Dec. 19, 1967 H. L. LEICHTER 3,359,083

COMPOSITE STRUCTURAL METAL MEMBERS WITH
IMPROVED FRACTURE TOUGHNESS

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Fig. 1.

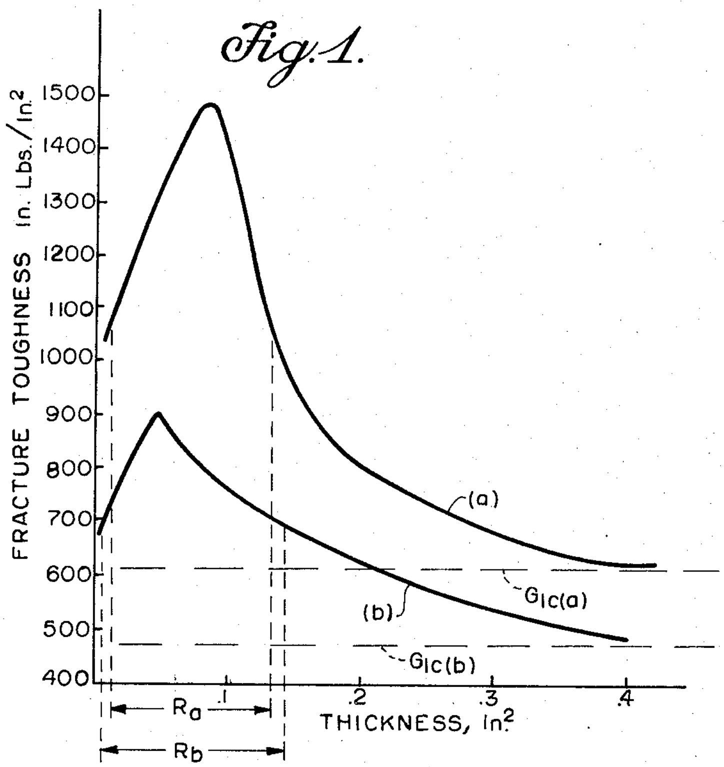
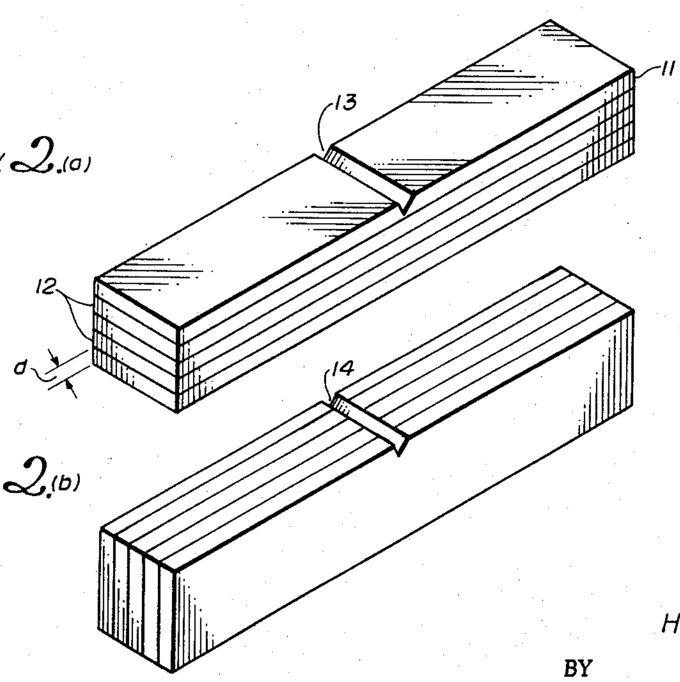


Fig. 2.(a)

Fig. 2.(b)



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COMPOSITE STRUCTURAL METAL MEMBERS WITH IMPROVED FRACTURE TOUGHNESS

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ABSTRACT OF THE DISCLOSURE

High fracture toughness laminate comprised of superposed sheets of metal joined together, each sheet having a thickness which is substantially equal to that at which the fracture toughness of the specific material of which the sheet is made is at a maximum.

The present invention relates to laminar structural materials, and more particularly to laminates having a predetermined laminar thickness to optimize the fracture toughness thereof.

The fracture toughness of a material is a quantity which is related to the force necessary to induce growth of a fracture or flaw to such an extent that failure of the material structure occurs. The stresses necessary to produce failure in structural materials having flaws, cracks, or similar imperfections are generally considerably less than the inherent ultimate or yield strength of the material.

