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(54) TI PARTICLE-DISPERSED MAGNESIUM-BASED COMPOSITE MATERIAL, AND MANUFACTURING METHOD THEREOF

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(57) **ABSTRACT**

A Ti particle-dispersed magnesium-based composite material is a material having titanium particles uniformly dispersed in a magnesium matrix, and is characterized by having a titanium-aluminum compound layer at an interface between the magnesium alloy matrix and the titanium particles dispersed in the magnesium alloy matrix.

CAST MATERIAL USING MOLTEN MIXED POWDER (Mg-6% Al-1% Mn)
WITH 10% Ti PARTICLES (MELTING TEMPERATURE: 700 ℃, HOLD TIME: 30 MIN)

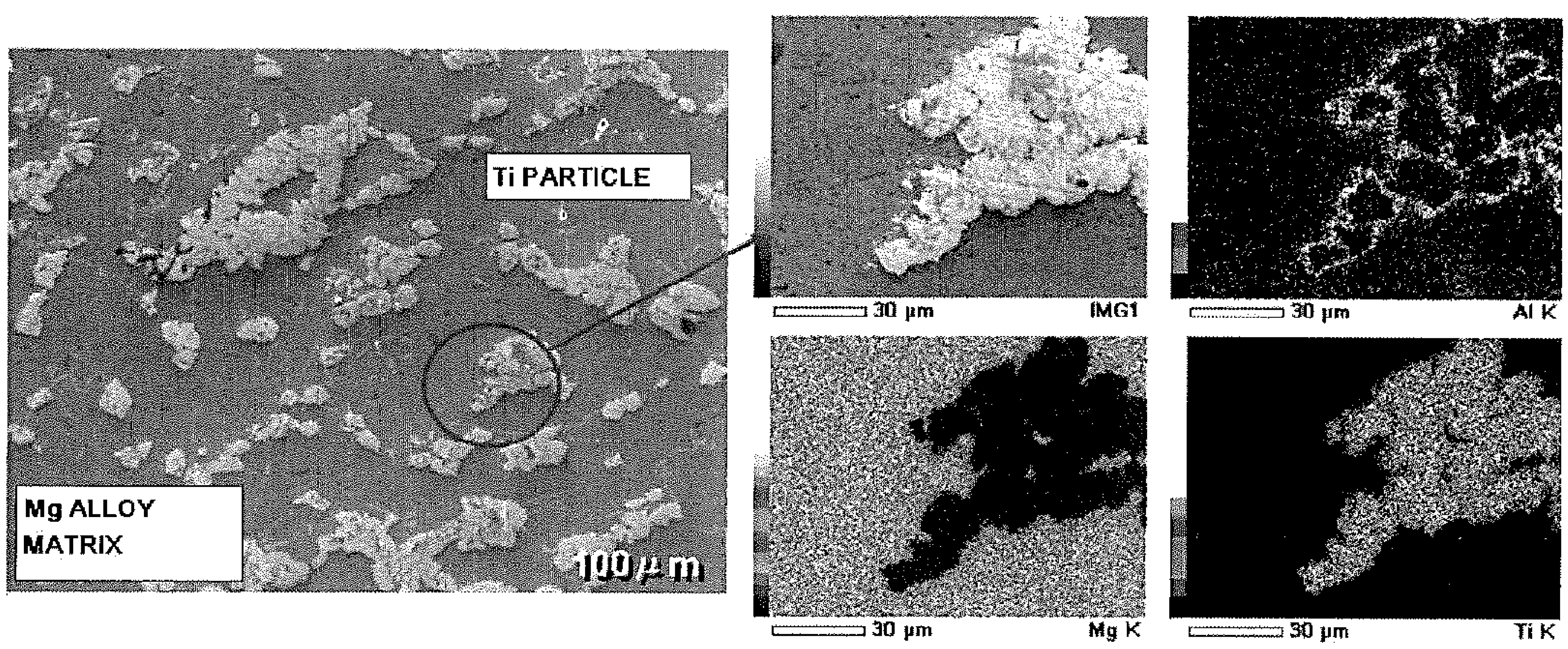


FIG. 1

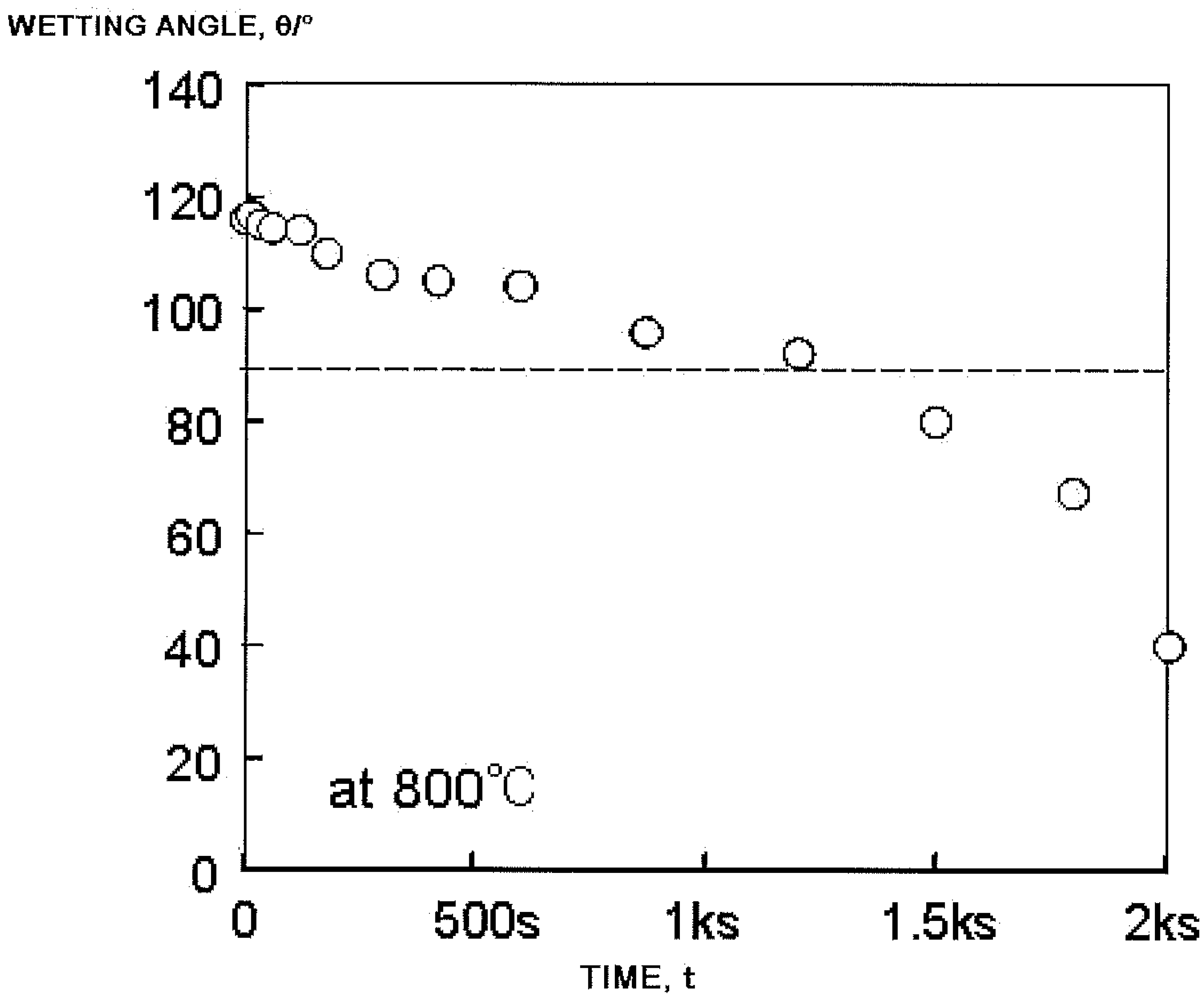

WETTING ANGLE, θ/°
140
120
100
80
60
40
20
0
at 800°C
0
500s
1ks
1.5ks
2ks
TIME, t

