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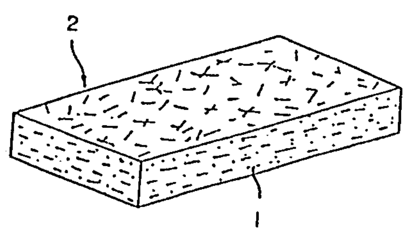
(54) Composite material including alumina-silica short fibers as reinforcing material and copper in its aluminum alloy matrix metal with the proportions thereof being related.

(57) A composite material is made from alumina - silica type short fibers embedded in a matrix of metal. The percentage fiber volume proportion X% of the alumina - silica type short fibers is between approximately 5% and approximately 50%. The metal is an alloy consisting essentially of a percentage Y% of copper and remainder substantially aluminum. And the inequalities $Y \leq -0.00092X^2 - 0.0094X + 7.85$ and $Y \geq -0.00092X^2 - 0.0094X + 3.55$ are satisfied. The fiber volume proportion of the alumina - silica type short fibers may more desirably be between approximately 5% and approximately 40%. And the alumina - silica type short fibers may be alumina short fibers, or alternatively may be crystalline alumina - silica short fibers, of which the mullite crystalline amount may be at least about 45%. Or the alumina - silica type short fibers may be amorphous alumina - silica short fibers.

FIG. 1



EP 0 213 528 A2

COMPOSITE MATERIAL INCLUDING ALUMINA - SILICA SHORT FIBERS AS REINFORCING MATERIAL AND COPPER IN ITS ALUMINUM ALLOY MATRIX METAL WITH THE PROPORTIONS THEREOF BEING RELATED

BACKGROUND OF THE INVENTION

The present invention relates to a composite material made up from reinforcing fibers embedded in a matrix of metal, and more particularly relates to such a composite material utilizing alumina - silica short fiber material as the reinforcing fiber material and aluminum alloy including some copper as the matrix metal.

In the prior art, the following aluminum alloys have been utilized as matrix metal for a fiber reinforced metal type composite material:

Cast type aluminum alloys

JIS standard AC8A (0.8 to 1.3% Cu, 11.0 to 13.0% Si, 0.7 to 1.3% Mg, 0.8 to 1.5% Ni, remainder substantially Al)

JIS standard AC8B (2.0 to 4.0% Cu, 8.5 to 10.5% Si, 0.5 to 1.5% Mg, 0.1 to 1% Ni, remainder substantially Al)

JIS standard AC4C (Not more than 0.25% Cu, 6.5 to 7.5% Si, 0.25 to 0.45% Mg, remainder substantially Al)

AA standard A356 (6.5 to 7.5% Si, 0.25 to 0.45% Mg, not more than 0.2% Fe, not more than 0.2% Cu, remainder substantially Al)

Al - 2 to 3% Li alloy (DuPont)

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Wrought type aluminum alloys

JIS standard 6061 (0.4 to 0.8% Si, 0.15 to 0.4% Cu, 0.8 to 1.2% Mg, 0.04 to 0.35% Cr, remainder substantially Al)

JIS standard 5056 (not more than 0.3% Si, not more than 0.4% Fe, not more than 0.1% Cu, 0.05 to 0.2% Mn, 4.5 to 5.6% Mg, 0.05 to 0.2% Cr, not more than 0.1% Zn, remainder substantially Al)

JIS standard 7075 (not more than 0.4% Si, not more than 0.5% Fe, 1.2 to 2.0% Cu, not more than 0.3 Mn, 2.1 to 2.9% Mg, 0.18 to 0.28% Cr, 5.1 to 6.1% Zn, 0.2% Ti, remainder substantially Al)

Previous research relating to composite materials incorporating aluminum alloys as their matrix metals has generally been carried out from the point of view and with the object of improving the strength and so forth of existing aluminum alloys, and therefore these aluminum alloys conventionally used in the manufacture of such prior art composite materials have not necessarily been of the optimum composition in relation to the type of reinforcing fibers utilized therewith to form a composite material, and therefore, in the case of using such conventional above mentioned aluminum alloys as the matrix metal for a composite material, it has not heretofore been attained to optimize the mechanical characteristics, and particularly the strength, of the composite materials using such aluminum alloys as matrix metal.

SUMMARY OF THE INVENTION

The inventors of the present application have considered the above mentioned problems in composite materials which use such conventional aluminum alloys as matrix metal, and in particular have considered the particular case of a composite material which utilizes alumina - silica short fibers as reinforcing fibers, since such alumina - silica short fibers, among the various reinforcing fibers used conventionally in the manufacture of a fiber reinforced metal composite material, have particularly high strength, and are exceedingly effective in improving the high temperature stability and strength, as well as being available in numerous convenient varieties. And the present inventors, as a result of various experimental researches to determine what composition of the aluminum alloy to be used as the matrix metal for such a composite material is optimum, have discovered that a composite material having a percentage content Y% of copper in its aluminum alloy matrix metal and a volume proportion X% of alumina - silica type short fibers which are related by the following inequalities:

$$Y \leq - 0.00092 X^2 - 0.0094 X + 7.85$$

and:

$$Y \geq - 0.00092 X^2 - 0.0094 X + 3.55$$

and having substantially no content of other elements such as silicon, magnesium, nickel, zinc, or the like in its aluminum alloy matrix metal, is optimal in view of its bending strength characteristics as well as in view of others of its characteristics such as its mechanical characteristics. The present invention is based on the knowledge obtained from the results of the various experimental researches carried out by the inventors of the present application, as will be detailed later in this specification.

Accordingly, it is the primary object of the present invention to provide a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which enjoys superior mechanical characteristics such as bending strength.

It is a further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which is cheap.

It is a further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which, for similar values of mechanical characteristics such as bending strength can incorporate a lower volume proportion of reinforcing fiber material than prior art such composite materials.

It is a further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which is improved over prior art such composite materials as regards machinability.

It is a further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which is improved over prior art such composite materials as regards workability.

It is a further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which has good characteristics with regard to amount of wear on a mating member.

It is a yet further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which is not brittle.

It is a yet further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which is durable.

It is a yet further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which has good wear resistance.

It is a yet further object of the present invention to provide such a composite material utilizing alumina - silica short fibers as reinforcing material and aluminum alloy as matrix metal, which has good uniformity.

According to the most general aspect of the present invention, these and other objects are accomplished by a composite material comprising alumina - silica type short fibers embedded in a matrix of metal, the percentage fiber volume proportion X% of said alumina - silica type short fibers being between approximately 5% and approximately 50%, and said metal being an alloy consisting essentially of a percentage Y% of copper and remainder substantially aluminum, said values X% and Y% approximately satisfying the following inequalities:
$Y \leq -0.00092 X^2 - 0.0094 X + 7.85$ and
$Y \geq -0.00092 X^2 - 0.0094 X + 3.55$; and, more particularly, the fiber volume proportion of said alumina - silica type short fibers may be between approximately 5% and approximately 40%; and said alumina - silica type short fibers may be alumina short fibers, or alternatively may be crystalline alumina - silica short fibers, of which the mullite crystalline amount of said alumina - silica type short fibers may be at least about 45%; or the alumina - silica type short fibers may be amorphous alumina - silica short fibers.

According to the present invention as described above, as reinforcing fibers there are used alumina - silica short fibers which have high strength, and are exceedingly effective in improving the high temperature stability and strength of the resulting composite material, and as matrix metal there is used an aluminum alloy with a copper content such as in concert with the volume proportion of the reinforcing alumina - silica short fibers to satisfy the inequalities detailed above and with the remainder thereof being substantially only aluminum, and the volume proportion of the alumina - silica short fibers is from 5% to 50%, whereby, as is clear from the results of experimental research carried out by the inventors of the present application as will be described below, a composite material with superior mechanical characteristics such as strength can be obtained.

Also according to the present invention, in cases where it is satisfactory if the same degree of strength as a conventional alumina - silica short fiber reinforced aluminum alloy is obtained, the volume proportion of alumina - silica short fibers in a composite material according to the present invention may be set to be lower than the value required for such a conventional composite material, and therefore, since it is possible to reduce the amount of alumina - silica short fibers used, the machinability and workability of the composite material can be improved, and it is also possible to reduce the cost of the composite material. Further, the characteristics with regard to wear on a mating member will be improved.

As will become clear from the experimental results detailed hereinafter, when copper is added to aluminum to make the matrix metal of the composite material according to the present invention, the strength of the aluminum alloy matrix metal is increased and thereby the strength of the composite material is improved, but that effect is not sufficient if the copper content is small, whereas if the copper content is too high the composite material becomes very brittle, and has a tendency to rapidly disintegrate. Moreover, as the volume proportion of the alumina - silica short fibers used is increased, the strength of the aluminum alloy matrix metal is increased and thereby the strength of the composite material is improved, but its toughness is reduced, and again there is a tendency for the composite material to become very brittle. Therefore the copper content of the aluminum alloy used as matrix metal in the composite material of the present invention is required to satisfy the two inequalities detailed above.

Furthermore, in a composite material with an aluminum alloy of the above composition as matrix metal, as also will become clear from the experimental researches given hereinafter: if the volume proportion of the alumina - silica short fibers is less than 5%, a sufficient strength cannot be obtained; when the volume proportion of the alumina - silica short fibers is between about 5% and about 30% the strength of the composite material increases substantially linearly along with increase in said short fiber volume proportion; and if the volume proportion of alumina - silica short fibers exceeds 40% and particularly if it exceeds 50% even if the volume proportion of the alumina - silica short fibers is increased, the strength of the composite material is not very significantly improved. Also, the wear resistance of the composite material increases with the volume proportion of the alumina - silica short fibers, but when the volume proportion of the alumina - silica short fibers is in the range from zero to approximately 5% said wear resistance increases rapidly with an increase in the volume proportion of the alumina - silica short fibers, whereas when the volume proportion of the alumina - silica short fibers is in the range of at least approximately 5%, the wear resistance of the composite material does not very significantly increase with an increase in the volume proportion of said alumina - silica short fibers. Therefore, according to one characteristic of the present invention, the volume proportion of the alumina - silica short fibers is required to be in the range of from approximately 5% to approximately 50%, and preferably is required to be in the range of from approximately 5% to approximately 40%.

If, furthermore, the copper content of the aluminum alloy used as matrix metal of the composite material of the present invention has a relatively high value, if there are unevennesses in the concentration of the copper within the aluminum alloy, the portions where the copper concentration is high will be brittle, and it will not therefore be possible to obtain a uniform matrix metal or a composite material of good and uniform quality. Therefore, according to another detailed characteristic of the present invention, in order that the concentration of copper within the aluminum alloy matrix metal should be uniform, such a composite material of which the matrix metal is aluminum alloy of which the copper content is less than approximately 3.5% is subjected to liquidizing processing for from about 2 hours to about 8 hours at a temperature of from about 480°C to about 520°C, and is preferably further subjected to aging processing for about 2 hours to about 8 hours at a temperature of from about 150°C to 200°C, while on the other hand such a composite material of which the matrix metal is aluminum alloy of which the copper content is at least approximately 3.5% and is less than approximately 6.5% is subjected to liquidizing processing for from about 2 hours to about 8 hours at a temperature of from about 460°C to about 510°C, and is preferably further subjected to aging processing for about 2 hours to about 8 hours at a temperature of from about 150°C to 200°C.