The present invention provides a laminar structural material which exhibits enhanced fracture toughness and which is, therefore, highly resistant to failure due to crack propagation at stresses below the inherent or ultimate yield strength. The present laminar material is comprised of a multiplicity of joined laminae, the thickness of each preferably being selected to be near the thickness at which the fracture toughness is at a maximum and the selected laminae are then bonded to provide a composite structure in which the fracture or stress failure resistance of the composite structure is optimized.

In mathematical terms, the fracture toughness of a material may be characterized by the expression

$$G=\frac{\pi a\sigma^2}{E}\ \frac{\text{in. lb.}}{\text{in.}^2}$$

where E is the modulus of elasticity of the material, π is the universal constant for a circle, and G represents the stored elastic strain energy which is released as a crack of length a advances over an additional unit area of the material if the material is under the influence of a stress σ normal to the plane of the crack. In the limit, G approaches a critical value G_c which is defined as the release of an amount of energy which in response to the loading of the material leads to immediate failure by rapid crack propagation. This value is commonly known as the fracture toughness of the material. The fracture toughness of a material appears to be a basic material property, and is a function of a number of variables, in particular the structure and composition of the material, the temperature of the material, the rate of loading, and the dimensions of the material.

Most important from the point of view of the subject of the present invention, the fracture toughness of certain laminar materials has been found to be a function of the thickness dimensions of a homogeneous specimen of material in which a crack may be located. Further, it has been discovered that the functional relation between fracture toughness and the thickness of materials exhibit a maximum over readily ascertainable thickness ranges. In the case of metals, it has been confirmed by experimental testing that the maximum generally occurs at a thickness of less than about 0.2 inch and down to about 0.01 inch. Moreover, it has been found that sheet or laminar materials, e.g. metal sheet, having a thickness dimension near that at which fracture toughness is a maximum can be bonded in intimate laminar relationship to yield a composite structural body having a fracture toughness which greatly exceeds what might be expected. The reason why laminar or sheet materials should exhibit a maximum fracture toughness related to thickness is not completely apparent. It is possible that the method used to produce the sheet material, e.g. rolling or other mechanical working with intervening heat treatment which necessarily varies with the thickness of the sheet being formed yields a metallographic structure at certain thicknesses connoting a particular treatment which yields a metallurgical structure of optional properties. Moreover, minute or incipient fracture defects may have a minimum occurrence in said range. Whatever the cause laminar materials exhibiting such maximal fracture toughness can be fabricated into composite structural bodies of exceptional toughness in accordance with the invention. For example, a titanium aluminum tin alloy composite laminate having a thickness of 0.4 inch and comprised of individual laminae having a thickness of 0.062 inch was found to have a fracture toughness for through-the-thickness cracking up to 7.8 times as great as that of a homogeneous body of the same material of equivalent dimensions. In the present context where even a doubling of fracture toughness would be of significant interest, the results obtained in practice are remarkable.

In the prior art materials which have anisotropic strength properties have been incorporated into laminar structure to provide high strength. For example, various textile and fibrous materials are strengthened in the direction perpendicular to the fibers by joining together layers in which the fibers are alternately perpendicular or angularly disposed to each other, i.e. with respect to the direction of maximum textile strength. Laminating procedures have also been used to join together materials having different properties in order to obtain a composite which has the combined properties of the constituent materials. Generally, flexural modulus is enhanced but the tensile strength is almost completely determined by the additive contributions of individual fibers.

As distinguished from these prior art laminates, the present invention provides a laminar body of improved fracture toughness due to the controlled laminar thickness. It should be understood that the improvement in fracture toughness can be achieved for materials having isotropic as well as anisotropic characteristics, whether the orientation of the material in successive layers is identical or in different directions. Accordingly, the present material may be thought of as being in the nature of a continuous structural body, which is a composite of laminae of selected thickness dimensions related to a maximum in the fracture toughness characteristic curve joined or bonded in face to face laminar relation to provide a composite structural member of exceptional fracture toughness.

The fracture toughness of a material has been shown to be a quantity which is extremely important in practical engineering work. In practice, many structural materials are likely to have flaws or cracks as a consequence of which structural failure is likely to occur due to crack propagation at loads considerably and unpredictably less that the ultimate strength of a material as determined from tests of a near perfect specimen. To allow for the unpredictable deleterious influence of cracks and flaws on the strength properties of materials, structures are usually designed with relatively large safety factors. In addition, structural materials are generally tested and inspected to locate cracks and flaws by procedures which are time-consuming and costly. Thereafter, appropriate remedial action may be taken, such as welding, or even discarding the member entirely at considerable economic loss. Obviously, to locate smaller imperfections in the interest of increased safety, the inspection procedures grow more elaborate and time consuming. It is evident therefore that the use of conventional structural materials involves a safety or weight penalty which is a serious disadvantage especially in aerospace applications, in the construction of submarine hulls, or any other application, where a structure is exposed to high and repetitive loading or high impulse shock loading conditions. For such applications, the laminate of the present invention is ideally suited by virtue of its improved fracture toughness characteristics.