FIG. 2

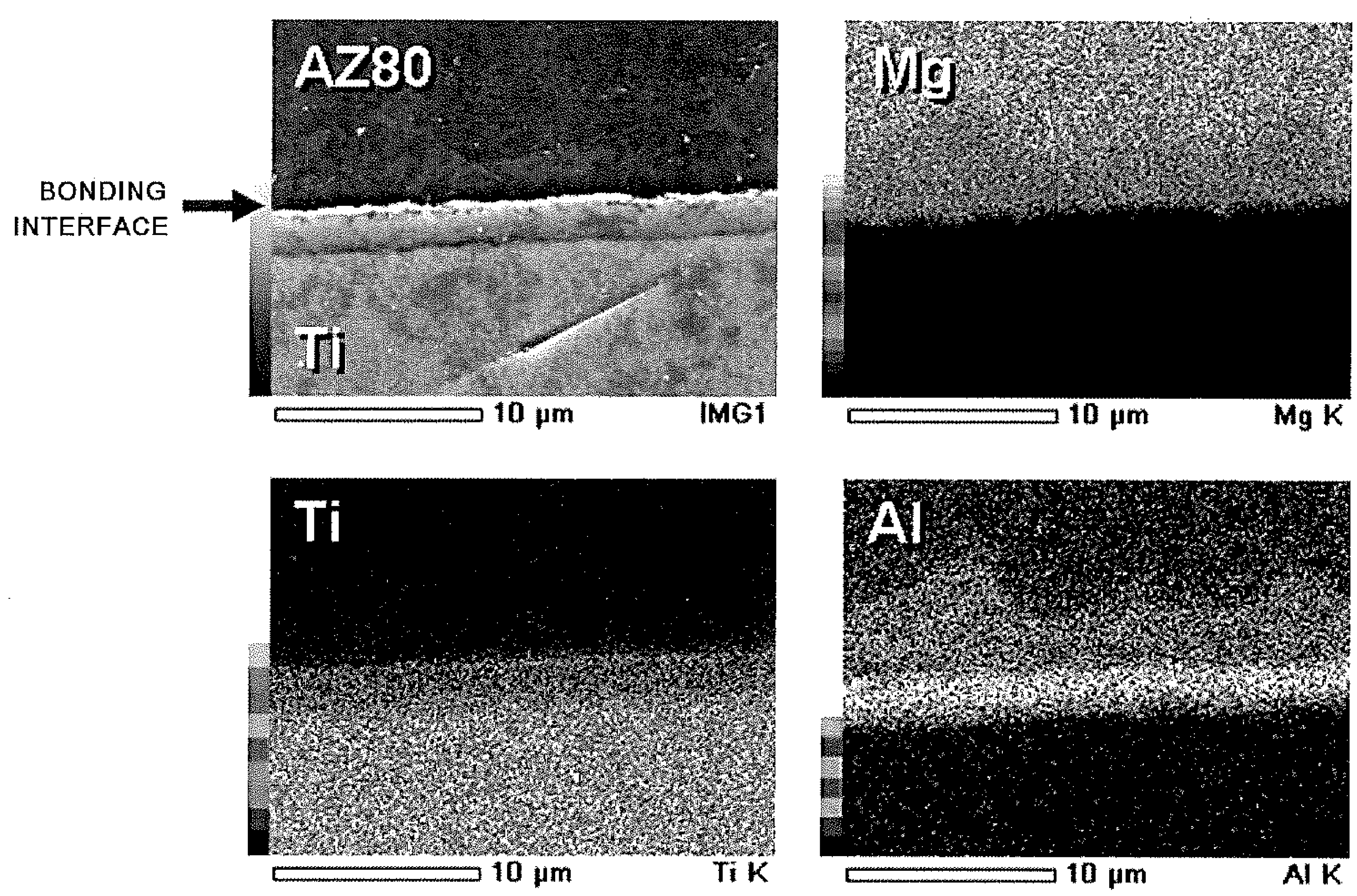

AZ80
BONDING INTERFACE
Ti
10 μm
IMG1
Mg
10 μm
Mg K
Ti
10 μm
Ti K
Al
10 μm
Al K

FIG. 3

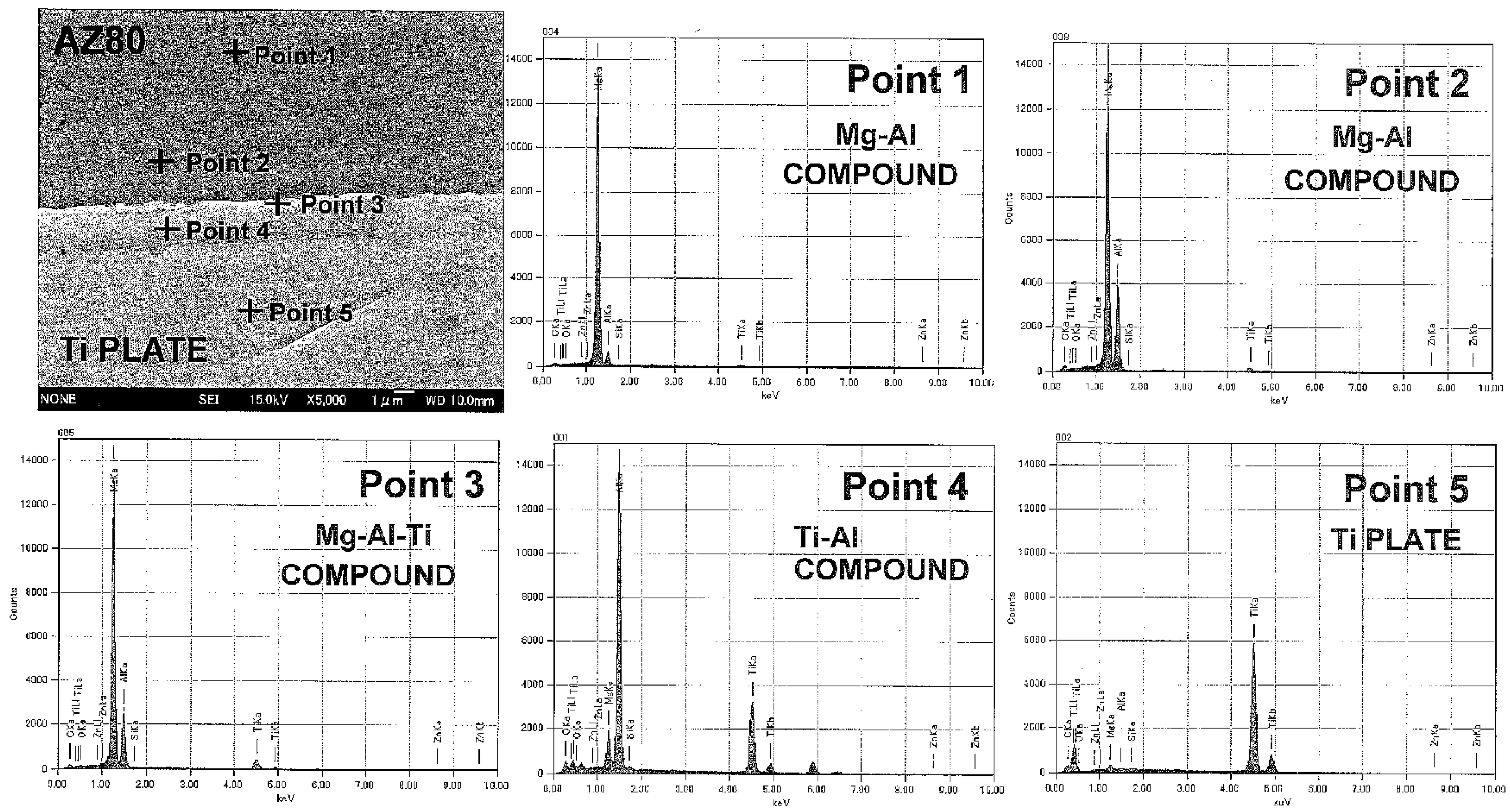

AZ80
Point 1
Point 2
Point 3
Point 4
Point 5
Ti PLATE
Point 1
Mg-Al
COMPOUND
Point 2
Mg-Al
COMPOUND
Point 3
Mg-Al-Ti
COMPOUND
Point 4
Ti-Al
COMPOUND
Point 5
Ti PLATE