Further the alumina - silica short fibers in the composite material of the present invention may be either alumina - silica continuous fibers cut to a predetermined length or may be or alumina - silica non continuous fibers. These alumina - silica short fibers either may be alumina short fibers having a composition of about 80% to about 100% Al_2O_3 and remainder substantially SiO_2, or may be crystalline or amorphous alumina - silica short fibers having a composition of not less than about 35% and not greater than about 80% Al_2O_3 and remainder substantially SiO_2; and, in the case that said alumina - silica short fibers are alumina short fibers the crystalline structure of the Al_2O_3 may be any of the alpha, the gamma, or the delta types.

Particularly in the case that the alumina - silica type short fibers are crystalline alumina - silica short fibers, as will be described in detail below: if the mullite crystalline amount in the crystalline alumina - silica short fibers is in the range of from about 0% to about 10%, even if the mullite crystalline amount increases the strength of the composite material is not significantly increased, but remains substantially constant; if the mullite crystalline amount in the crystalline alumina - silica short fibers is in the range of from about 10% to about 20%, then as the mullite crystalline amount increases the strength of the composite material increases gradually and substantially linearly with said mullite crystalline amount; if the mullite crystalline amount in the crystalline alumina - silica short fibers is in the range of from about 20% to about 40%, then even if the mullite crystalline amount increases the strength of the composite material is not significantly improved, but remains substantially constant; if the mullite crystalline amount in the crystalline alumina - silica short fibers is in the range of from about 40% to about 45%, then with an increase in the mullite crystalline amount the strength of the composite material is improved rapidly and by a large amount; and, if the mullite crystalline amount in the crystalline alumina - silica short fibers is greater than about 45%, then with an increase in the mullite crystalline amount the strength of the composite material increases slightly and linearly with said mullite crystalline amount. Therefore, according to another detailed characteristic of the present invention, in the case that the alumina - silica type short fibers are crystalline alumina - silica short fibers, the mullite crystalline amount of these crystalline alumina - silica short fibers is set at to be at least about 45%.

Also, the fiber length of the alumina - silica short fibers is preferably from approximately 10 microns to approximately 7 cm, and particularly is preferably from approximately 10 microns to approximately 5 cm, and the fiber diameter thereof is preferably from approximately 1 micron to approximately 30 microns, and particularly is preferably from approximately 1 micron to approximately 25 microns.

It should be noted that in this specification all percentages, except in the expression of volume proportion of reinforcing fiber material, are percentages by weight, and in expressions relating to the composition of an aluminum alloy, "substantially of aluminum and copper alone" means that, apart from aluminum and copper, the total of the inevitable metallic elements such as silicon, iron, zinc, manganese, nickel, titanium, and chromium included in the aluminum alloy used as matrix metal is not more than 1%. Also, in this specification, in expressions relating to the composition of the reinforcing alumina - silica type short fibers, "substantially SiO_2" means that, apart from the Al_2O_3 and the SiO_2 forming the reinforcing alumina - silica type short fibers, other constituents are present only to the extent of being impurities.

It should further be noted that, in this specification, in descriptions of ranges of compositions, temperatures and the like, the expressions "at least", "not less than", "at most", "no more than", and "from ... to ..." and so on are intended to include the boundary values of the respective ranges.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be shown and described with regard to certain of the preferred embodiments thereof, and with reference to the illustrative drawings, which however should not be considered as limitative of the present invention in any way, since the scope of the present invention is to be considered as being delimited solely by the accompanying claims, rather than by any particular features of the disclosed embodiments or of the drawings. In these drawings:

Fig. 1 is a perspective view of a preform made of alumina - silica short fiber material, with said alumina - silica short fibers being aligned substantially randomly in two dimensions and substantially being stacked in the third dimension, for incorporation into composite materials according to various preferred embodiments of the present invention;

Fig. 2 is a schematic perspective view showing said preform as fitted into a stainless steel case which is shaped as a parallelopiped, ready for a high pressure casting process;

Fig. 3 is a schematic sectional diagram showing a high pressure casting device in the process of performing said high pressure casting process for manufacturing a composite material with the Fig. 1 alumina - silica short fiber material preform incorporated in a matrix of matrix metal;

Fig. 4 is a set of graphs in which copper content in percent is shown along the horizontal axis and bending strength in kg/mm^2 is shown along the vertical axis, derived from data relating to bending strength tests for the first set of preferred embodiments of the composite material of the present invention, each said graph showing the relation between copper content and bending strength of certain composite material test pieces for a particular fixed volume proportion of reinforcing alumina - silica fiber material in the matrix metal of the composite material;

Fig. 5 is a graph in which volume proportion in percent of the reinforcing alumina - silica fibers in the composite material is shown along the horizontal axis and copper content of the aluminum alloy matrix metal thereof in percent is shown along the vertical axis, showing the area defined by the above detailed inequalities between said fiber volume proportion and said copper percentage content, in which defined area, according to the present invention, the point defined by these characteristics of an embodiment of the present invention is required to lie;

Fig. 6 is a set of graphs, similar to Fig. 4 for the first set of preferred embodiments, in which copper content in percent is shown along the horizontal axis and bending strength in kg/mm^2 is shown along the vertical axis, derived from data relating to bending strength tests for the second set of preferred embodiments of the material of the present invention, each said graph showing the relation between copper content and bending strength of certain composite material test pieces for a particular fixed volume proportion of reinforcing alumina - silica fiber material in the matrix metal of the composite material;

Fig. 7 is a set of graphs, similar to Figs. 4 and 6 for the first and second sets of preferred embodiments respectively, in which copper content in percent is shown along the horizontal axis and bending strength in kg/mm^2 is shown along the vertical axis, derived from data relating to bending strength tests for the third set of preferred embodiments of the material of the present invention, each said graph showing the relation between copper content and bending strength of certain composite material test pieces for a particular fixed volume proportion of reinforcing alumina - silica fiber material in the matrix metal of the composite material;

Fig. 8 is similar to Fig. 1, being a perspective view of a preform made of alumina - silica short fiber material, with said alumina - silica short fibers however this time being aligned substantially randomly in three dimensions, for incorporation into composite materials according to certain other preferred embodiments of the present invention;

Fig. 9 is a set of graphs, similar to Figs. 4, 6 and 7 for the first through the third sets of preferred embodiments respectively, in which copper content in percent is shown along the horizontal axis and bending strength in kg/mm^2 is shown along the vertical axis, derived from data relating to bending strength tests for the fourth set of preferred embodiments of the material of the present invention, each said graph showing the relation between copper content and bending strength of certain composite material test pieces for a particular fixed volume proportion of reinforcing alumina - silica fiber material in the matrix metal of the composite material;

Fig. 10 is a set of graphs, in which volume proportion in percent of the reinforcing alumina - silica fibers in the composite material is shown along the horizontal axis and bending strength in kg/mm^2 is shown along the vertical axis, derived from data relating to bending strength tests for various composite materials having various different types and amounts of alumina - silica short fiber material as reinforcing material and an alloy containing approximately 4% of copper and remainder substantially aluminum as matrix metal, and showing the relation between fiber volume proportion of the composite material test pieces and their bending strengths; and:

Fig. 11 is a graph, in which mullite crystalline content in percent is shown along the horizontal axis and bending strength in kg/mm² is shown along the vertical axis, derived from data relating to bending strength tests for various composite materials having crystalline alumina - silica short fiber material with varying amounts of the mullite crystalline form therein as reinforcing material and an alloy containing approximately 5% of copper and remainder substantially aluminum as matrix metal, and showing the relation between the mullite crystalline percentage of the reinforcing short fiber material of the composite material test pieces and their bending strengths.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention will now be described with reference to the various preferred embodiments thereof. It should be noted that all the tables referred to in this specification are to be found at the end of the specification and before the claims thereof: the present specification is arranged in such a manner in order to maximize ease of pagination.

THE FIRST SET OF PREFERRED EMBODIMENTS

In order to assess what might be the most suitable composition for an aluminum alloy to be utilized as matrix metal for a contemplated composite material of the type described in the preamble to this specification, the reinforcing material of which is to be alumina - silica short fibers, the present inventors manufactured by using the high pressure casting method samples of various composite materials, utilizing as reinforcing material alumina - silica fiber material of type "KaoWool" (this is a trademark) made by Isolite Babcock Taika K.K., which were approximately 48% Al_2O_3 and remainder substantially SiO_2, and which had average fiber length 1 mm and average fiber diameter 3 microns, and utilizing as matrix metal Al-Cu type aluminum alloys of various compositions. Then the present inventors conducted evaluations of the bending strength of the various resulting composite material sample pieces.

First, a set of aluminum alloys designated as A1 through A15 were produced, having as base material aluminum and having various quantities of copper mixed therewith, with substantially no impurities, as shown in the appended Table 1. And, for each aluminum alloy A1 through A15, six preforms were made of amorphous, in this case, alumina - silica short fiber material by, in each case, subjecting a quantity of the above specified alumina - silica short fiber material to compression forming without using any binder. Each of these six alumina - silica fiber material preforms was, as schematically illustrated in perspective view in Fig. 1 wherein an exemplary such preform is designated by the reference numeral 2 and the alumina - silica fibers therein are generally designated as 1, about 38 x 100 x 16 mm in dimensions, and the individual alumina - silica fibers 1 in each of said preforms 2 were oriented substantially randomly in two dimensions, i.e. in the x-y plane parallel to the 38 x 100 mm face of the preform, and were overlapped in a two dimensionally random manner in the axis perpendicular to this plane. And the approximate fiber volume proportions in these six preforms 2 were respectively 5%, 10%, 15%, 20%, 30%, and 40%.

Next, each of these alumina - silica fiber material preforms 2 was subjected to high pressure casting together with an appropriate quantity of one of the aluminum alloys A1 through A15 described above, in the following manner. First, the preform 2 was inserted into a stainless steel case 2a, as shown in Fig. 2; this stainless steel case 2a was a rectangular parallelopiped and was open at both its ends. Then the preform 2 and the stainless steel case 2a were together heated up to a temperature of approximately 600°C, and then said preform 2 and the enclosing case 2a were placed within a mold cavity 4 of a casting mold 3, which itself had previously been preheated up to a temperature of approximately 250°C. Next, a quantity 5 of the appropriate one of the aluminum alloys A1 to A15 described above, molten and at a temperature of approximately 710°C, was relatively rapidly poured into said mold cavity 4, so as to surround the preform 2 therein, and then as shown in schematic view in Fig. 3 a pressure plunger 6, which itself had previously been preheated up to a temperature of approximately 200°C, which closely cooperated with the upper portion of said mold cavity 4 was inserted into said upper mold cavity portion, and was pressed downwards by a means not shown in the figure so as to pressurize said to a pressure of approximately 1000 kg/cm². Thereby, the molten aluminum alloy was caused to percolate into the interstices of the alumina - silica material preform 2. This pressurized state was maintained until the quantity 5 of molten aluminum alloy had completely solidified, and then the pressure plunger

6 was removed and the solidified aluminum alloy mass with the preform 2 included therein was removed from the casting mold 3, and the peripheral portion of said solidified aluminum alloy mass was machined away, and then from the stainless steel case 2a there was further extracted a sample piece of composite material which had alumina - silica short fiber material as reinforcing material in the appropriate volume proportion and the appropriate one of the aluminum alloys A1 through A15 as matrix metal. And, next, the composite material samples were subjected to liquidizing processing at a temperature of approximately 510°C for approximately 8 hours, and then they were subjected to artificial aging processing at a temperature of approximately 160°C for approximately 8 hours.