Accordingly, in summary, the principal objects or advantages of the present invention are:

(1) To provide a structural material having greatly improved fracture toughness without increasing size or impairment of other physical properties;

(2) To diminish the necessity for rigorous inspection of the material for small order defects by providing a structural material which is less liable to fracture due to crack propagation;

(3) To provide a material especially suited for use where impulse shock loading is encountered; and

(4) To provide a laminated configuration for structural members which is characterized by an inherently high margin of safety against failure due to defect growth as compared to similar and continuous homogeneous structural members of isotropic composition.

Other objects and advantages will become apparent to those skilled in the art upon consideration of the following description and accompanying figures of which:

FIGURE 1 is a graph of the fracture toughness of various metals as related to the thickness of the material.

FIGURE 2*a* is an isometric drawing of a laminated structural test specimen which is notched and fatigue cracked across the face of the top lamina.

FIGURE 2*b* is an isometric drawing of a laminated structural test specimen which is notched and fatigue cracked through-the-thickness perpendicular to the plane of the laminae.

In general, as mentioned above, the present invention is a composite laminated structural material formed of bonded laminar or sheet materials which is characterized by the property that its fracture toughness varies with the thickness of the material and exhibits a maximum. The laminate is comprised of a multiplicity of individual laminar layers, the thickness of each being selected at or near the thickness corresponding to the maximum fracture toughness. The laminar layers are joined together in face to face relation into an integral body having the overall dimensions of a desired structural member.

For practical application, the present laminates are used in the manufacture of structural beam members or plate, the total thickness of which exceeds the optimum fracture toughness of the material by at least a factor of about two.

However, it is noted, that the failure resistance of a structural material is increased whenever the weighted

average of the fracture toughness of the individual laminae exceeds the fracture toughness of a continuous homogeneous body of the same material as said laminae. Due to the properties of the composite laminar structure the toughness properties of structural bodies fabricated in this manner are with great reliability in excess of the equivalent unlaminated conventional structures while other advantages, e.g. reduced weight can often be attained since a considerably reduced safety margin can be reliably used.

To obtain a composite which is characterized by an enhanced fracture toughness compared to a continuous body of the same dimensions, e.g. produced by molding, casting, forging, machining as one solid piece, the laminae of appropriate shape may be joined by any bonding method, including adhesive and brazing or by mechanical means, such as spotwelding, riveting, or parts may be punched from laminates, in some instances. For structural materials, however, it is preferred to achieve distribution of the stresses over the entire member and for structural purposes, the laminae preferably are joined in face to face relation by using an appropriate bonding medium to render an integral or unitary body where the bond between the laminae extends uniformly over the entire faces of the laminae. Forces exerted on such a body, e.g. shear stresses, etc., are thereby transmitted between the laminae and evenly distributed over the entire structural member to provide bodies of high flexural modulus, strength, etc., while simultaneously obtaining the greatly enhanced fracture toughness.

Referring now to FIGURE 1, graphs are presented illustrating the fracture toughness-thickness relation of two alloys. The graph labelled (*a*) is for a titanium alloy, specifically Ti-5Al-2.5Sn, and the graph designated (*b*) is for grade 300, 18% Ni maraging steel. Both of these curves are seen to exhibit a maximum fracture toughness in the thickness region between 0.025 and 0.1 inch. The fracture toughness decreases with increasing thickness of the sheet or member and asymptotically approaches a constant value. The fracture toughness of a continuous homogeneous material is equal to the fracture toughness corresponding to its thickness as given by the graph. The fracture toughness of a laminate, however, is determined in large measure by the selected thickness of individual laminae providing toughness of the individual laminae, and further by the combination of selected laminae to provide a composite structural body. If the individual laminae have a thickness equal to the thickness at which the fracture toughness of the material is a maximum, the laminate comprised of such laminae will have a fracture toughness which is significantly superior to any continuous homogeneous body of equal or even greater total thickness constructed of the same material.

To determine the fracture toughness of a material, several methods may be employed. Tests performed at slow strain rates are the Center-Notch Tensile Test and the Slow-Bend Prenotched Charpy Method. These methods are described in detail in the following references: "American Society for Testing Material (ASTM) Committee Reports on Fracture Testing of High Strength Metallic Materials," ASTM Bulletin, January and February 1960; and "Sheet Fracture Toughness Evaluation by Impact and Slow Bend," G. M. Orner and C. E. Hartbower, Welding Journal, Research Supplement, September 1961.