FIG. 4

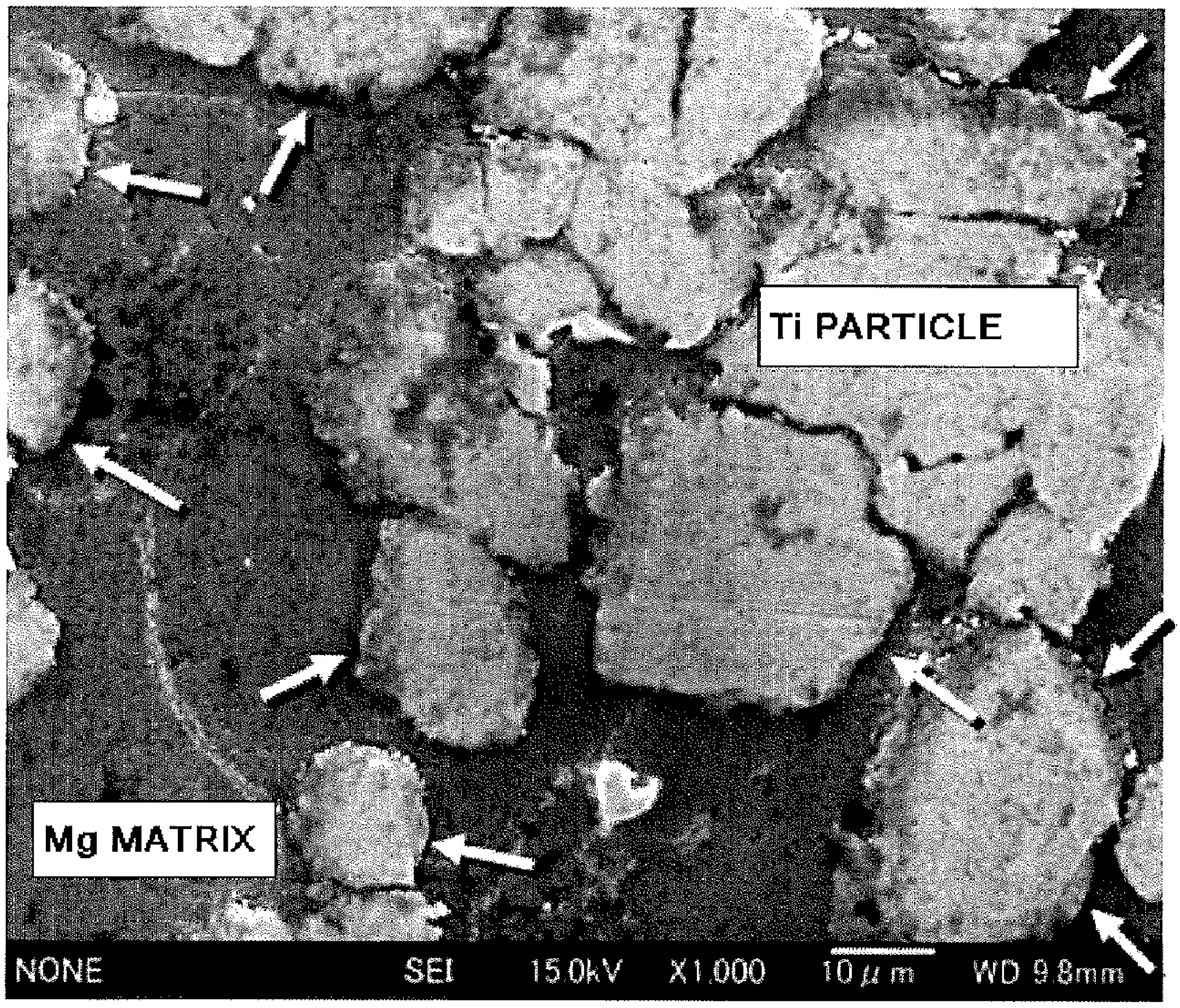



FIG. 5

CAST MATERIAL USING MOLTEN AZ61 (Mg-6% Al-1% Zn)
CONTAINING Ti PARTICLES (MELTING TEMPERATURE: 700°C, HOLD TIME: 30 MIN)