From each of the composite material sample pieces manufactured as described above, to which heat treatment had been applied, there was cut a bending strength test piece of length approximately 50 mm, width approximately 10 mm, and thickness approximately 2 mm, with the 50 x 10 mm surface parallel to the plane of random two dimensional fiber orientation, and for each of these composite material bending strength test pieces a bending strength test was carried out, with a gap between supports of approximately 40 mm. In these bending strength tests, the bending strength of the composite material bending strength test piece was measured as the surface stress at breaking point M/Z (M is the bending moment at the breaking point, while Z is the cross section coefficient of the composite material bending strength test piece).

The results of these bending strength tests were as shown in the appended Table 2, and as summarized in the graph of Fig. 4. The numerical values in Table 2 indicate the bending strengths (in kg/mm^2) of the composite material bending strength test pieces having as matrix metals aluminum alloys as shown down the left edge of the table and having reinforcing alumina - silica short fiber volume proportions as shown along the upper edge of the table. The graph of Fig. 4 is based upon the data in Table 2, and shows the relation between copper content and the bending strength (in kg/mm^2) of the composite material test pieces, for reinforcing amorphous alumina - silica short fiber volume proportion X fixed along the various lines thereof.

From Table 2 and Fig. 4 it will be understood that, for the case that the reinforcing amorphous alumina - silica short fiber volume proportion X was approximately 40%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 1% to approximately 4.5%; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of from approximately 6% to approximately 6.5%.

From Table 2 and Fig. 4 it will be further understood that, for the case that the reinforcing amorphous alumina - silica short fiber volume proportion X was approximately 30%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 2% to approximately 4.5%; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 6.5%.

From Table 2 and Fig. 4 it will be further understood that, for the case that the reinforcing amorphous alumina - silica short fiber volume proportion X was approximately 20%: when the copper content was in the range from approximately 0% to approximately 5.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 2.5% to approximately 4%; when the copper content reached approximately 5.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 5.5% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 7%.

From Table 2 and Fig. 4 it will be further understood that, for the cases that the reinforcing amorphous alumina - silica short fiber volume proportion X was approximately 15%, or 10%, or 5%: when the copper content was in the range from approximately 0% to approximately 6% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the respective ranges of from approximately 3% to approximately 6%, from approximately 3% to approximately 5.5%, and from approximately 3% to approximately 4.5%; when the copper content reached approximately 6% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 6% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 7.5%.

From the results of these bending strength tests detailed in Table 2 and Fig. 4 it will be seen that, in order to increase the strength of a composite material having as reinforcing fiber material such amorphous type alumina - silica short fibers and having as matrix metal an Al-Cu type aluminum alloy, it is preferable that the copper content of said Al-Cu type aluminum alloy matrix metal should be varied according to the volume proportion of the reinforcing fibers, and it will be seen that the preferable ranges for the copper content of the aluminum alloy matrix metal for the various fiber volume proportions are as in the appended Table 3. These preferable ranges for the copper content of the Al-Cu type aluminum alloy matrix metal are values which, if X (in percent) represents the volume proportion of the amorphous type alumina - silica short fibers and Y (likewise in percent) represents the copper content of the matrix metal, satisfy the two inequalities detailed previously, i.e.:

$$Y \leq -0.00092 X^2 - 0.0094 X + 7.85 \quad \ldots\ldots\ldots\ldots (1)$$

and:

$$Y \geq - 0.00092\ X^2 - 0.0094\ X + 3.55 \quad \ldots\ldots\ldots\ldots\ldots (2)$$

And, referring to Fig. 5 which is a graph in which the reinforcing alumina - silica fiber volume proportion X in percent in the composite material is shown along the horizontal axis and copper content Y of the aluminum alloy matrix metal thereof in percent is shown along the vertical axis, such values of X and Y as satisfy the two inequalities (1) and (2) detailed above fall within the area defined by the two quadratic curves shown.

THE SECOND SET OF PREFERRED EMBODIMENTS

Next, the present inventors manufactured further samples of various composite materials. As reinforcing material there was utilized an alumina - silica fiber material made by subjecting a quantity of the same type of alumina - silica fiber material as before - i.e. a quantity of alumina - silica fiber material of type "KaoWool" (this is a trademark) made by Isolite Babcock Taika K.K., which were approximately 48% Al_2O_3 and remainder substantially SiO_2, and which had average fiber length 1 mm and average fiber diameter 3 microns - to heat procesing so that the percentage of the mullite crystalline form included therein was about 60%. And as matrix metal there were utilized the same Al-Cu type aluminum alloys as before, i.e. the alloys A1 through A15 of the first set of preferred embodiments detailed above. Again, various composite material samples were produced for each type of aluminum alloy matrix metal, with fiber volume proportions being varied as before. Then the present inventors again conducted evaluations of the bending strength of the various resulting composite material sample pieces.

In detail, first, a set of aluminum alloys substantially the same as those designated as A1 through A15 in the case of the first set of preferred embodiments detailed above were produced in the same manner as before, and said alloys thus again had as base material aluminum and had various quantities of copper mixed therewith. No particular table of proportions of copper relating to these alloys of this second set of preferred embodiments like Table 1 and 3 for the alloys of the first set of preferred embodiments is appended, since none is required. And for each matrix metal sample six alumina - silica fiber material preforms were made as before, without using any binder, said six alumina - silica fiber material preforms 2 again having approximate fiber volume proportions of respectively 5%, 10%, 15%, 20%, 30%, and 40%; and these preforms 2 had substantially the same dimensions as the preforms 2 of the first set of preferred embodiments. Next, substantially as before, each of these alumina - silica short fiber material preforms 2 was subjected to high pressure casting while included in a stainless steel case, together with an appropriate quantity of one of the aluminum alloys described above, utilizing operational parameters substantially as before, and, after machining away the peripheral portions of the resulting solidified aluminum alloy masses and extraction from the cases, sample pieces of composite material which had alumina - silica short fiber material as reinforcing material in the appropriate fiber volume proportion and the appropriate one of the above described aluminum alloys as matrix metal were obtained. Post processing steps were performed on the composite material samples, substantially as before, and from each of the composite material sample pieces manufactured as described above, to which heat treatment had been applied, there was cut a bending strength test piece of dimensions substantially as in the case of the first set of preferred embodiments, and for each of these composite_material bending strength test pieces a bending strength test was carried out, again substantially as before.

The results of these bending strength tests were as shown in the appended Table 4, and as summarized in the graph of Fig. 6. Thus, Table 4 and Fig. 6 correspond respectively to Table 2 and Fig. 4 relating to the first set of preferred embodiments. As before, the numerical values in Table 4 indicate the bending strengths (in kg/mm^2) of the composite material bending strength test pieces having as matrix metals aluminum alloys as shown down the left edge of the table and having reinforcing alumina - silica short fiber volume proportions as shown along the upper edge of the table. The graph of Fig. 6 is based upon the data in Table 4, and shows the relation between copper content and the bending strength (in kg/mm^2) of the composite material test pieces, for reinforcing mullite crystalline alumina - silica short fiber volume proportion X fixed along the various lines thereof.

From Table 4 and Fig. 6 it will be understood that, for the case that the reinforcing mullite crystalline alumina - silica short fiber volume proportion X was approximately 40%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 1% to approximately 4.5%; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of from approximately 6% to approximately 6.5%.

From Table 4 and Fig. 6 it will be further understood that, for the case that the reinforcing mullite crystalline alumina - silica short fiber volume proportion X was approximately 30%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 2% to approximately 4.5%; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range from approximately 6.5% to approximately 7%.

From Table 4 and Fig. 6 it will be further understood that, for the case that the reinforcing mullite crystalline alumina - silica short fiber volume proportion X was approximately 20%: when the copper content was in the range from approximately 0% to approximately 5.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 2.5% to approximately 4%; when the copper content reached approximately 5.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 5.5% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of from approximately 7% to approximately 7.5%.

From Table 4 and Fig. 6 it will be further understood that, for the cases that the reinforcing mullite crystalline alumina - silica short fiber volume proportion X was approximately 15%, or 10%, or 5%: when the copper content was in the range from approximately 0% to approximately 6% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range of from approximately 3% to approximately 6%; when the copper content reached approximately 6% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 6% the bending strength of the composite material had a tendency to reduce relatively rapidly along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 7.5%.

From the results of these bending strength tests detailed in Table 4 and Fig. 6 it will be seen that, also in order to increase the strength of a composite material having as reinforcing fiber material such mullite crystalline type alumina - silica short fibers and having as matrix metal an Al-Cu type aluminum alloy, it is preferable that the copper content of said Al-Cu type aluminum alloy matrix metal should be varied according to the volume proportion of the reinforcing fibers, and it will be seen that the preferable ranges for the copper content of the aluminum alloy matrix metal for the various fiber volume proportions are as in the previously detailed Table 3; said preferable ranges for the copper content of the Al-Cu type aluminum alloy matrix metal therefore likewise being values which satisfy the two inequalities (1) and (2) detailed previously and which fall within the area defined by the two quadratic curves shown in Fig. 5 and explained above.

THE THIRD SET OF PREFERRED EMBODIMENTS

Next, the present inventors manufactured further samples of various composite materials, again utilizing as matrix metal the fifteen Al-Cu type aluminum alloys A1 through A15 detailed above, but this time using as reinforcing material a different type of alumina - silica fiber material, consisting of alumina short fibers. Then the present inventors again conducted evaluations of the bending strength of the various resulting composite material sample pieces.

First, a set of aluminum alloys again designated as A1 through A15 were produced in the same manner as before, again having as base material aluminum and having various quantities of copper mixed therewith, as before. And for each said aluminum alloy sample altogether six alumina - silica fiber material preforms were made similarly to what was done before by, in each case, subjecting a quantity of a fiber material, this time being alumina short fibers of type "Saffil RF" (this is a trademark) manufactured by ICI KK and being composed of approximately 95% delta Al_2O_3 and remainder substantially SiO_2 and having average fiber length approximately 2 cm and average fiber diameter approximately 3 microns, to compression forming without using any binder, the six said alumina - silica fiber material preforms 2 for each aluminum alloy sample as before having approximate fiber volume proportions of respectively 5%, 10%, 15%, 20%, 30%, and 40%, as before. These preforms 2 had substantially the same dimensions as the preforms 2 of the first and second sets of preferred embodiments.

Next, substantially as before, each of these alumina - silica fiber material preforms 2 was subjected to high pressure casting in a stainless steel case together with an appropriate quantity of the appropriate one of the aluminum alloys A1 through A15 described above, utilizing operational parameters substantially as before. The solidified aluminum alloy mass with the preform 2 included therein was then removed from the casting mold, and the peripheral portion of said solidified aluminum alloy mass was machined away, leaving, after extraction from the stainless steel case, a sample piece of composite material which had alumina - silica short fiber material as reinforcing material in the appropriate fiber volume proportion and the appropriate one of the aluminum alloys A1 through A15 as matrix metal. And post processing steps were performed on the composite material samples, substantially as before. From each of the composite material sample pieces manufactured as described above, to which heat treatment had been applied, there was cut a bending strength test piece of dimensions substantially as in the case of the first and second sets of preferred embodiments, and for each of these composite material bending strength test pieces a bending strength test was carried out, again substantially as before.