Another method for determining the fracture toughness of materials is the Prenotched Charpy Impact test, which is carried out at high strain rates of about 10^3 in./in. sec. This test has limitations the values obtained for very tough materials are generally low. While measuring *absolute* fracture toughness values is somewhat subject to error, the Prenotched Charpy Impact Test yields a fracture toughness-thickness curve with a reliable shape and relative values. However, for present purposes the primary purpose is to determine the material thickness at which the fracture toughness is a maximum and to obtain a knowledge of the relative increase of the fracture toughness which can be achieved by a laminate over a continuous homogeneous body. Since this information can be obtained from the test with reasonable accuracy the impact tests at high strain rates are preferred because of the relative speed and economy for preparing and testing large numbers of specimens. The procedure is described in detail by Hartbower and Orner in "Metallurgical Variables Affecting Fracture Toughness in High Strength Sheet Alloys" Technical Documentary Report No. ASD–TDR–62–868, June 1963. The Prenotched Charpy specimens are fatigue cracked at the base of the notch with a fatigue cracking machine. The application of stress is continued until the cracks become about 0.025 to about 0.035 inch deep. The variation of the depth of the fatigue cracks within these limits does not significantly affect the results of the tests. The fracture toughness is defined as the energy absorbed in fracturing the specimen, divided by the area of the fracture. This value is determined for a number of specimens of varying thicknesses and plotted. A smooth curve joining the individual measurements will then result in a graph as illustrated in FIGURE 1. Of particular interest for purposes of the present invention are portions of enhanced fracture toughness of the curves (*a*) and (*b*) in the thickness ranges R_a and R_b for the titanium alloy and the steel. The fracture toughness of the material having a thickness in this range substantially exceeds the fracture toughness values G_{Ic} which the curve approaches.

For purposes of the present invention and practical application, the region of enhanced fracture toughness is defined as extending between the thickness values at which the fracture toughness is intermediate between the maximum fracture toughness and G_{Ic}.

Referring now to FIGURES 2*a* and 2*b*, there are shown laminated structural beams constructed in accordance with the present invention. Individual laminae **11** are joined together in face to face relationship. The thickness *d* of each lamina corresponds to the thickness of the sheet material under the elevated portion of the fracture toughness curve shown in FIG. 1. The joints **12** are formed most commonly and preferably by a layer of metallic bonding or joining alloy, e.g. brazing material fused to the faces of adjacent laminae **11**. The bond formed between the braze material and the laminae **11** extends continuously over the entire face of the laminae. The braze material is selected in accord with usual engineering practice on the basis of the quality of the bond which the braze forms with the lamina material, and on the basis of its physical properties which must be commensurate with the environmental demands on the laminate. While the preferred method of bonding the laminae **11** is brazing, which will be taken to include all appropriate methods using a bonding alloy or a diffusion bonding agent, e.g., silver, it will be realized, that when the environmental conditions permit their use, other joining methods may be used in place of brazes, provided that a firm bond is formed between the laminae **11**. Thus, in low temperature applications requiring only moderate bonds strength, synthetic adhesives such as catalyzed epoxy adhesive resins can be used to join laminae **11**. With brazing or diffusion bonding, the present laminates are constructed by heating a pressurized stack of alternate layers of brazing foil and laminar plates to the brazing temperature of the foil, preferably in an inert atmosphere.

A preferred method of making the laminate is by the "Hortonclad®" process, described in detail in U.S. Patent No. 2,713,196 issued to R. L. Brown on July 19, 1955. According to this method material sheets are stacked with braze alloy in foil form interposed between the sheets. This stack of alternating laminar material and braze alloy foil is sealed in a flexible steel envelope, placed under a vacuum, and heated to the brazing temperature and held at this temperature for a specified period depending on the brazing material.

A preferred method to carry out the brazing step, which is especially suitable for brazing in small lots, where less than one atmosphere of pressure is required, is to dispose the stack of laminar material and interposed braze foil in a stainless steel envelope. This envelope is hermetically sealed and adapted for evacuation. Prior to disposing the stack in a furnace, the envelope is evacuated to a pressure of the order of 100 microns. The stainless steel envelope collapses and compresses the stack, while excluding most of the air from the stack during the heating step. The envelope is then heated to and held at the brazing temperature in a furnace for a specified period. The composite laminate of the invention and manufacturing method will be further illustrated in the following specific examples.

