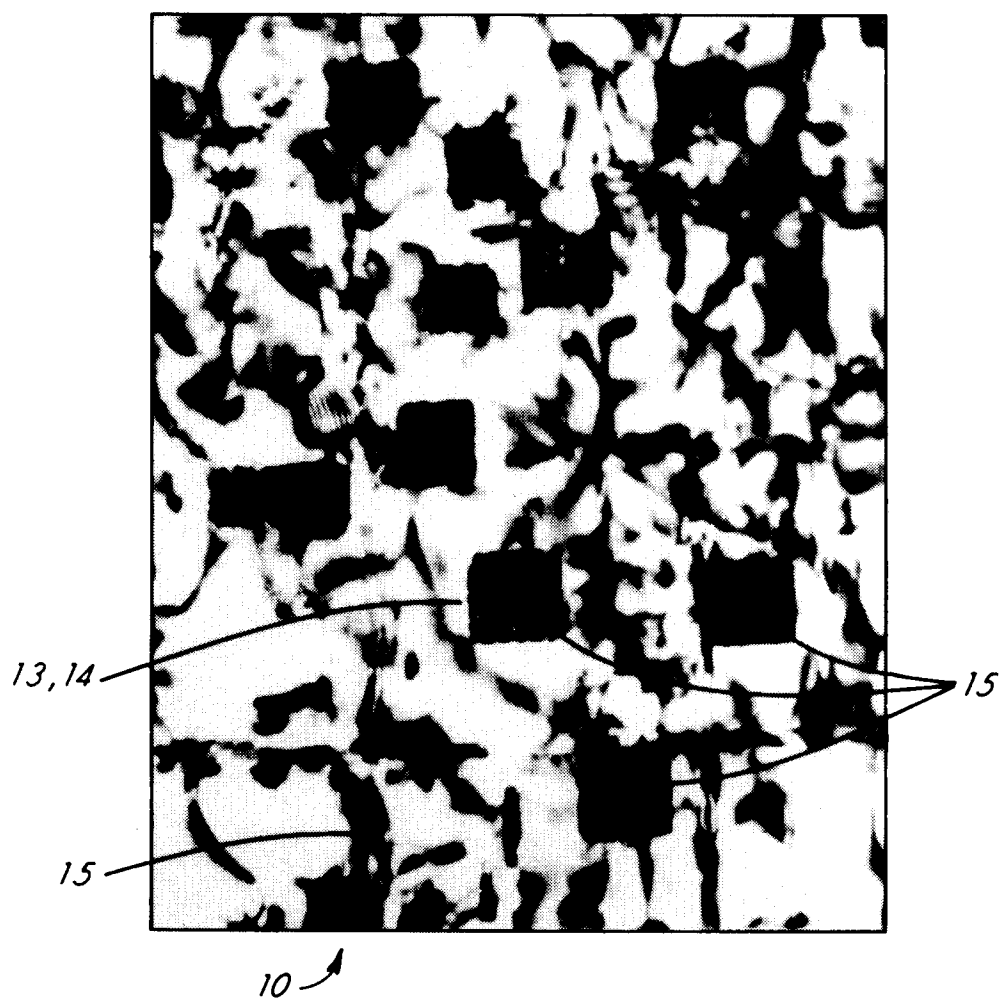


Fig.1.

Fig. 2.

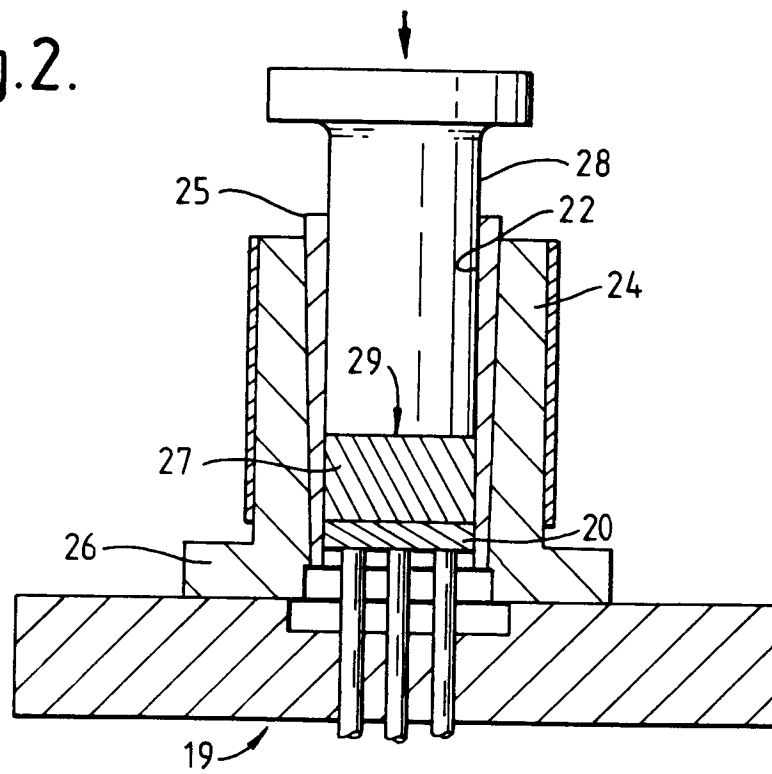


Fig. 3.