The results of these bending strength tests were as shown in the appended Table 5, and as summarized in the graph of Fig. 7. Thus, Table 5 and Fig. 7 correspond respectively to Table 2 and Fig. 4 relating to the first set of preferred embodiments, and also respectively to Table 4 and Fig. 6 relating to the second set of preferred embodiments. As before, the numerical values in Table 5 indicate the bending strengths (in kg/mm^2) of the composite material bending strength test pieces having as matrix metals aluminum alloys as shown down the left edge of the table and having reinforcing alumina - silica short fiber volume proportions as shown along the upper edge of the table. The graph of Fig. 7 is based upon the data in Table 5, and shows the relation between copper content and the bending strength (in kg/mm^2) of the composite material test pieces, for reinforcing delta alumina type alumina - silica short fiber volume proportion X fixed along the various lines thereof.

From Table 5 and Fig. 7 it will be understood that, for the case that the reinforcing delta alumina type alumina - silica short fiber volume proportion X was approximately 40%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased relatively rapidly along with an increase in the copper content; when the copper content reached approximately

4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5% the bending strength of the composite material reduced along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of from approximately 6% to approximately 6.5%.

From Table 5 and Fig. 7 it will be further understood that, for the case that the reinforcing delta alumina type alumina - silica short fiber volume proportion X was approximately 30%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased relatively rapidly along with an increase in the copper content; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5%, the bending strength of the composite material reduced along with an increase in the copper content, and particularly said bending strength reduced rapidly along with an increase in the copper content when the copper content was in the range of above approximately 6.5%.

From Table 5 and Fig. 7 it will be further understood that, for the case that the reinforcing delta alumina type alumina - silica short fiber volume proportion X was approximately 20%: when the copper content was in the range from approximately 0% to approximately 5.5% the bending strength of the composite material increased along with an increase in the copper content; when the copper content reached approximately 5.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 5.5% the bending strength of the composite material reduced along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 7%.

From Table 5 and Fig. 7 it will be further understood that, for the cases that the reinforcing delta alumina type alumina - silica short fiber volume proportion X was approximately 15%, or 10%, or 5%: when the copper content was in the range from approximately 0% to approximately 6% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range of from approximately 3% to approximately 6%; when the copper content reached approximately 6% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 6% the bending strength of the composite material had a tendency to reduce along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 7.5%.

From the results of these bending strength tests detailed in Table 5 and Fig. 7 it will be seen that, also in order to increase the strength of a composite material having as reinforcing fiber material such delta alumina type type alumina - silica short fibers and having as matrix metal an Al-Cu type aluminum alloy, it is preferable that the copper content of said Al-Cu type aluminum alloy matrix metal should be varied according to the volume proportion of the reinforcing fibers, and it will be seen that the preferable ranges for the copper content of the aluminum alloy matrix metal for the various fiber volume proportions are as in the previously detailed Table 3; said preferable ranges for the copper content of the Al-Cu type aluminum alloy matrix metal therefore likewise being values which satisfy the two inequalities (1) and (2) detailed previously and which fall within the area defined by the two quadratic curves shown in Fig. 5 and explained above.

Further, although the details are not disclosed in this specification in the interests of brevity of description, in fact, bending strength tests in the same manner and under the same conditions as in this third set of preferred embodiments were conducted, except that as alumina - silica type short fibers there were used alumina short fibers obtained by cutting alumina short fiber material of the type "Sumi-Ka alumina fibers" manufactured by Sumitomo Kagaku Kogyo KK, which were composed approximately of 85% gamma type Al_2O_3, the remainder being substantially SiO_2, and which had average fiber diameter 17 microns, to a length of approximately 1 cm. The results of these tests showed a similar trend to that of the results for the third set of preferred embodiments detailed above and shown in Fig. 7. From these tests it could be discerned that, also in the case that alumina short fibers having a principal constituent of gamma type Al_2O_3 were used as the alumina - silica type short reinforcing fiber material, the copper content required to obtain a composite material of superior bending strength depended on the fiber volume proportion, and that the preferable ranges for the copper content of the aluminum alloy matrix metal for the various fiber volume proportions were as in the previously detailed Table 3; said preferable ranges for the copper content of the Al-Cu type aluminum alloy matrix metal therefore likewise being values which satisfied the two inequalities (1) and (2) detailed previously and which fell within the area defined by the two quadratic curves shown in Fig. 5 and explained above.

THE FOURTH SET OF PREFERRED EMBODIMENTS

For the fourth set of preferred embodiments of the present invention, the present inventors manufactured by using the high pressure casting method samples of various composite materials, again utilizing as matrix metal the fifteen Al-Cu type aluminum alloys A1 through A15 detailed above, but this time using as reinforcing material a different type of alumina - silica fiber material, the alumina of which consisted of alpha alumina and mullite crystals. Then the present inventors again conducted evaluations of the bending strength of the various resulting composite material sample pieces.

First, a set of aluminum alloys again designated as A1 through A15 were produced in the same manner as before, again having as base material aluminum and having various quantities of copper mixed therewith, as before. And for each said aluminum alloy sample altogether six alumina - silica fiber material preforms were made similarly to what was done before by, in each case, subjecting a quantity of a fiber material, this time being alumina short fibers of type "Arusen" (this is a trademark) manufactured by Denki Kagaku Kogyo KK and being composed of approximately 80% Al_2O_3 - which consisted of alpha Al_2O_3 crystals and mullite crystals - and remainder substantially SiO_2 and having average fiber length approximately 2 cm and average fiber diameter approximately 3 microns, to compression forming without using any binder, the six said alumina - silica fiber material preforms 2 for each aluminum alloy sample as before having approximate fiber volume proportions of respectively 5%, 10%, 15%, 20%, 30%, and 40%, as before. In this case, each of these six alumina - silica fiber material preforms was again, as schematically illustrated in perspective view in Fig. 8 wherein an exemplary such preform is designated by the reference numeral 8 and the alumina - silica fibers therein are generally designated as 7, about 38 x 100 x 16 mm in dimensions, while the individual alumina - silica fibers 7 in each of said preforms 8 were oriented substantially randomly in three dimensions.

Next, substantially as before, each of these alumina - silica fiber material preforms 2 was subjected to high pressure casting in a stainless steel case together with an appropriate quantity of the appropriate one of the aluminum alloys A1 through A15 described above, utilizing operational parameters substantially as before. The solidified aluminum alloy mass with the preform 2 included therein was then removed from the casting mold, and the peripheral portion of said solidified aluminum alloy mass was machined away, leaving, after extraction from the stainless steel case, a sample piece of composite material which had alumina - silica short fiber material as reinforcing material in the appropriate fiber volume proportion and the appropriate one of the aluminum alloys A1 through A15 as matrix metal. And post processing steps were performed on the composite material samples, substantially as before. From each of the composite material sample pieces manufactured as described above, to which heat treatment had been applied, there was cut a bending strength test piece of dimensions substantially as in the case of the first and second sets of preferred embodiments, and for each of these composite material bending strength test pieces a bending strength test was carried out, again substantially as before.

The results of these bending strength tests were as shown in the appended Table 6, and as summarized in the graph of Fig. 9. Thus, Table 6 and Fig. 9 correspond respectively to Table 2 and Fig. 4 relating to the first set of preferred embodiments, respectively to Table 4 and Fig. 6 relating to the second set of preferred embodiments, and also to Table 5 and Fig. 7 relating to the third set of preferred embodiments. As before, the numerical values in Table 6 indicate the bending strengths (in kg/mm^2) of the composite material bending strength test pieces having as matrix metals aluminum alloys as shown down the left edge of the table and having reinforcing alumina - silica short fiber volume proportions as shown along the upper edge of the table. The graph of Fig. 9 is based upon the data in Table 6, and shows the relation between copper content and the bending strength (in kg/mm^2) of the composite material test pieces, for reinforcing alpha alumina type alumina - silica short fiber volume proportion X fixed along the various lines thereof.

From Table 6 and Fig. 9 it will be understood that, for the case that the reinforcing alpha alumina type alumina - silica short fiber volume proportion X was approximately 40%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased relatively rapidly along with an increase in the copper content; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5% the bending strength of the composite material reduced along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of from approximately 6% to approximately 6.5%.

From Table 6 and Fig. 9 it will be further understood that, for the case that the reinforcing alpha alumina type alumina - silica short fiber volume proportion X was approximately 30%: when the copper content was in the range from approximately 0% to approximately 4.5% the bending strength of the composite material increased relatively rapidly along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the range from approximately 2% to approximately 3.5%; when the copper content reached approximately 4.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 4.5%, the bending strength of the composite material reduced along with an increase in the copper content, and particularly said bending strength reduced rapidly along with an increase in the copper content when the copper content was in the range of from approximately 6.5% to approximately 7%.

From Table 6 and Fig. 9 it will be further understood that, for the case that the reinforcing alpha alumina type alumina - silica short fiber volume proportion X was approximately 20%: when the copper content was in the range from approximately 0% to approximately 5.5% the bending strength of the composite material increased along with an increase in the copper content, and particularly that when the copper content was in the range from approximately 2.5% to approximately 3.5% the bending strength of the composite material increased relatively rapidly along with an increase in the copper content; when the copper content reached approximately 5.5% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 5.5% the bending strength of the composite material reduced along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being between approximately 7% and approximately 7.5%.

From Table 6 and Fig. 9 it will be further understood that, for the cases that the reinforcing alpha alumina type alumina - silica short fiber volume proportion X was approximately 15%, or 10%, or 5%: when the copper content was in the range from approximately 0% to approximately 6% the bending strength of the composite material increased along with an increase in the copper content, and particularly increased relatively rapidly along with an increase in the copper content when the copper content was in the ranges, respectively, of from approximately 3% to approximately 3.5%, from approximately 3% to approximately 5%, and from approximately 3% to approximately 3.5%; when the copper content reached approximately 6% the bending strength of the composite material reached a substantially maximum value; and, when the copper content was in the range of being greater than approximately 6% the bending strength of the composite material had a tendency to reduce along with an increase in the copper content, and particularly reduced rapidly along with an increase in the copper content when the copper content was in the range of being greater than approximately 7.5%.

From the results of these bending strength tests detailed in Table 6 and Fig. 9 it will be seen that, also in order to increase the strength of a composite material having as reinforcing fiber material such alpha alumina type type alumina - silica short fibers and having as matrix metal an Al-Cu type aluminum alloy, it is preferable that the copper content of said Al-Cu type aluminum alloy matrix metal should be varied according to the volume proportion of the reinforcing fibers, and it will be seen that the preferable ranges for the copper content of the aluminum alloy matrix metal for the various fiber volume proportions are as in the previously detailed Table 3; said preferable ranges for the copper content of the Al-Cu type aluminum alloy matrix metal therefore likewise being values which satisfy the two inequalities (1) and (2) detailed previously and which fall within the area defined by the two quadratic curves shown in Fig. 5 and explained above.