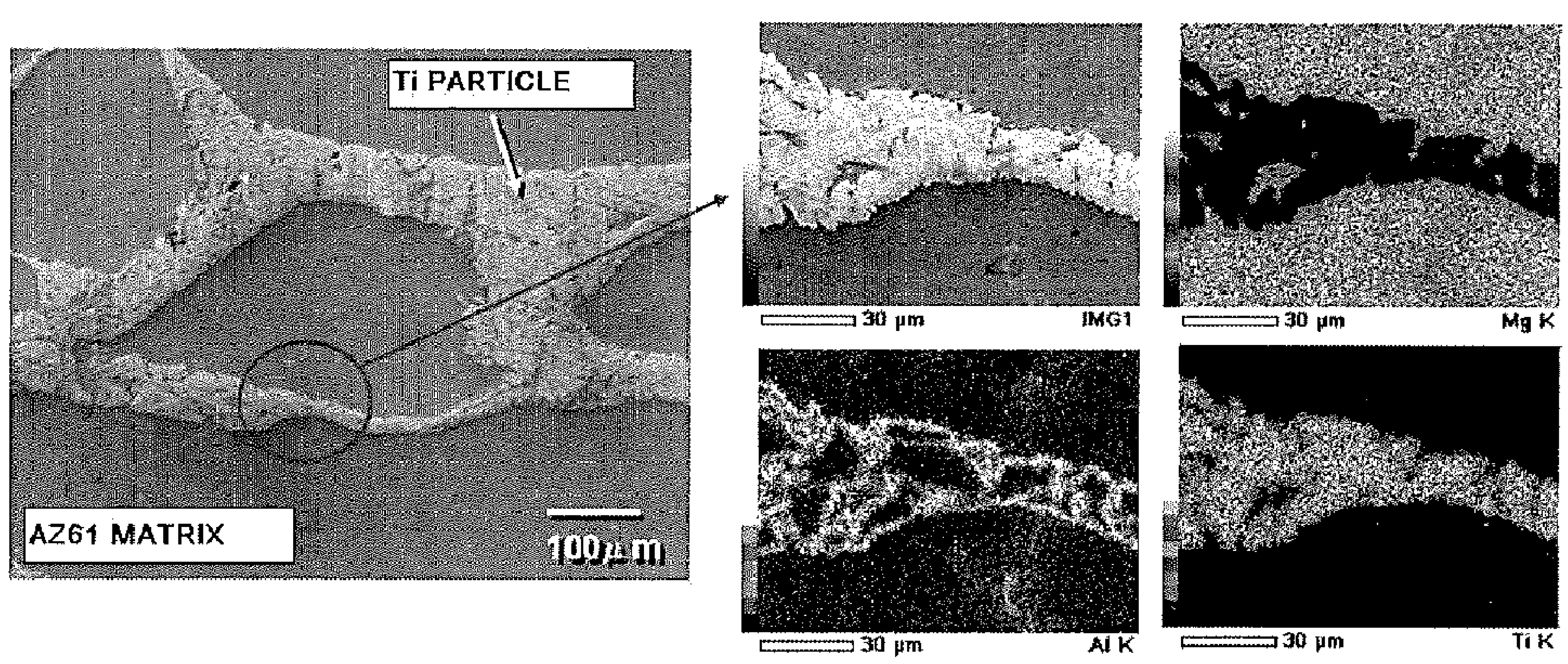


FIG. 6

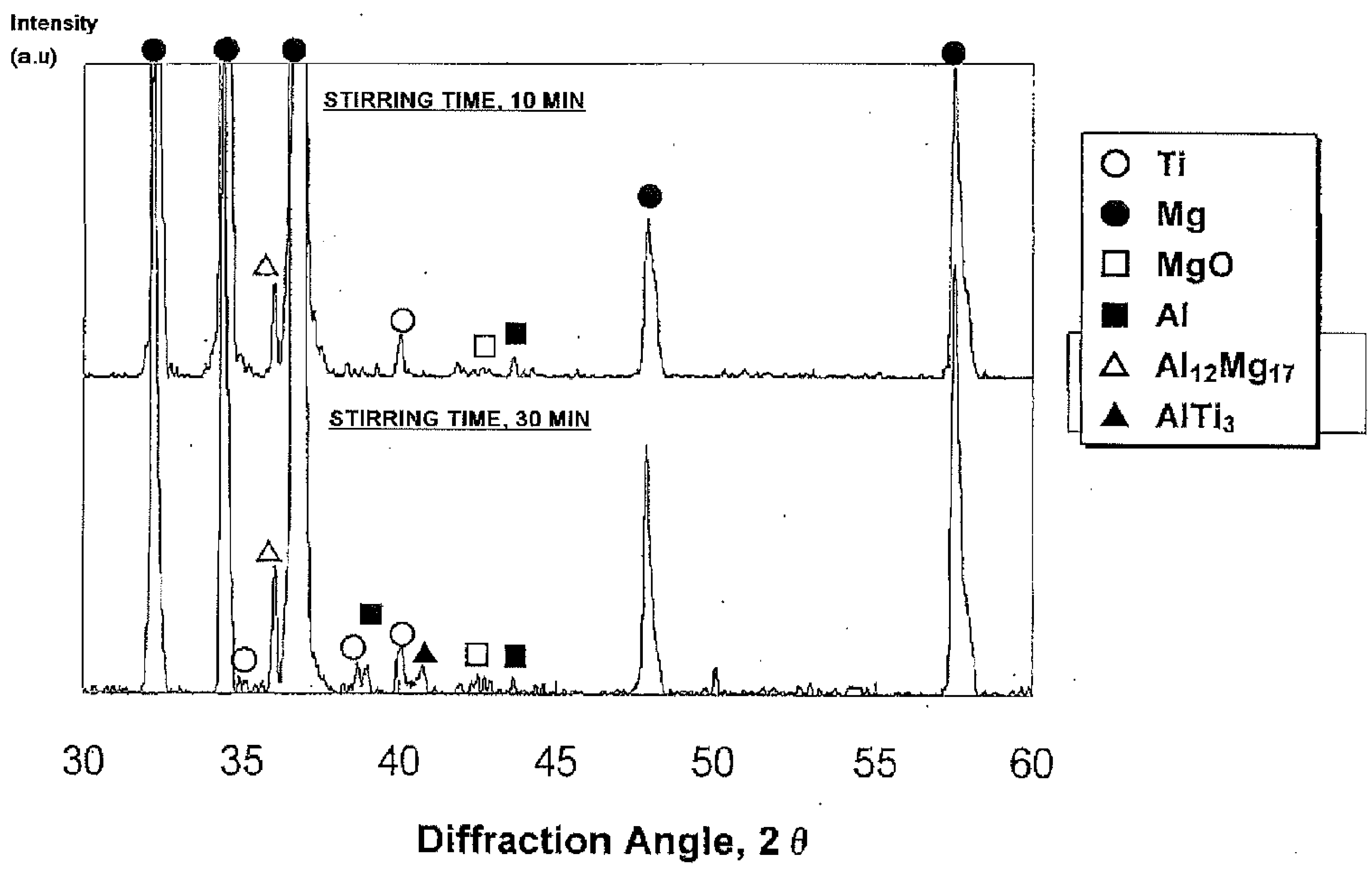



FIG. 7

CAST MATERIAL USING MOLTEN MIXED POWDER (Mg-6% Al-1% Mn)
WITH 10% Ti PARTICLES (MELTING TEMPERATURE: 700 °C, HOLD TIME: 30 MIN)

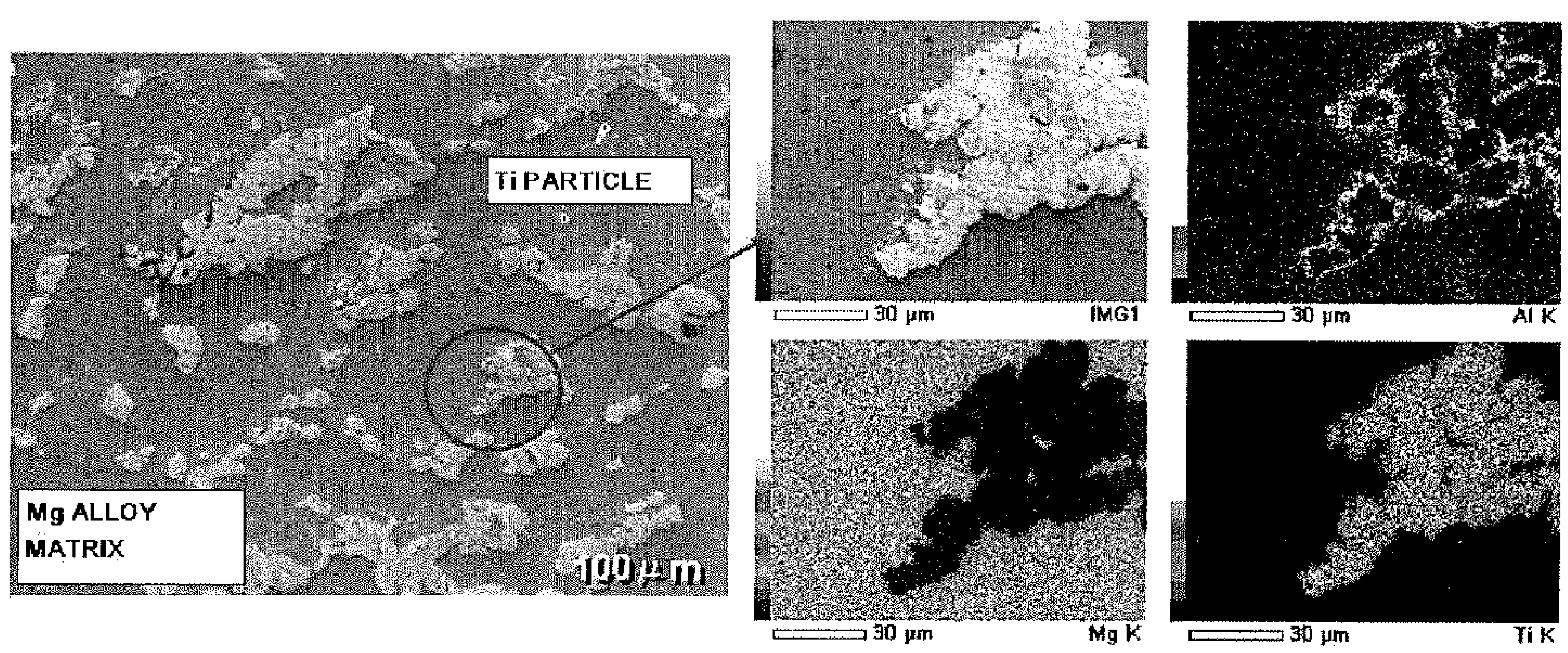
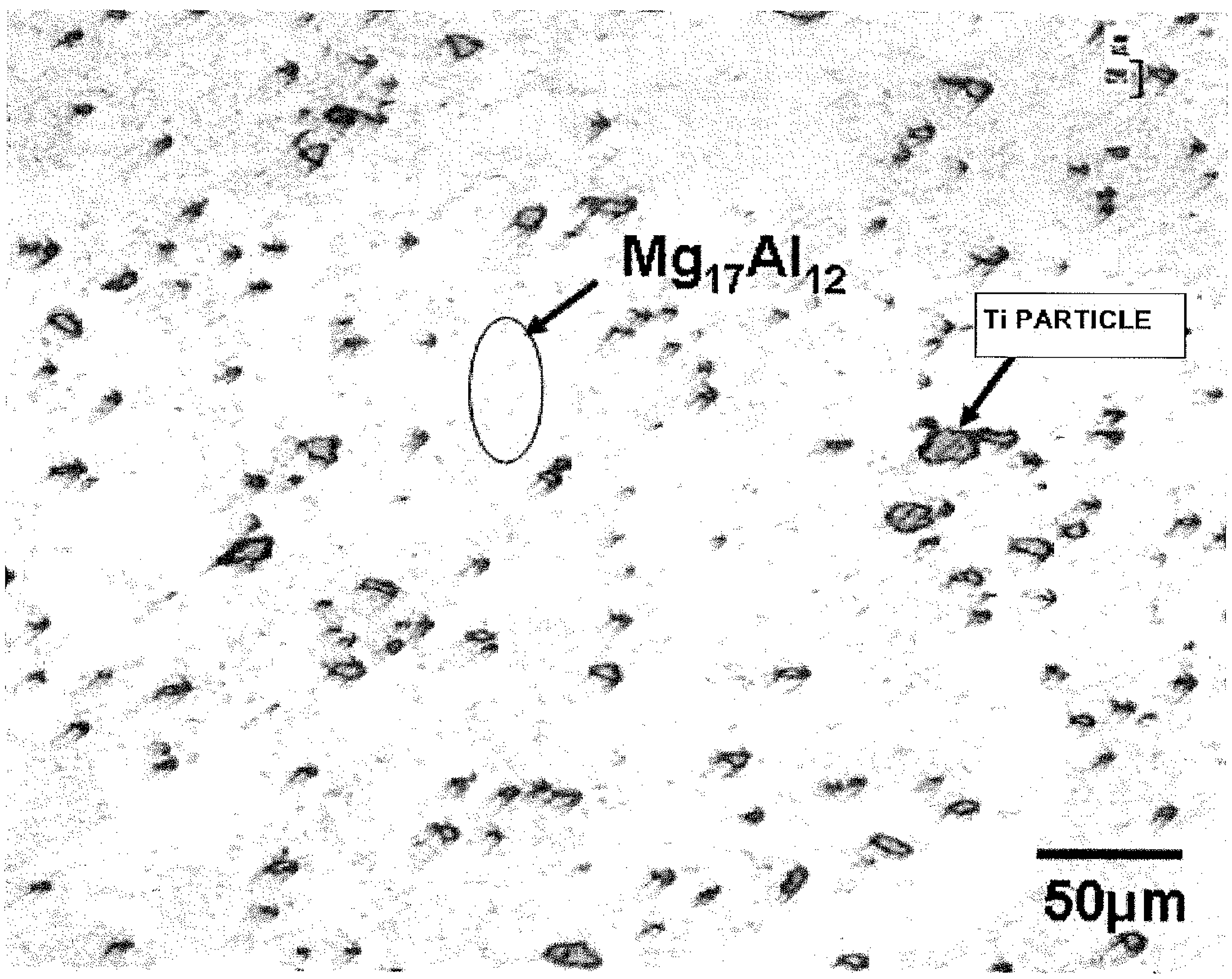