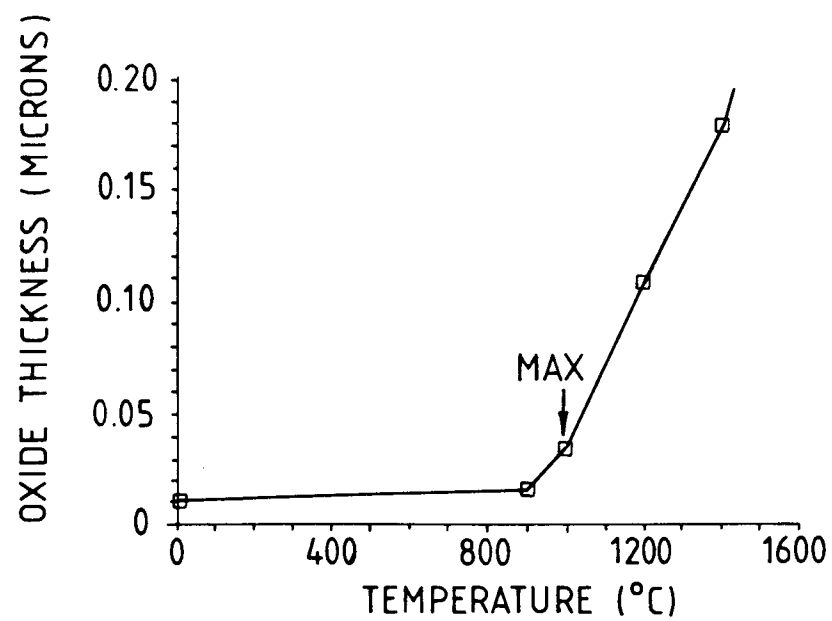


Fig. 4.

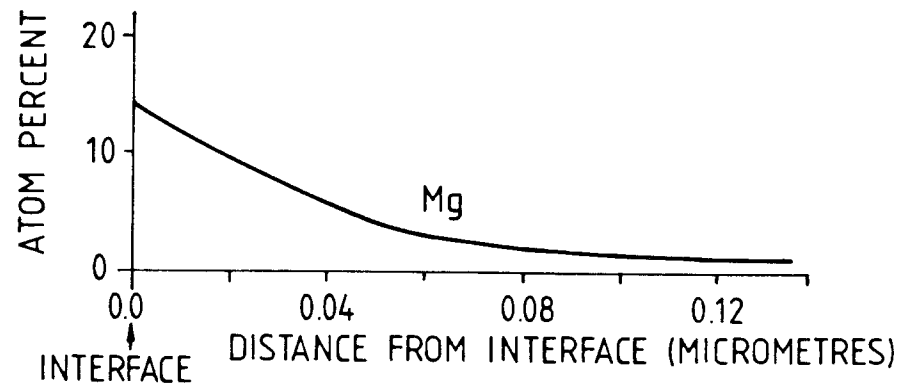


Fig. 7.