Further, although the details are not disclosed in this specification in the interests of brevity of description, in fact, bending strength tests in the same manner and under the same conditions as in this fourth set of preferred embodiments were conducted, except that as alumina - silica type short fibers there were used alumina short fibers obtained by cutting alumina short fiber material of the type "FP fiber" manufactured by Dupont, which were composed approximately of 99.5% alpha type Al_2O_3 and which had average fiber diameter 20 microns, to a length of approximately 1 cm. The results of these tests showed a similar trend to that of the results for the fourth set of preferred embodiments detailed above and shown in Fig. 9. From these tests it could be discerned that, also in the case that alumina short fibers having substantially their only constituent being alpha type Al_2O_3 were used as the alumina - silica type short reinforcing fiber material, the copper content required to obtain a composite material of superior bending strength depended on the fiber volume proportion, and that the preferable ranges for the copper content of the aluminum alloy matrix metal for the various fiber volume proportions were as in the previously detailed Table 3; said preferable ranges for the copper content of the Al-Cu type aluminum alloy matrix metal therefore likewise being values which satisfied the two inequalities (1) and (2) detailed previously and which fell within the area defined by the two quadratic curves shown in Fig. 5 and explained above.

THE FIFTH SET OF PREFERRED EMBODIMENTS

Since the experimental researches undertaken by the present inventors as detailed above in terms of the above embodiments had clearly demonstrated that it is preferable for the copper content of the aluminium alloy to be a value satisfying the inequalities (1) and (2) above, with respect to any particular fiber volume proportion for the reinforcing alumina - silica short fiber material, next, in order to assess what value of the volume proportion of the alumina-silica type short fibers which are the reinforcing fibers was most appropriate, the following set of experiments was performed. Using an aluminium alloy of which the copper content was 4% and the remainder was substantially aluminium as matrix metal, and using the amorphous alumina - silica short fibers used in the first set of preferred embodiments, the crystalline alumina - silica short fibers used in the second set of preferred embodiments, the alumina short fibers used in the third set of preferred embodiments, and the alumina short fibers used in the fourth set of preferred embodiments above respectively as reinforcing fibers, composite material sample sets B1 to B7, C1 to C7, D1 to D7 and E1 to E7 were manufactured, with, in each said set of seven samples, the fiber volume proportions being variously 5%, 10%, 15%, 20%, 30%, 40%, and 50%. This manufacture was carried out in the same manner and under the same conditions as in the first set of preferred embodiments detailed above (except that in the case of the composite material sample set E1 to E7 the same process and conditions were utilized as in the fourth set of preferred embodiments detailed above), and the various resulting composite material samples were subjected to liquidizing processing and artificial aging processing in the same manner and under the same conditions as in the various sets of preferred embodiments detailed above. Then, bending test pieces were cut in the same manner and of the same dimensions as in the first or the fourth sets of preferred embodiments detailed above from each composite material sample piece, and for each bending test sample piece a bending test was carried out in the same manner and under the same conditions as in the first set of preferred embodiments detailed above. Also a cast aluminium alloy sample piece having a copper content of 4% and remainder being substantially aluminium was subjected to liquidizing processing and artificial aging processing under the same conditions as in the first set of preferred embodiments detailed above, a bending test piece was cut in the same manner and of the same dimensions as in the first set of preferred embodiments detailed above from this cast piece, and for this bending test piece a bending test was carried out in the same manner and under the same conditions as in the first set of preferred embodiments detailed above. These bending test results are shown in the graph of Fig. 10.

From Fig. 10 it will be seen that when the volume proportion of fibers is in the range from about 0% to about 5% the bending strength of the sample pieces hardly increases as the fiber volume proportion is increased, and said bending strength is close to the bending strength of the aluminium alloy which is the matrix metal, by itself; when the fiber volume proportion is in the range from about 5% to 30% the bending strength of the bending test sample piece increases greatly and substantially linearly with the increase in the fiber volume proportion; when the fiber volume proportion is in the range from about 30% to about 40% the bending strength of the bending test sample piece increases gradually with an increase in the fiber volume proportion; and, when the fiber volume proportion is in the range greater than about 40%, the bending strength is not significantly increased even if the fiber volume proportion is increased. Therefore, it will be seen that it is preferable that the fiber volume proportion of the alumina - silica type short fiber material utilized as reinforcing fibers is, irrespective of the type of said reinforcing fiber material, in the range of from about 5% to about 50%, and more preferably in the range of from about 5% to about 40%.

Further, from the results of these bending tests and from the test results of the first through the fourth sets of preferred embodiments as detailed above, it will be seen that in the relation with the fiber volume proportion the preferable range for the copper content of the aluminium alloy which is the matrix metal is the range indicated by hatching in Fig. 5, and the particularly preferable range is that indicated by cross hatching.

THE SIXTH SET OF PREFERRED EMBODIMENTS

In the particular case that crystalline alumina - silica short fiber material is used as the alumina - silica type short fiber material, in order to assess what value of the mullite crystalline amount of the crystalline alumina - silica short fiber material yields a high value for the bending strength of the composite material, several samples of the amorphous alumina - silica type short fiber material used in Embodiment 1 above were subjected to heat treatment under various conditions not particularly detailed here because they are per se known in the art, whereby crystalline alumina - silica type short fiber material samples were formed with mullite crystalline amounts of 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60 and 65%, and then, from each of these crystalline alumina - silica type short fiber material samples, a preform with a fiber volume proportion of approximately 15% was formed in the same manner and under the same conditions as in the first set of preferred embodiments detailed above, and then, using each such preform as a reinforcing fiber mass and an aluminium alloy of which the copper content was 5% and the remainder was substantially aluminium as matrix metal, various composite material sample pieces were manufactured in the same manner and under the same conditions as in the first set of preferred embodiments detailed above, the various resulting composite material sample pieces were subjected to liquidizing processing and artificial aging processing in the same manner and under the same conditions as in the first set of preferred embodiments detailed above, from each composite material sample piece a bending test piece was cut in the same manner and under the same conditions as in the first set of preferred embodiments detailed above, and for each bending test piece a bending test was carried out, as before. The results of these bending tests are shown in Fig. 11. It should be noted that in Fig. 11 the mullite crystalline amount (in percent) of the crystalline alumina - silica short fiber material which was the reinforcing fiber material is shown along the horizontal axis .

From Fig. 11 it will be seen that: in the case that the mullite crystalline amount is in the range from about 0% to about 10% the bending strength of the composite material is a substantially constant low value; in the case that the mullite crystalline amount is in the range from about 10% to about 20% the bending strength of the composite material increases gradually and substantially linearly with an increase in the mullite crystalline amount; in the case that the mullite crystalline amount is in the range from about 20% to about 40% the bending strength of the composite material increases only extremely slightly with an increase in the mullite crystalline amount; in the case that the mullite crystalline amount is in the range from about 40% to about 45% the bending strength of the composite material increases extremely rapidly with an increase in the mullite crystalline amount; and in the case that the mullite crystalline amount is in the range of greater than about 45% the bending strength of the composite material has an extremely high value and increases slightly and substantially linearly with an increase in the mullite crystalline amount. Therefore it will be seen that, in the case that crystalline alumina - silica short fiber material is used as the alumina - silica short fiber material, it is preferable for the value of the mullite crystalline amount therein to be at least 45%.

Although the present invention has been shown and described in terms of certain sets of preferred embodiments thereof, and with reference to the appended drawings, it should not be considered as being particularly limited thereby. The details of any particular embodiment, or of the drawings, could be varied without, in many cases, departing from the ambit of the present invention. Accordingly, the scope of the present invention is to be considered as being delimited, not by any particular perhaps entirely fortuitous details of the disclosed preferred embodiments, or of the drawings, but solely by the legitimate and properly interpreted scope of the accompanying claims, which follow after the Tables.

TABLE 1

ALLOY NO.	COPPER CONTENT (WT %)
A1	0.04
A2	1.02
A3	2.04
A4	2.48
A5	3.03
A6	3.51
A7	4.05
A8	4.53
A9	4.98
A10	5.54
A11	6.01
A12	6.49
A13	6.98
A14	7.50
A15	7.95

TABLE 2

Alloy No.	Alumina - silica fiber volume proportion (%)					
	5	10	15	20	30	40
A1	33	35	36	38	40	41
A2	34	36	38	39	42	43
A3	36	38	39	41	44	49
A4	37	39	40	42	48	51
A5	38	40	41	47	51	53
A6	41	42	44	49	54	57
A7	43	45	47	52	57	60
A8	45	47	50	53	59	62
A9	47	49	51	55	58	59
A10	49	51	53	56	54	56
A11	51	52	54	53	52	52
A12	49	51	52	50	50	45
A13	46	47	48	48	44	42
A14	43	43	45	40	39	39
A15	34	35	37	36	35	35

TABLE 3

Fiber volume proportion (%)	Desired copper content (%)
5	3.5 - 7.5
10	3.5 - 7.5
15	3.5 - 7.5
20	3.0 - 7.0
30	2.5 - 6.5
40	2.0 - 6.0

TABLE 4

Alloy No.	Alumina - silica fiber volume proportion (%)					
	5	10	15	20	30	40
A1	34	36	37	39	41	44
A2	35	38	39	41	43	47
A3	36	39	41	44	46	53
A4	37	41	42	45	53	56
A5	38	42	44	51	57	60
A6	41	45	47	53	60	63
A7	42	47	49	56	63	66
A8	44	49	52	57	65	68
A9	45	51	53	59	64	66
A10	47	52	55	60	62	63
A11	48	54	57	58	60	59
A12	47	53	55	56	57	49
A13	45	51	53	52	46	45
A14	43	48	49	42	41	40
A15	35	35	36	37	37	37

TABLE 5

	Alumina - silica fiber volume proportion (%)					
Alloy No.	5	10	15	20	30	40
A1	34	37	38	39	41	45
A2	36	39	40	42	47	49
A3	36	41	43	46	53	56
A4	37	42	45	48	56	58
A5	38	43	46	51	57	60
A6	40	46	49	53	61	65
A7	42	48	52	55	64	66
A8	44	50	54	57	68	70
A9	46	52	55	59	67	68
A10	48	54	57	61	64	66
A11	50	56	59	59	61	64
A12	49	55	57	57	60	50
A13	48	53	55	55	53	47
A14	47	51	53	47	46	44
A15	38	44	44	41	40	38

0213528

TABLE 6

Alloy No.	Alumina - silica fiber volume proportion (%)					
	5	10	15	20	30	40
A1	33	35	37	38	39	44
A2	34	37	39	40	43	48
A3	36	39	42	43	46	54
A4	37	40	43	45	52	57
A5	39	41	45	50	56	58
A6	41	45	50	53	61	63
A7	43	48	52	55	62	66
A8	44	50	55	57	65	67
A9	46	52	57	58	64	65
A10	47	54	58	59	63	63
A11	48	56	59	58	61	61
A12	47	55	57	57	59	51
A13	46	54	56	56	48	47
A14	45	52	53	47	44	45
A15	39	43	43	43	42	43

WHAT IS CLAIMED IS:

1. A composite material comprising alumina - silica type short fibers embedded in a matrix of metal, the percentage fiber volume proportion X% of said alumina - silica type short fibers being between approximately 5% and approximately 50%, and said metal being an alloy consisting essentially of a percentage Y% of copper and remainder substantially aluminum, said values X% and Y% approximately satisfying the following inequalities:

$$Y \leq -0.00092 X^2 - 0.0094 X + 7.85$$

and:

$$Y \geq -0.00092 X^2 - 0.0094 X + 3.55$$

2. A composite material according to claim 1, wherein the fiber volume proportion of said alumina - silica type

short fibers is between approximately 5% and approximately 40%.