FIG. 8




AZ91D-3mass%Ti

# TI PARTICLE-DISPERSED MAGNESIUM-BASED COMPOSITE MATERIAL, AND MANUFACTURING METHOD THEREOF

## TECHNICAL FIELD

**[0001]** The present invention relates to magnesium alloys, and more particularly to titanium (Ti) particle-dispersed magnesium-based composite materials that can be used in various fields such as household electric appliances, automotive parts, and aircraft members by increasing both strength and ductility, and manufacturing methods thereof.

## BACKGROUND ART

**[0002]** Due to the lowest specific gravity of magnesium (Mg) among metal materials for industrial use, magnesium is expected to be used for parts and members of two-wheeled vehicles, automobiles, aircrafts, etc. for which reduction in weight is strongly desired. However, the use of magnesium alloys is limited as magnesium is not strong enough as compared to conventional industrial materials such as ferrous materials and aluminum alloys.

**[0003]** Composite materials in which particles, fibers, etc. having higher strength and hardness characteristics than those of magnesium are dispersed as a second phase have been developed in order to solve this problem. One example of an effective second phase to be dispersed is titanium (Ti). The rigidity of Mg is 45 GPa, whereas the rigidity of Ti is 105 GPa. The hardness of Mg is 35 to 45 Hv (Vickers hardness), whereas the hardness of Ti is 110 to 120 Hv. Thus, dispersing titanium particles in a magnesium matrix can be expected to increase the strength and hardness of magnesium-based composite materials.

**[0004]** In conventional composite materials, ceramic particles and ceramic fibers such as oxides, carbides, and nitrides are commonly dispersed. Such particles and fibers have high rigidity and high hardness, but have poor ductility. Thus, dispersing these particles and fibers in magnesium alloys reduces the ductility (e.g., breaking elongation) of the resultant composite materials. On the other hand, since titanium is a metal and has high ductility, adding and dispersing titanium particles does not reduce the ductility of the resultant composite materials.

**[0005]** However, magnesium has lower corrosion resistance. Magnesium has less noble characteristics, and has, e.g., a standard electrode potential Es (the standard hydrogen (H) electrode is zero volt) as low as −2.356 V. If a small amount of iron (Fe: Es=−0.44 V) or copper (Cu: Es=+0.34 V) is contained in magnesium, a galvanic corrosion phenomenon occurs due to the potential difference between Mg and Fe and between Mg and Cu. On the other hand, titanium has a standard electrode potential of −1.75 V, and the potential difference between Mg and Ti is smaller than that between Mg and aluminum (Al: Es=−1.676 V) as an element that is added to Mg. That is, dispersing titanium in magnesium does not significantly affect the corrosion phenomenon.

**[0006]** Thus, it is effective to use titanium particles as a dispersion strengthening material in magnesium matrix.

**[0007]** For example, the following non-patent documents have been reported as techniques related to Ti particle-dispersed magnesium composite materials. Non-Patent Document 1: Collected Abstracts of the 2008 Spring Meeting of the Japan Institute of Metals (Mar. 26, 2008), p. 355, No. 464 (Kataoka and Kitazono: Effect of Microstructure on

**[0008]** Mechanical Characteristics of Ti Particle-Dispersed Mg-Based Composite Material). Non-Patent Document 2: Collected Abstracts of the 2008 Spring Meeting of the Japan Institute of Metals (May 11, 2008), p. 13, No. 7 (Kitazono, Kataoka, and Komazu: Effect of Addition of Titanium Particles on Mechanical Characteristics of Magnesium). Non-Patent Document 3:

**[0009]** Abstracts of Spring Meeting of Japan Society of Powder and Powder Metallurgy, 2007 (Jun. 6, 2007), p. 148, No. 2-51A (Enami, Fujita, Ohara, and Igarashi: Development of Magnesium Composite Material by Bulk Mechanical Alloying Method). Non-Patent Document 4: Journal of Japan Society of Powder and Powder Metallurgy, Vol. 55, No. 4 (2008), p. 244 (Enami, Fujita, Hone, Ohara, Igarashi, and Kondo: Development of Magnesium Composite Material by Bulk Mechanical Alloying Method). Non-Patent Document 5: Journal of Japan Institute of Light Metals, Vol. 54, No. 11 (2004), pp. 522-526 (Sato, Watanabe, Miura, and Miura: Development of Titanium Particle-Dispersed Magnesium-Based Functionally Graded Material by Centrifugal Solid-Particle Method).

**[0010]** Non-Patent Documents 1 and 2 disclose production of a Ti particle-dispersed magnesium-based composite material by the following method. Pure titanium particles are applied to the surface of a pure magnesium plate, and another pure magnesium plate is placed thereon. In this state, the pure magnesium plates are heated and pressed to produce a composite material having the titanium particles interposed between the pure magnesium plates. A plurality of such a composite material are superposed on each other, and are heated and pressed to produce a Ti particle-dispersed magnesium-based composite material having the titanium particles arranged in the direction of the plane of the plates.

**[0011]** Non-Patent Documents 3 and 4 disclose production of a Ti particle-dispersed magnesium-based composite material by the following method. Magnesium alloy powder is mixed with pure titanium powder, and molds are filled with the mixed powder. In this state, the mixed powder is continuously subjected to a severe plastic working process, and is then subjected to a hot extrusion process to produce a Ti particle-dispersed magnesium-based composite material.

**[0012]** In each of Non-Patent Documents 1 to 4, the heating temperature is sufficiently lower than the melting point of magnesium, and composite materials are produced in a completely solid-phase temperature range without melting. The tensile test result of the composite materials shows that the strength is increased by about 5 to 10% but the ductility (breaking elongation) is reduced by about 20 to 30%, as compared to materials containing no Ti particle. Since magnesium and titanium do not form a compound, the strength of the bonding interface therebetween is not sufficient, and thus the strength is not increased sufficiently. On the other hand, a stress concentrates on the interface, whereby the ductility is reduced.

**[0013]** Thus, adhesion at the Mg—Ti interface needs to be increased in order to significantly increase both the strength and ductility of titanium particle-dispersed magnesium-based composite materials.

**[0014]** Non-Patent Document 5 describes a manufacturing method in which molten magnesium or a molten magnesium alloy (AZ91D) containing titanium particles that are present as a solid phase is subjected to a centrifugal force, and a composition gradient is controlled by using the difference in traveling speed which is caused by the difference in centrifugal force due to the difference in density between the dispersed particles and the molten magnesium or the molten magnesium alloy. Since the specific gravity of titanium is at least twice that of magnesium, it is difficult to uniformly disperse titanium particles in the molten magnesium or the molten magnesium alloy by the centrifugal solid-particle method disclosed in Non-Patent Document 5. In fact, this document describes that "it was found difficult to disperse titanium particles by this method." This document also describes that, in the case of adding titanium particles to a molten magnesium alloy (AZ91D) containing aluminum, and using the centrifugal solid-particle method, the aluminum concentration is very high in a portion where the titanium particles are aggregated, and regions where aluminum is solid-solved are also present in the outer periphery of the titanium particles. As a reason for this, this document describes that "there is a possibility that the initial melt having a high aluminum concentration may have penetrated the gaps between the titanium particles due to a capillary phenomenon, and may have been involved in aggregation and sintering of the titanium particles. Thus, it was found that the use of the centrifugal solid-particle method in the AZ91D alloy containing aluminum is problematic in view of the composition of the melt."