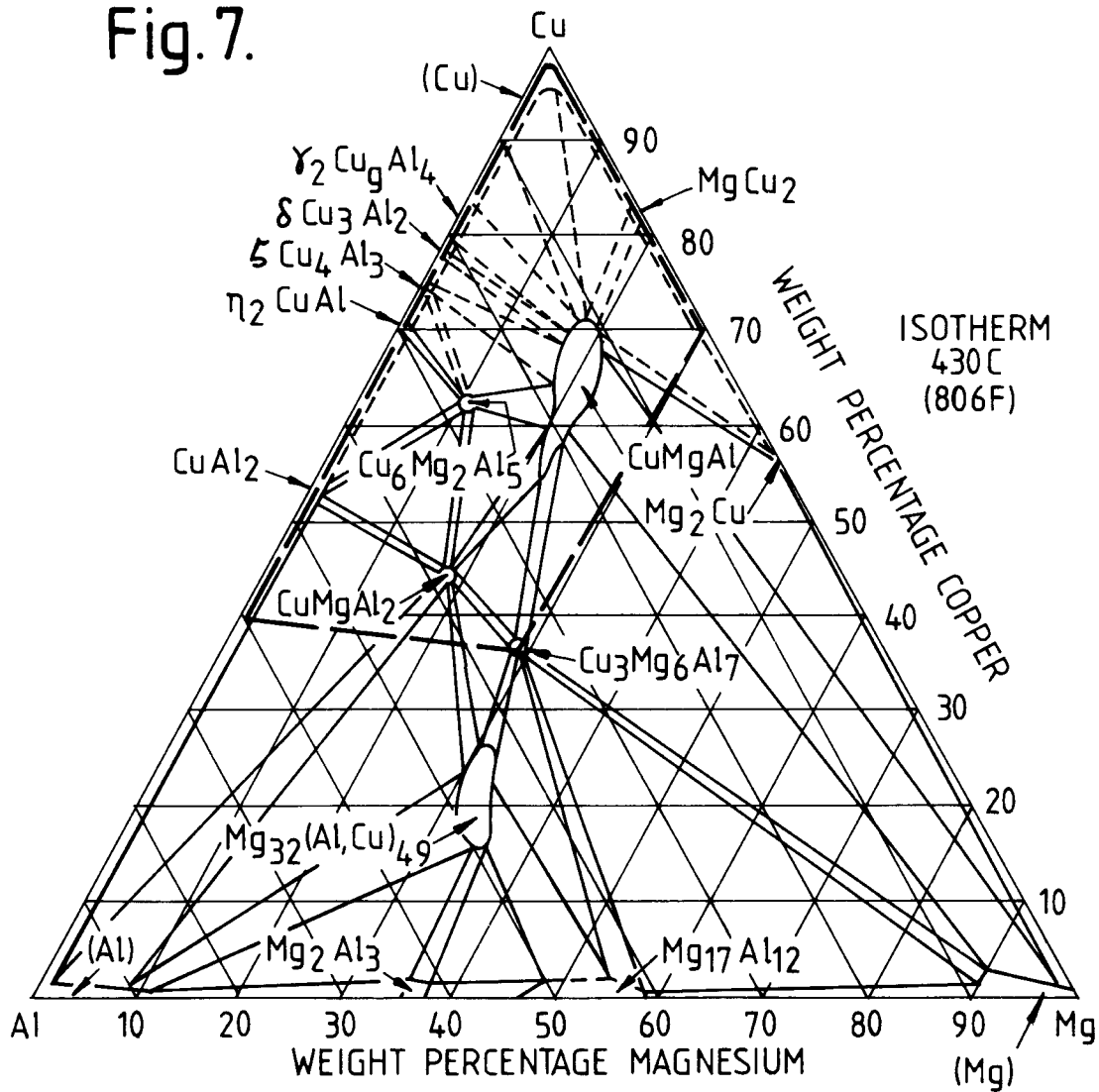


Fig.5.

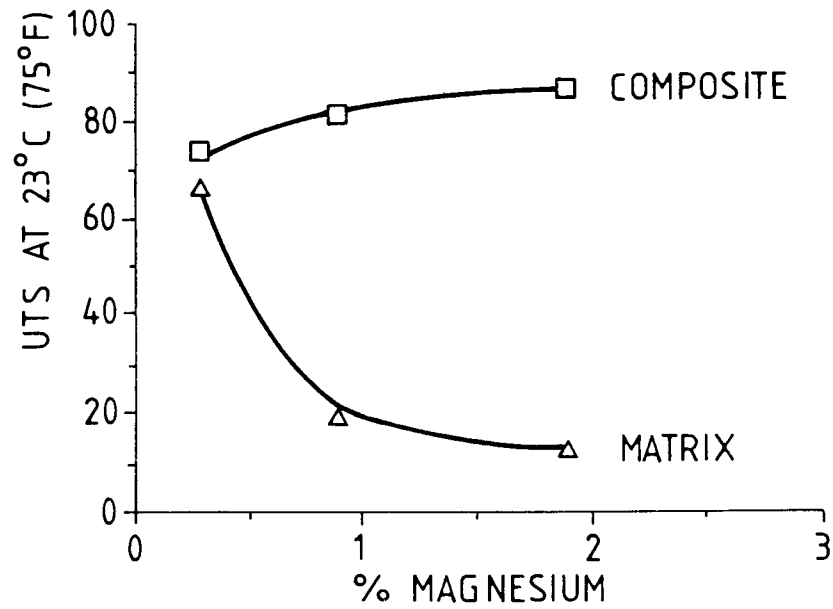


Fig.6.