3. A composite material according to claim 1 or claim 2, wherein said alumina - silica type short fibers are alumina short fibers.

4. A composite material according to claim 1 or claim 2, wherein said alumina - silica type short fibers are crystalline alumina - silica short fibers.

5. A composite material according to claim 4, wherein the mullite crystalline amount of said alumina - silica type short fibers is at least about 45%.

6. A composite material according to claim 1 or claim 2, wherein said alumina - silica type short fibers are amorphous alumina - silica short fibers.

FIG. 1

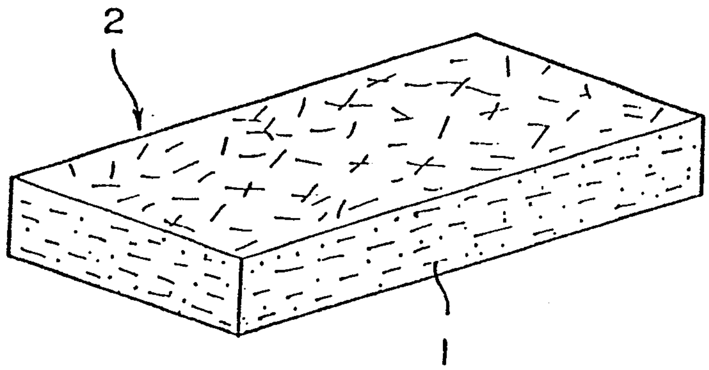


FIG. 2

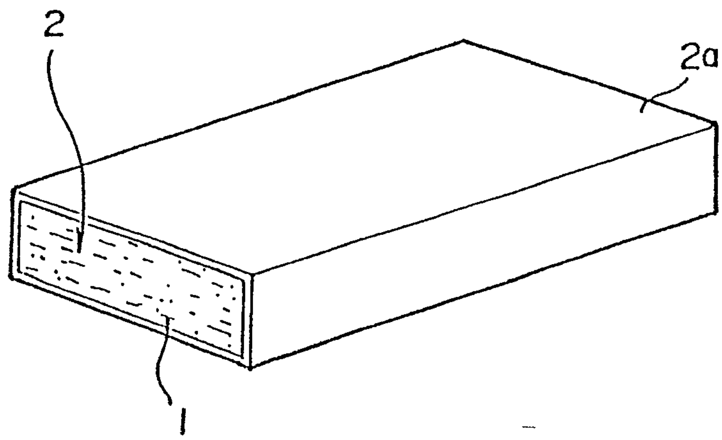


FIG. 3

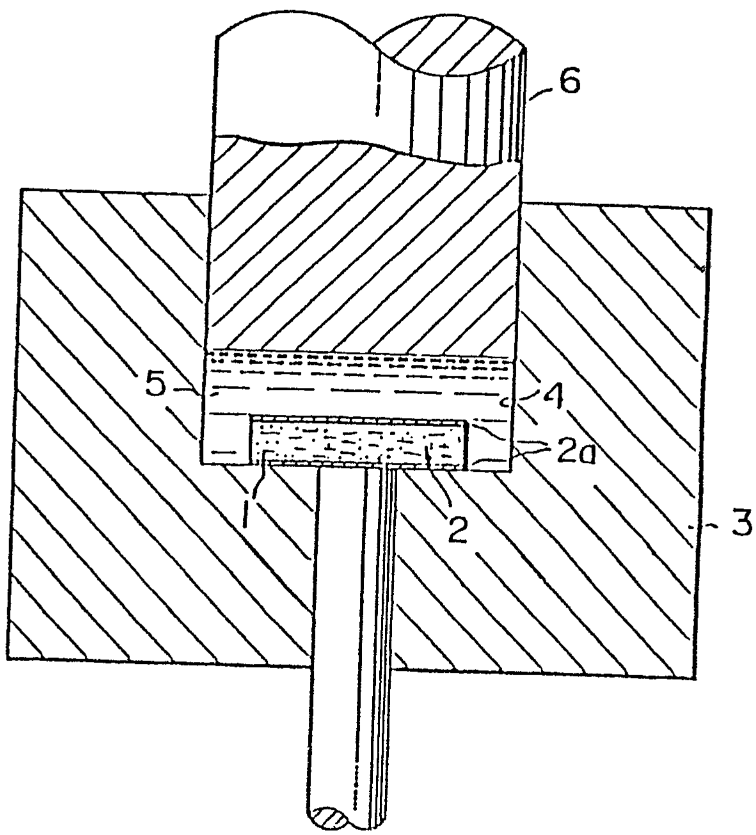
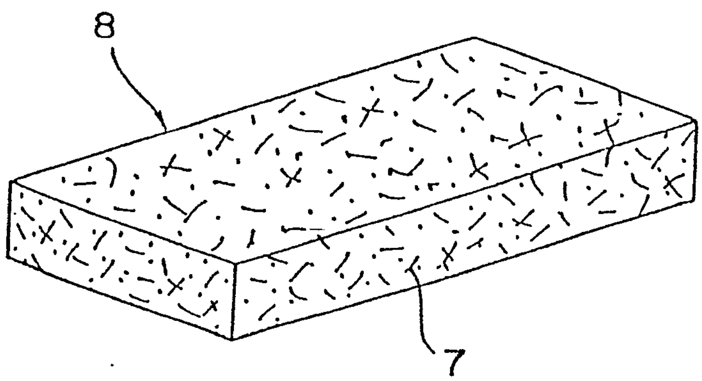