## DISCLOSURE OF THE INVENTION

**[0015]** The present invention was developed to solve the above problems, and it is an object of the present invention to provide a Ti particle-dispersed magnesium-based composite material having high strength by uniformly dispersing titanium particles in a magnesium matrix, and increasing adhesion at the interface between titanium and magnesium.

**[0016]** A Ti particle-dispersed magnesium-based composite material according to the present invention is a Ti particle-dispersed magnesium-based composite material having titanium particles uniformly dispersed in a magnesium matrix, characterized by including a titanium-aluminum compound layer at an interface between the titanium particles dispersed in the magnesium alloy matrix and the matrix.

**[0017]** In one embodiment, the Ti particle-dispersed magnesium-based composite material is produced by subjecting to a hot plastic working process a cast material that is produced by solidifying a molten material containing magnesium, aluminum, and titanium particles.

**[0018]** In another embodiment, the Ti particle-dispersed magnesium-based composite material is produced by machining a cast material that is produced by solidifying a molten material containing magnesium, aluminum, and titanium particles, so as to make the cast material into powder.

**[0019]** In still another embodiment, the Ti particle-dispersed magnesium-based composite material is powder that is produced by solidifying a molten material containing magnesium, aluminum, and titanium particles into powder by using an atomization process.

**[0020]** In yet another embodiment, the Ti particle-dispersed magnesium-based composite material is a sintered solidified body of mixed powder of magnesium alloy powder containing aluminum, and titanium particles. In this case, the Ti particle-dispersed magnesium-based composite material may be produced by subjecting the sintered solidified body to a hot plastic working process.

**[0021]** In one aspect, a method for manufacturing a Ti particle-dispersed magnesium-based composite material according to the present invention includes the steps of; placing titanium particles into a molten material containing magnesium and aluminum; stirring the molten material so that the titanium particles are uniformly dispersed therein; and producing a composite material by solidifying the molten material, the composite material having a titanium-aluminum compound layer at an interface between a magnesium matrix and the titanium particles dispersed in the matrix.

**[0022]** In one embodiment, the step of producing the composite material includes solidifying the molten material to produce a cast material having the titanium-aluminum compound layer at the interface between the magnesium matrix and the titanium particles dispersed in the matrix, and subjecting the cast material to a hot plastic working process.

**[0023]** In another embodiment, the step of producing the composite material includes solidifying the molten material to produce a cast material having the titanium-aluminum compound layer at the interface between the magnesium matrix and the titanium particles dispersed in the matrix, and machining the cast material so as to make the cast material into powder.

**[0024]** In still another embodiment, the step of producing the composite material includes solidifying the molten material into powder by using an atomization process.

**[0025]** In another aspect, a method for manufacturing a Ti particle-dispersed magnesium-based composite material according to the present invention includes the steps of; mixing magnesium alloy powder containing aluminum with titanium particles; and sintering and solidifying the mixed powder while holding the mixed powder at a temperature higher than a liquid phase transition temperature of the magnesium alloy powder, thereby forming a titanium-aluminum compound layer at an interface between the titanium particles and a magnesium matrix.

**[0026]** The method according to one embodiment further includes the step of subjecting the sintered body to a hot plastic working process.

**[0027]** The technical significance or the functions and effects of the above structures of the present invention will be described in detail in the following sections.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0028]** FIG. **1** is a graph for evaluating the wettability between a magnesium alloy containing aluminum and pure titanium.

**[0029]** FIG. **2** shows scanning electron microscope-energy dispersive spectroscopy (SEM-EDS) images of the interface between an AZ80 alloy and a titanium plate.

**[0030]** FIG. **3** shows the analysis result of the vicinity of the interface between the AZ80 alloy and the titanium plate.

**[0031]** FIG. **4** shows an image of the bonding interface between a magnesium matrix and titanium particles.

**[0032]** FIG. **5** shows images showing the SEM-EDS analysis result of Ti particle-dispersed magnesium-based composite materials.

**[0033]** FIG. **6** is a graph of the X-ray diffraction result showing the progress of compound formation.

**[0034]** FIG. **7** shows images showing the SEM-EDS analysis result of Ti particle-dispersed magnesium-based composite materials.

[0035] FIG. 8 shows an image showing the observation result of the inner structure of a billet.

## BEST MODE FOR CARRYING OUT THE INVENTION

[0036] In order to develop titanium particle-dispersed magnesium-based composite materials capable of increasing the interface bonding strength between titanium and magnesium, the inventors of the present application focused on formation of a Ti—Al compound layer at the interface by using a diffusion phenomenon of aluminum (Al) contained in a Mg alloy.

(1) Wettability between Magnesium Alloy Containing Al and Pure Titanium

[0037] The inventors of the present application examined wettability between Al-containing magnesium alloy droplets and pure titanium plates. Specifically, AZ80 (Mg-8% Al-0.5% Mn) magnesium alloy droplets (held at 800° C.) melted in a high vacuum state were statically discharged from the tip of a nozzle made of magnesium oxide (MgO) onto the surface of a pure titanium plate, and the wettability between Magnesium Alloy Containing Al and pure Ti at 800° C. was evaluated by continuous shooting.

[0038] As shown in FIG. 1, the wetting angle (contact angle) was about 118° when the Al-containing magnesium alloy contacted the Ti plate surface (t=0 seconds). The wetting angle decreased with time, and decreased to 40° after 35 minutes. In general, it is determined that the wet phenomenon has occurred if the wetting angle becomes smaller than 90°. The wettability increases as the wetting angle becomes closer to 0°. In view of the fact that titanium carbide (TiC), which is said to have satisfactory wettability with magnesium, has a wetting angle of about 33° at 900° C. (reference: A. Contrerasa et al., Scripta Materialia, 48 (2003) 1625-1630), the wettability between the AZ80 magnesium alloy containing 8 mass % of Al components and pure Ti is satisfactory.

[0039] After evaluating the wettability, the interface between the solidified AZ80 alloy and the titanium plate of a test piece was observed by using scanning electron microscope-energy dispersive spectroscopy (SEM-EDS). The result is shown in FIG. 2. A film having a thickness of about 2 μm is formed on the Ti plate side of the bonding interface, and the film has satisfactory adhesion to both the AZ80 magnesium alloy and the pure Ti plate with no void therebetween. The analysis result of the vicinity of the interface is shown in FIG. 3.

[0040] The film having a thickness of about 2 μm is a layer made of Ti—Al components, and formed by a reaction between the Al components contained in AZ80 and the Ti plate. Formation of such a reaction layer enables a satisfactory adhesion interface having strong bonding power with both the magnesium alloy and the Ti particles to be obtained.

[0041] For comparison, such composite materials as reported in related art (Non-Patent Documents 1 to 4) were produced. That is, composite materials were produced by heating and pressing mixed powder of pure titanium powder and pure magnesium powder at a solid phase temperature of magnesium powder, and the bonding interface between pure magnesium and pure titanium was observed. The result is shown in FIG. 4. In producing the composite materials, the heating temperature was 520° C., which is lower than the melting point (650° C.) of pure magnesium so as to obtain a completely solid phase state. As shown by arrows, many gaps or voids were observed at the interface between the Ti particles and the Mg matrix, which shows that adhesion is not sufficient. Thus, in the manufacturing methods disclosed in related art, since heating and sintering are performed at a solid phase temperature that is lower than the melting point of Mg, adhesion between Mg and Ti is not sufficient, whereby strength and ductility of the composite materials are not increased.

(2) Composite Materials using Ti Particle-Dispersed Molten Mg—Al Alloy

[0042] Based on the above result, the inventors produced Ti particle-dispersed magnesium-based composite materials by the following method in order to increase the interface bonding strength between a magnesium matrix and Ti particles. By using a magnesium alloy containing aluminum components as a material for the matrix, the molten magnesium alloy was held at a temperature higher than the melting point of the magnesium alloy, and Ti particles were added thereto. After sufficiently stirring the molten magnesium alloy so that the titanium particles were uniformly dispersed therein, the molten magnesium alloy was solidified. In the Ti particle-dispersed magnesium-based composite materials produced by this manufacturing method, magnesium that forms the matrix and titanium particles are bonded together, with high interface bonding strength due to satisfactory wettability and reactivity between Al and titanium, with a titanium-aluminum compound layer formed at the interface therebetween.

[0043] Composite materials having titanium particles uniformly dispersed in a magnesium matrix can also be manufactured by conventional methods such as a casting method and a die casting method. The cast materials can be made into powder by a machining process such as a cutting process or a crushing process. In the magnesium-based composite powder thus obtained, the titanium particles are uniformly dispersed in the magnesium matrix.

[0044] Magnesium-based composite powder having titanium particles uniformly dispersed in a magnesium matrix can also be obtained by solidifying a molten Mg—Al alloy having titanium particles uniformly dispersed therein by using an atomization process. The atomization process is a process for producing powder by ejecting high pressure water or high pressure gas to a molten metal flow (a spraying method). In the powder thus produced as well, the titanium particles are uniformly dispersed therein, and a Ti—Al compound layer is formed at the interface between the Ti particles and the magnesium alloy matrix, whereby the produced powder has satisfactory interface bonding strength.

[0045] As described above, either in the case where a magnesium-based composite material is produced by adding titanium particles to a molten magnesium alloy containing Al components, and after sufficient uniform stirring, performing a casting method or a die casting method, or in the case where a molten Mg—Al alloy having titanium particles uniformly dispersed therein is directly made into powder by using an atomization process, titanium particles are firmly bonded to magnesium as a matrix with a void-free, satisfactory bonding interface therebetween due to high wettability and high reactivity between Al and Ti.

[0046] The Ti particle-dispersed magnesium-based composite material produced by a casting method or a die casting method may be heated to a predetermined temperature, and then the composite material may be subjected to a hot plastic working process such as a hot extrusion process, a hot rolling process, or a forging process. This reduces the crystal grain size of the matrix, and further increases the strength of the composite material.

[0047] The Ti particle-dispersed magnesium-based composite material produced from the cast material by a machining process such as a cutting process, or the Ti particle-dispersed magnesium-based composite powder obtained by ejecting high pressure water or high pressure gas to the molten Mg—Al alloy flow, may be compacted and solidified to produce a compacted molded body or a sintered solidified body. Subsequently, the compacted molded body or the sintered solidified body may be subjected to a hot plastic working process such as a hot extrusion process, a hot rolling process, or a forging process, as necessary. A Ti particle-dispersed magnesium-based composite material having particles of the composite powder metallurgically bonded or sintered together can be produced in this manner.

[0048] Although a proper amount of titanium particles is added to the molten Mg—Al alloy in the above embodiment, a Ti particle-dispersed magnesium-based composite material can also be obtained by the following manufacturing method as another embodiment. In this embodiment, magnesium alloy powder containing aluminum is mixed with titanium particles, and the mixed powder is sintered and solidified while being held at a predetermined temperature. The important thing is to hold the mixed powder at a temperature higher than a liquid phase transition temperature of the magnesium alloy powder. By holding the mixed powder at such a high temperature, magnesium that forms the matrix and the titanium particles are firmly bonded together in the sintered solidified body with satisfactory wettability and high interface bonding strength, with a titanium-aluminum compound layer formed at the interface therebetween. The strength of the composite material is further increased by subjecting this sintered solidified body to a hot plastic working process.

[0049] Note that in the above embodiments, the titanium-aluminum compound layer that is formed at the interface between magnesium that forms the matrix and the titanium particles may entirely surround the titanium particles, or partially cover the surface of the titanium particles.

## Example 1

[0050] A mass of an AZ61 (Mg-5.9% Al-1.1% Zn) magnesium alloy, and titanium powder having an average particle size of 29.8 μm were prepared as starting materials. The magnesium alloy mass was melted by heating to 700° C. in a carbon crucible, and 5 mass % of the titanium particles in a weight percentage relative to the total weight was added to the molten magnesium alloy. After sufficiently uniformly stirring the molten magnesium alloy for 30 minutes to prevent segregation of the Ti particles and sedimentation thereof at the bottom, the molten magnesium alloy was cast into water-cooled molds to produce cast materials.

[0051] FIG. **5** shows the SEM-EDS analysis result of the cast materials thus obtained. It is recognized that there is no void at the interface between the titanium particles and the matrix, and the titanium particles are bonded to the matrix with satisfactory adhesion. Moreover, the result of elemental analysis shows that aluminum (Al) components are present in a layer form on the surface of the titanium particles, and a Ti—Al compound layer is formed at the interface between the titanium particles and the AZ61 matrix. Satisfactory adhesion between the titanium particles and the matrix is obtained by this reaction layer.

[0052] Note that composite materials were also produced by performing the uniform stirring process for 10 minutes after adding the titanium powder to a molten magnesium alloy, and the progress of compound formation was observed in these composite materials and the above composite materials by using X-ray diffraction. The result is shown in FIG. **6**.

[0053] A diffraction peak of an $Al_3Ti$ intermetallic compound is detected in the case of performing the uniform stirring process for 30 minutes, whereas no peak of the compound is detected in the materials produced by performing the uniform stirring process for 10 minutes. That is, if the stirring time is not enough, the diffusion reaction of the Al components in the magnesium alloy and the titanium particles does not proceed, which makes it difficult to form a Ti—Al compound layer as a characteristic of the present invention. Thus, it is desirable to perform the uniform stirring process for at least 30 minutes after adding the titanium particles to the molten magnesium alloy.

## Example 2

[0054] Pure magnesium powder and Al—Mn alloy powder were prepared, and were mixed together so that the mixed powder had an AZ61 alloy composition (Mg-6% Al-1% Zn) as a whole. This mixed powder was compacted and solidified by a hydraulic press, and the resultant molded solidified body was placed into a carbon crucible, and was heated and held at 700° C. to produce a molten AZ61 magnesium alloy. 10 mass % of the above titanium particles in a weight percentage relative to the total weight was added to the molten AZ61 magnesium alloy. After uniformly stirring the AZ61 molten magnesium alloy for 30 minutes to prevent segregation of the Ti particles and sedimentation thereof at the bottom, the AZ61 molten magnesium alloy was cast into water-cooled molds to produce cast materials.

[0055] FIG. **7** shows the SEM-EDS analysis result of the cast materials thus obtained. It is recognized that although 10 mass % of the titanium particles was added, no significant aggregation/segregation structure of the particles is observed, and the titanium particles are uniformly dispersed in the matrix. There is no void at the interface between the titanium particles and the matrix, and the titanium particles are bonded to the matrix with satisfactory adhesion. Moreover, the result of elemental analysis shows that aluminum (Al) components are present in a layer form so as to surround the surface of the titanium particles, and a Ti—Al compound layer is formed at the interface between the titanium particles and the AZ61 matrix. Satisfactory adhesion between the titanium particles and the matrix is obtained by this reaction layer.

## Example 3

[0056] A mass sample of an AZ91D magnesium alloy (Mg-9.1% Al-1.1% Zn-0.2% Mn), and titanium powder having an average particle size of 29.8 μm were prepared as starting materials. The AZ91D magnesium alloy mass was melted by heating to 720° C. in a carbon crucible, and 3 mass % of the titanium particles in a weight percentage relative to the total weight was added to the molten AZ91D magnesium alloy. After sufficiently uniformly stirring the molten AZ91D magnesium alloy for 40 minutes to prevent segregation of the Ti particles and sedimentation thereof at the bottom, the molten AZ91D magnesium alloy was cast into cylindrical molds to produce billets having a diameter of 60 mm.

[0057] FIG. **8** shows the observation result of the inner structure of the billet. Fine $Mg_{17}Al_{12}$ compounds (β-phase) are uniformly dispersed in the matrix, and the titanium particles are similarly uniformly dispersed in the matrix without aggregation or segregation.

**[0058]** The Ti particle-dispersed AZ91D cast billets were machined to produce extrusion billets having a diameter of 45 mm. These billets were heated and held at 350° C. for 5 minutes in an argon gas atmosphere, and then immediately subjected to a hot extrusion process (extrusion ratio: 37) to produce round-bar shaped extruded materials having a diameter of 7 mm. Tensile test pieces were obtained from the extruded materials thus obtained, and a tensile test was performed at normal temperature.

**[0059]** For comparison, AZ91D magnesium cast billets were produced under the same conditions as those described above without adding titanium particles, and were similarly machined to produce extrusion billets having a diameter of 45 mm. These extrusion billets were similarly subjected to an extrusion process. The extruded materials thus obtained were similarly subjected to a tensile test at normal temperature. The tensile test result is shown in Table 1.