FIG. 8



3/9

0213528

FIG. 4

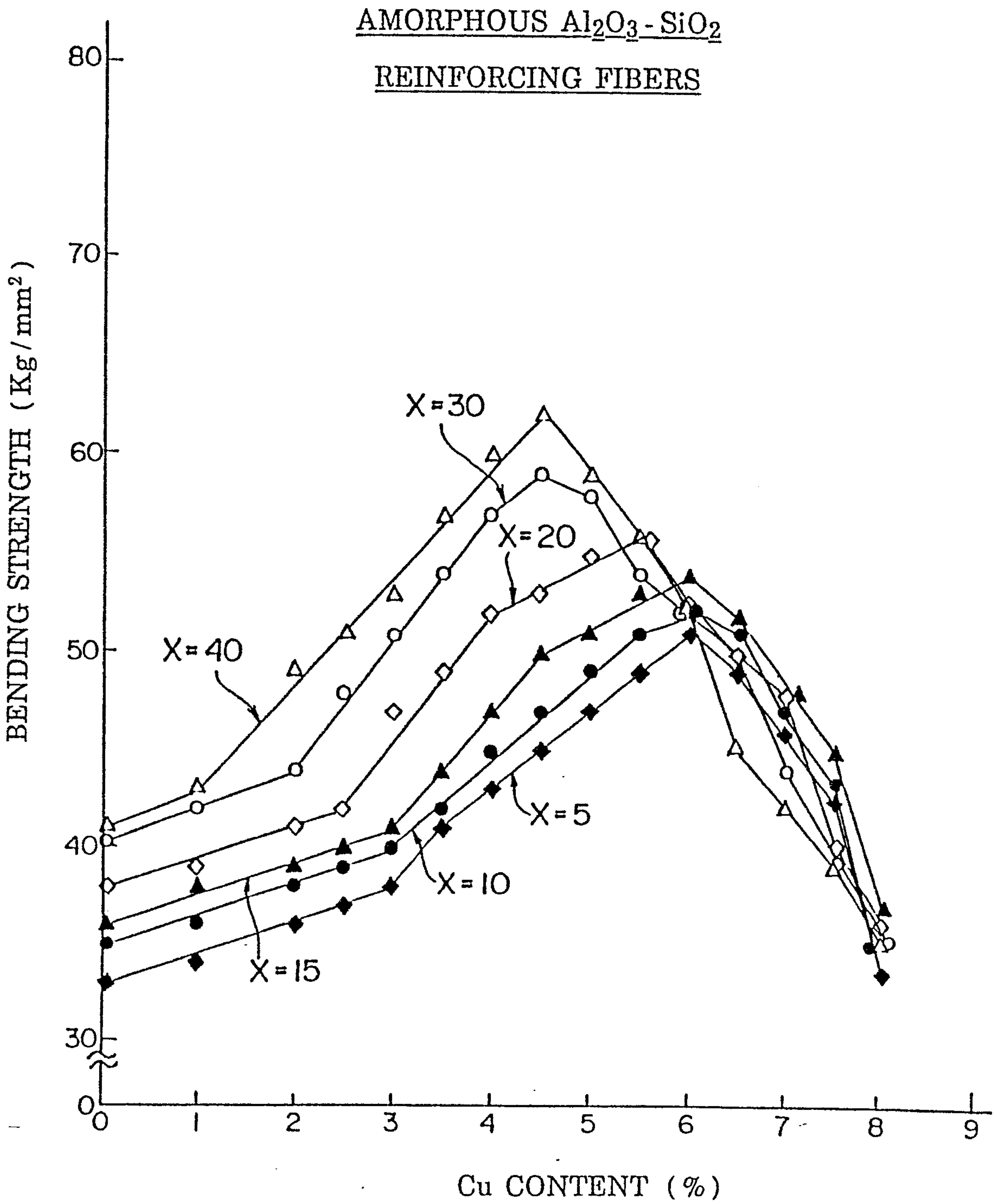


FIG. 5

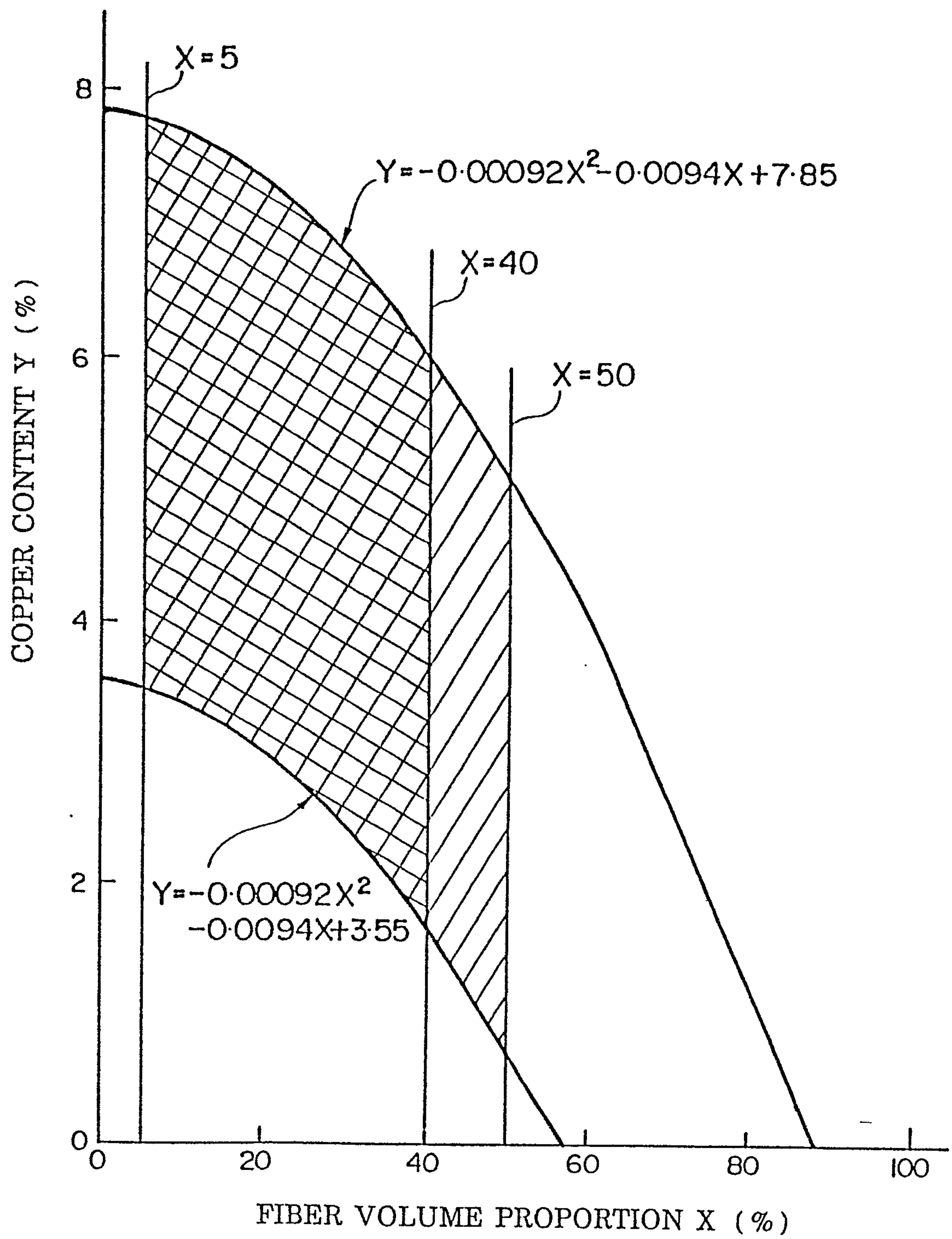

X=5
X=40
X=50
Y=-0·00092X²-0·0094X+7·85
Y=-0·00092X²
-0·0094X+3·55
COPPER CONTENT Y (%)
FIBER VOLUME PROPORTION X (%)
0
2
4
6
8
0
20
40
60
80
100

FIG. 6

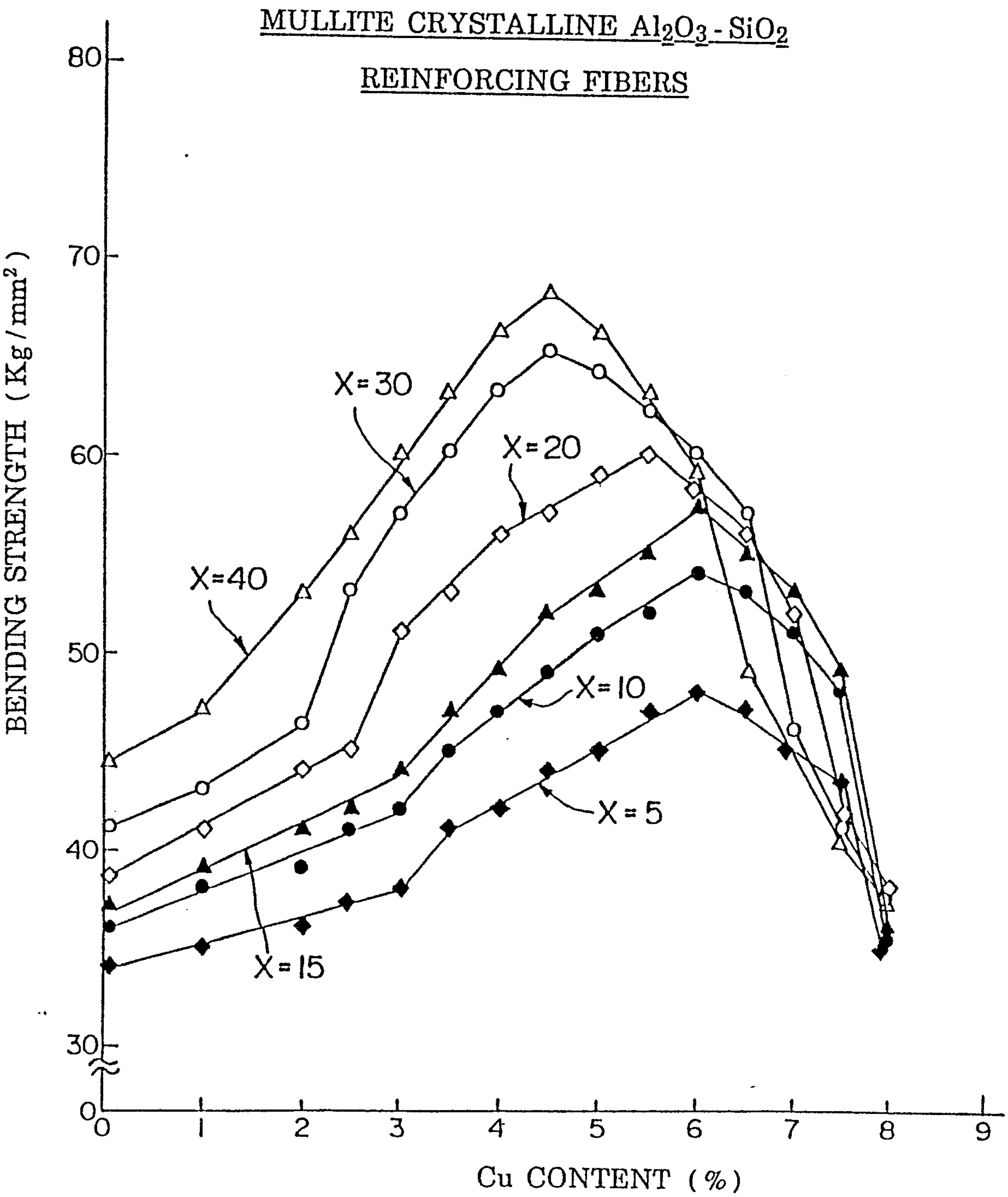

MULLITE CRYSTALLINE Al_2O_3 - SiO_2
REINFORCING FIBERS
BENDING STRENGTH (Kg/mm^2)
Cu CONTENT (%)
X=40
X=30
X=20
X=15
X=10
X=5
80
70
60
50
40
30
0
1
2
3
4
5
6
7
8
9

FIG. 7

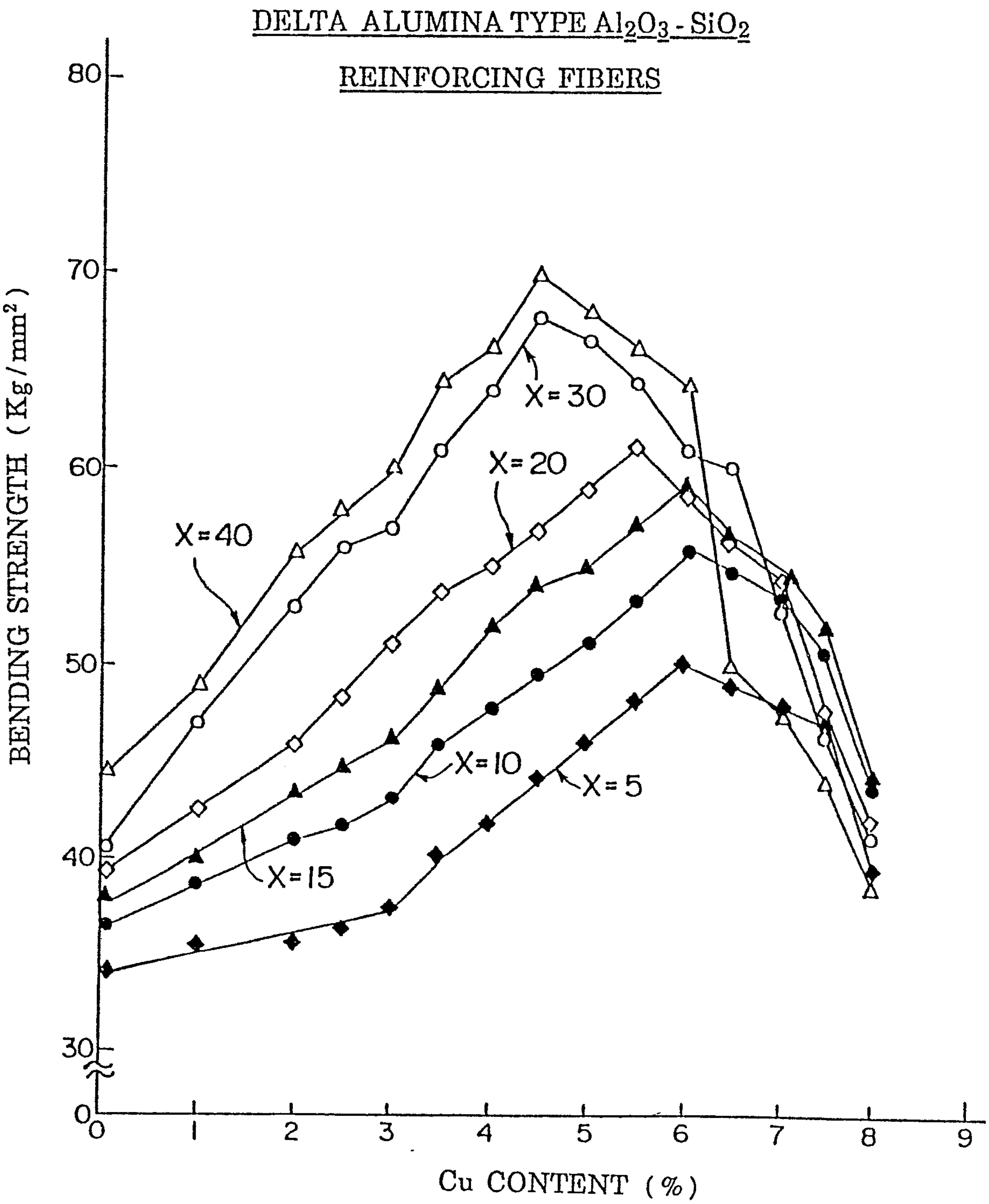

DELTA ALUMINA TYPE Al_2O_3 - SiO_2
REINFORCING FIBERS
BENDING STRENGTH (Kg/mm^2)
Cu CONTENT (%)
X=40
X=30
X=20
X=15
X=10
X=5
0
30
40
50
60
70
80
1
2
3
4
5
6
7
8
9

FIG. 9

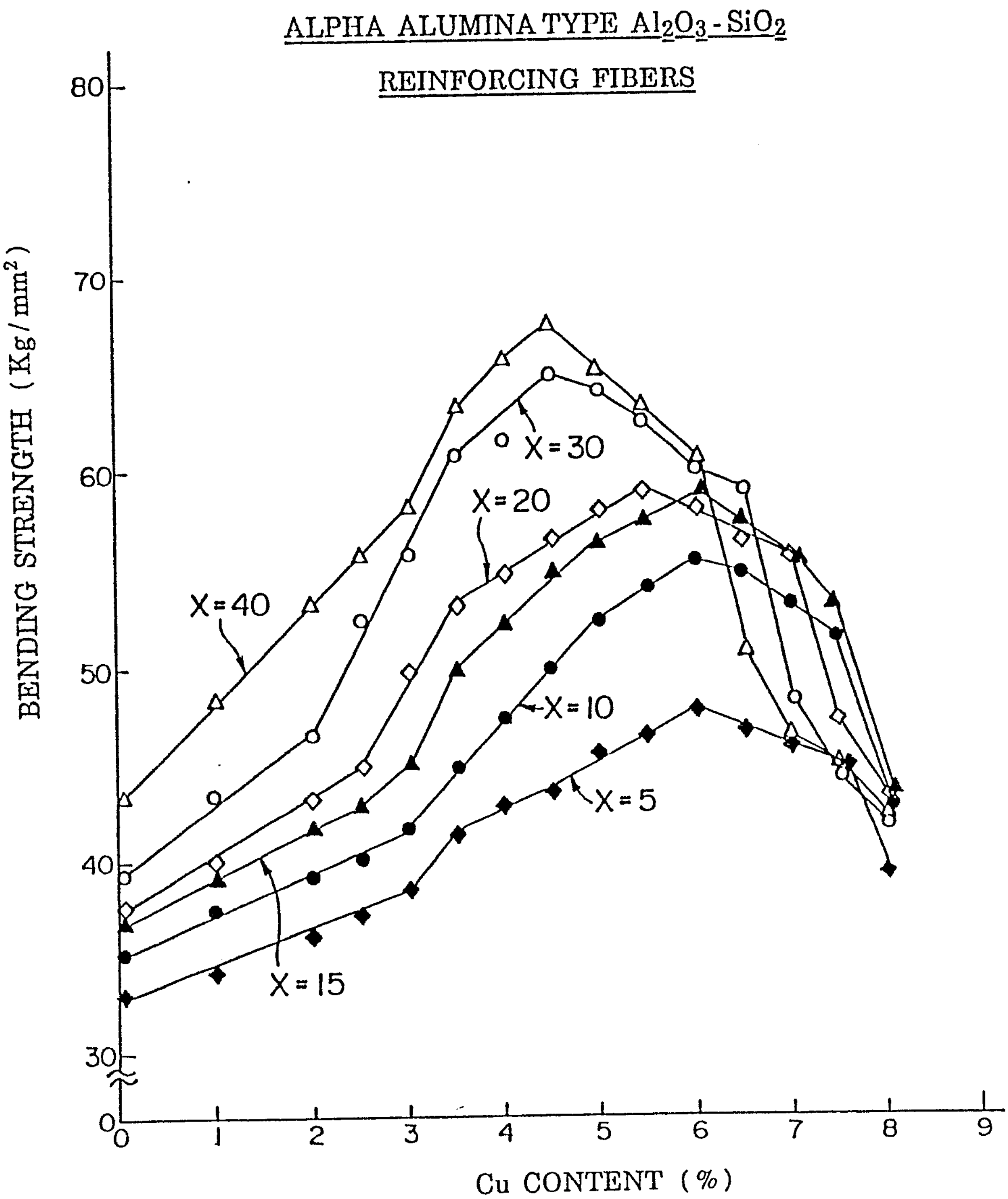
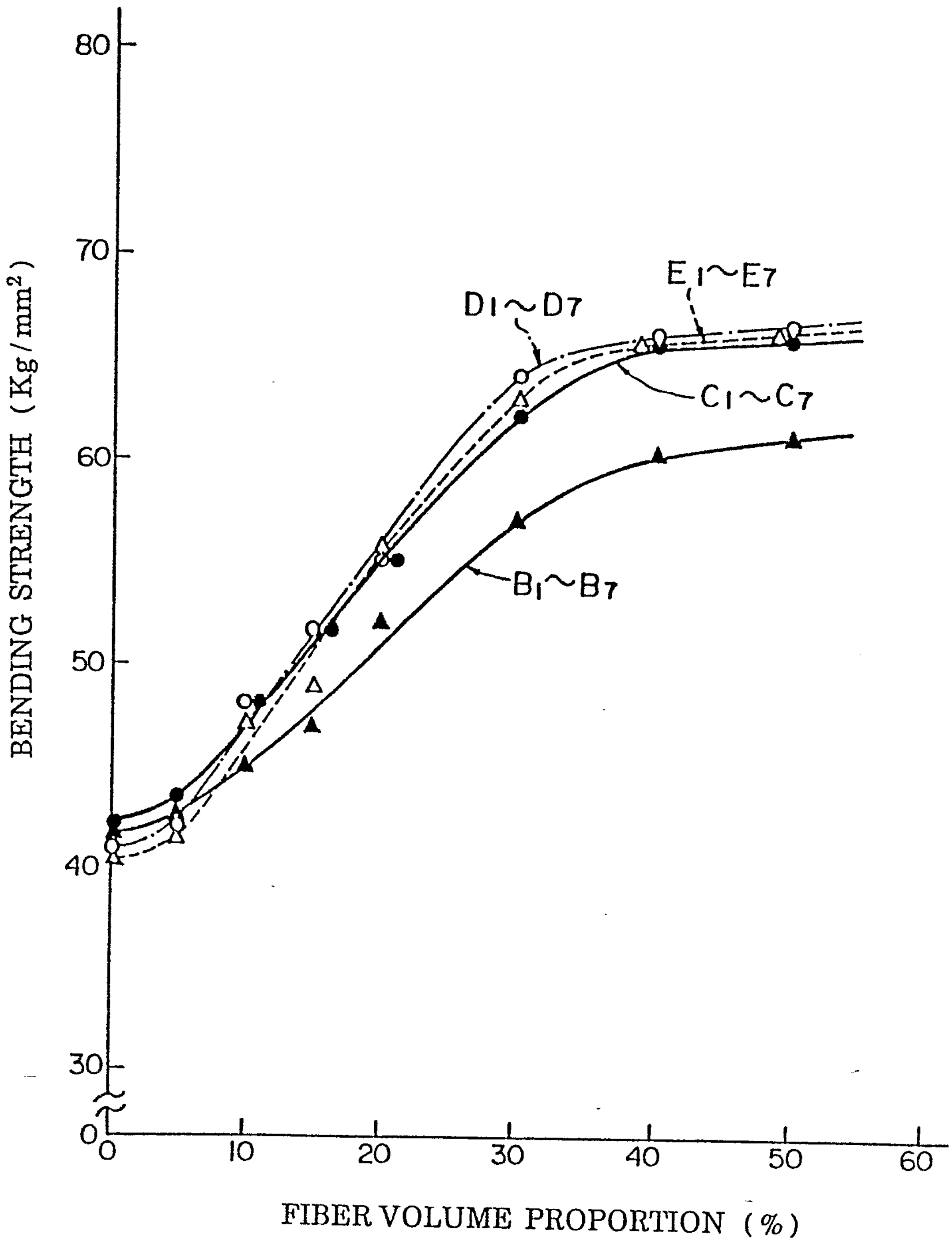
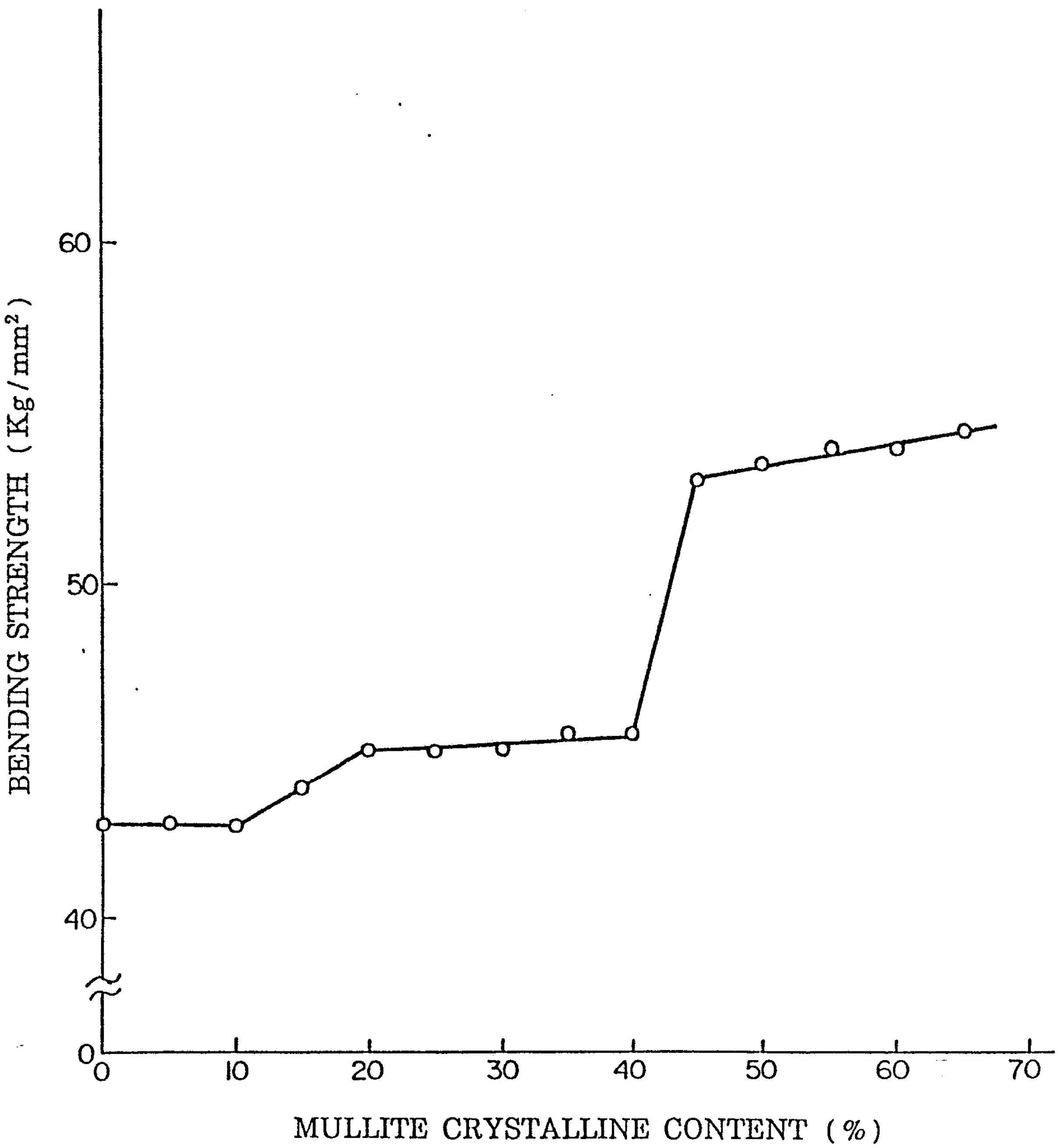

ALPHA ALUMINA TYPE Al_2O_3 - SiO_2
REINFORCING FIBERS
BENDING STRENGTH (Kg/mm^2)
80
70
60
50
40
30
0
X=40
X=30
X=20
X=15
X=10
X=5
0
1
2
3
4
5
6
7
8
9
Cu CONTENT (%)

FIG. 10



80
70
60
50
40
30
0
BENDING STRENGTH (Kg/mm²)
0
10
20
30
40
50
60
FIBER VOLUME PROPORTION (%)
D1～D7
E1～E7
C1～C7
B1～B7

FIG. 11


BENDING STRENGTH (Kg / mm^2)
60
50
40
0
0
10
20
30
40
50
60
70
MULLITE CRYSTALLINE CONTENT (%)