TABLE 1

| | | |
|---|---|---|
| Amount of Ti Particles (mass %) | 0 | 3 |
| Tensile Strength (MPa) | 344 | 382 |
| Yield Strength (MPa) | 254 | 287 |
| Breaking Elongation (%) | 11.3 | 9.1 |

**[0060]** As compared to the materials extruded from the AZ91D cast billets containing no titanium particle, the tensile strength and the yield strength are significantly increased, while the breaking elongation is not significantly reduced in the AZ91D cast billet extruded materials containing 3 mass % of titanium particles. In the Ti particle-dispersed AZ91D composite material of the present invention, formation of a $TiAl_3$ intermetallic compound is verified in the X-ray diffraction result, and there is no void at the interface between the titanium particles and the AZ91D matrix. The titanium particles and the AZ91D matrix thus form a satisfactory bonding interface therebetween.

**[0061]** Based on the above result, in the Ti particle-dispersed Mg—Al-based composite material of the present invention, a Ti—Al compound is formed at the surface of the titanium particles without causing aggregation and segregation of the titanium particles. The bonding strength between the titanium particles and the matrix is increased via the Ti—Al compound, whereby the strength of the magnesium-based composite material can be increased.

**[0062]** Note that in the case where Ti particle-dispersed magnesium-based composite materials are manufactured by using Ti-6Al-4V alloy powder (average particle size: 22.8 μm) having higher hardness, instead of titanium particles, the titanium alloy particles are also uniformly dispersed in the matrix without aggregation and segregation, and formation of a $TiAl_3$ intermetallic compound is verified at the interface between the titanium alloy powder and the AZ91D matrix. Thus, it is recognized that the bonding state between the titanium alloy powder and the AZ91D matrix is satisfactory with no void at the interface therebetween. In the case of adding 3 mass % of Ti-6Al-4V alloy powder, the tensile strength is 414 MPa, and it was able to be verified that the strength is increased as compared to the composite materials containing 3 mass % of pure titanium particles. Thus, the strength of the magnesium composite materials increases as the hardness and strength of the titanium particles that are dispersed in the magnesium alloy matrix increase.

Example 4

**[0063]** A mass sample of an AZ91D magnesium alloy (Mg-9.1% Al-1.1% Zn-0.2% Mn), and titanium powder having an average particle size of 29.8 μm were prepared as starting materials. The AZ91D magnesium alloy mass was melted by heating to 720° C. in a carbon crucible, and 3 mass % of the titanium particles in a weight percentage relative to the total weight was added to the molten AZ91D magnesium alloy. After sufficiently uniformly stirring the molten AZ91D magnesium alloy for 40 minutes to prevent segregation of the Ti particles and sedimentation thereof at the bottom, the molten AZ91D magnesium alloy was cast into cylindrical molds to produce billets having a diameter of 60 mm.

**[0064]** Chips having a total length of about 1 to 4 mm were produced from the Ti particle-dispersed AZ91D cast billets by a cutting process. Then, SKD11 molds were filled with the chips, and were pressed with a pressure of 600 MPa by a hydraulic press to produce billets of a powder molded body having a diameter of 45 mm. The compacted molded billets were heated and held at 350° C. for 5 minutes in an argon gas atmosphere, and then immediately subjected to a hot extrusion process (extrusion ratio: 37) to produce round-bar shaped extruded materials having a diameter of 7 mm. Tensile test pieces were obtained from the obtained extruded materials, and a tensile test was performed at normal temperature.

**[0065]** For comparison, AZ91D magnesium cast billets were produced under the same conditions as those described above without adding titanium particles, and chips having a total length of 1 to 4 mm were similarly produced from the AZ91D magnesium cast billets. 3 mass % of titanium particles were added to the AZ91D chips, and the titanium particles and the AZ91D chips were mixed together for one hour by using a dry ball mill. The mixed powder was compacted and molded by a hydraulic press in a manner similar to that described above, and the compacted molded body was subjected to an extrusion process after a heating process at 350° C. The extruded materials thus obtained were similarly subjected to a tensile test at normal temperature. The tensile test result is shown in Table 2.

TABLE 2

| | Comparative Material | Material of the Present Invention |
|---|---|---|
| Amount of Ti Particles (mass %) | 3 | 3 |
| Tensile Strength (MPa) | 313 | 391 |
| Yield Strength (MPa) | 204 | 282 |
| Breaking Elongation (%) | 7.2 | 8.9 |

**[0066]** In the comparative materials, since the heating temperature is as low as 350° C., the Al components contained in AZ91D do not react with the titanium particles. Thus, no Ti—Al compound was formed at the surface of the titanium particles, and the bonding strength at the interface between the titanium particles and the matrix was not sufficiently high. As a result, both the tensile strength and the yield strength are reduced, and the breaking elongation is also reduced as compared to the strength characteristics of the extruded materials using only AZ91D shown in Example 3.

**[0067]** On the other hand, as in the example of the present invention shown in Example 3, in the extruded materials produced from the Ti particle-dispersed AZ91D composite powder of the present invention, the tensile strength and the yield strength are significantly increased, while the breaking elongation is not significantly reduced, as compared to the materials extruded from the AZ91D cast billets containing no titanium particle. In the Ti particle-dispersed AZ91D composite material of the present invention, formation of a $TiAl_3$ intermetallic compound is verified in the X-ray diffraction result, and there is no void at the interface between the titanium particles and the AZ91D matrix. The titanium particles and the AZ91D matrix thus form a satisfactory bonding interface therebetween.

**[0068]** Based on the above result, in the Ti particle-dispersed Mg—Al-based composite material of the present invention, a Ti—Al compound is formed at the surface of the titanium particles without causing aggregation and segregation of the titanium particles. The bonding strength between the titanium particles and the matrix is increased via the Ti—Al compound, whereby the strength of the magnesium-based composite material can be increased.

**[0069]** Although the embodiments of the present invention are described above with reference to the drawings, the present invention is not limited to the illustrated embodiments. Various modifications and variations can be made to the illustrated embodiments within a scope that is the same as, or equivalent to the present invention.

## INDUSTRIAL APPLICABILITY

**[0070]** The present invention can be advantageously used as a Ti particle-dispersed magnesium-based composite material having high strength, and a manufacturing method thereof.

**1-12**. (canceled)

**13**. A Ti particle-dispersed magnesium-based composite material, characterized in that

pure titanium particles are uniformly dispersed in a magnesium alloy matrix containing aluminum, and a titanium-aluminum compound layer is formed at an interface between the dispersed pure titanium particles and the magnesium alloy matrix by using a diffusion phenomenon of aluminum components in the magnesium alloy matrix.

**14**. A method for manufacturing a Ti particle-dispersed magnesium-based composite material, comprising the steps of:

placing pure titanium particles into a molten material containing magnesium and aluminum;

stirring the molten material for at least 30 minutes so as to uniformly disperse the pure titanium particles therein and to cause a diffusion reaction of the molten aluminum components and the pure titanium particles to proceed; and

producing a composite material by solidifying the molten material, the composite material having a titanium-aluminum compound layer formed at an interface between a magnesium alloy matrix containing aluminum and the pure titanium particles dispersed in the matrix.

**15**. The method according to claim **14**, wherein

the step of producing the composite material includes solidifying the molten material to produce a cast material having the titanium-aluminum compound layer formed at the interface between the magnesium alloy matrix and the pure titanium particles dispersed in the matrix, and subjecting the cast material to a hot plastic working process.

**16**. The method according to claim **14**, wherein

the step of producing the composite material includes solidifying the molten material to produce a cast material having the titanium-aluminum compound layer formed at the interface between the magnesium alloy matrix and the pure titanium particles dispersed in the matrix, and machining the cast material so as to make the cast material into powder.

**17**. The method according to claim **14**, wherein

the step of producing the composite material includes solidifying the molten material into powder by using an atomization process.

**18**. A method for manufacturing a Ti particle-dispersed magnesium-based composite material, comprising the steps of:

mixing magnesium alloy powder containing aluminum with pure titanium particles; and

sintering and solidifying the mixed powder while holding the mixed powder at a temperature higher than a liquid phase transition temperature of the magnesium alloy powder, thereby forming a titanium-aluminum compound layer at an interface between the pure titanium particles and a magnesium alloy matrix, by using a diffusion phenomenon of aluminum components in the magnesium alloy powder.

**19**. The method according to claim **18**, further comprising the step of subjecting the sintered body to a hot plastic working process.

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