EXAMPLE I.—Ti-5Al-2.5Sn LAMINATE

The fracture toughness-thickness relation for the titanium alloy Ti-5Al-2.5Sn laminate was determined as outlined in the description above. The graph was found to exhibit a maximum in the thickness region at about 0.075″, as illustrated in FIG. 1*a*. Accordingly, a laminate plate was fabricated using titanium alloy sheet of a thickness 0.062 in. which falls within the enhanced fracture toughness region. A stack of 6 alloy laminae was assembled with coextensive sheets of braze alloy foil interposed therebetween. The preferred braze alloy composition was 92% Ag, 7.5% Cu and .5% Li, and the thickness of the foil sheets was 2 mils. The stack was placed into a stainless steel envelope and compressed by evacuating the envelope to about 150 microns. The envelope was placed into a furnace and the composite was heated to a temperature of 1727±2° F. This temperature and the pressure of 150 microns were maintained for a period of about 5 minutes to produce a brazing joint between the titanium alloy laminae. Thereafter the envelope containing the laminate was air cooled under vacuum. The integrity of the bonds between the laminae was checked for defects by ultrasonic methods.

Charpy specimens were cut from the laminated plate, notched and fatigue precracked to a depth of about 0.03″ and the properties tested by the Prenotched Charpy Impact Test described above. With reference to FIG. 2*a*, one type of specimen was notched across the face **13** of the top layer normal to the plane of the lamina. A second type of specimen, illustrated in FIG. 2*b* was notched across the sides **14** and a through-the-thickness fatigue crack introduced at the bottom of the V-shaped notch. The physical properties of both laminar specimens and identical specimens of a continuous forged bar were tested under the same conditions. The laminates which were notched and cracked across the face of the top layer could not be completely broken at the maximum impact loading of 240 ft. lbs. delivered by the pendular hammer of the testing machine. The results of the tests with the through-the-thickness cracked specimen and the continuous bar are given in Table I.

EXAMPLE II.—GRADE 250 18% NICKEL MARAGING STEEL

250 grade maraging steel exhibits maximum in the region between about 0.02 and 0.08 inch. A six-ply laminated plate of grade 250 18% nickel maraging steel was made by assembling a stack of 6 steel laminae of a thickness of 0.062 inch. A 2.0 mil thick braze alloy foil having a composition of 92% silver, 7.5% copper and 0.5% lithium was placed between successive steel sheets. The assembly was disposed into a flexible steel envelope, placed into a furnace and heated to a brazing temperature of 1755±5° F. for a period of 10 minutes, while maintaining the vacuum at about 40 microns. The laminate was then air cooled and reheated to the austenitizing temperature of 1500° F. After 40 minutes the laminate was again air cooled. Notched Charpy structural members were prepared from the laminate and from homoge-

neous maraging steel bar stock and tested as outlined above. The results are also given in Table I. Again the specimens notched across the face of the top layer exceeded the 240 ft. lb. capacity of the testing equipment. Rough calculation based on the partially fractured specimens indicated a fracture toughness between about 30 and 40 times as great as the fracture toughness of the continuous bar.

TABLE I.—FRACTURE TOUGHNESS OF LAMINATES, SINGLE SHEET, AND CONTINUOUS PLATE MATERIALS AT ROOM TEMPERATURE

Material	Constitution of thickness	Fracture Toughness in lb./in.[2]	Yield Strength, lb./in.[2]	Ultimate Strength, lb./in.[2]	Elongation, percent
Ti, SAl, 2.5 Sn AMS 4910	.374" plate	[1] 517	130,300	132,300	21.0
Ti, SAl, 2.5 Sn AMS 4910	.062 sheet	[1] 5,410	115,000	120,700	21.8
Ti, SAl, 2.5 Sn AMS 4910	.062 sheet	[2] 4,540	115,000	120,700	21.8
Ti, SAl, 2.5 Sn AMS 4910	6 ply laminate of .062 sheet	[1] 4,046	115,000	120,750	19.5
Ti, SAl, 2.5 Sn AMS 4910	do	[2] 4,040	115,000	120,750	19.5
250 grade maraging steel	.394 plate	[1] 574	[3] 271,400	[3] 279,600	[3] 11.0
Do	do	[2] 403	[3] 271,400	[3] 279,600	[3] 11.0
Do	.062 sheet	[1] 1,200	[3] 274,300	[3] 287,300	[3] 3.2
Do	do	[2] 1,204	[3] 274,300	[3] 287,300	[3] 3.2
Do	6 ply laminate of .062 sheet	[1] 1,045	[3] 264,000	[3] 276,000	[3] 8.25
Do	do	[2] 860	[3] 264,000	[3] 276,000	[3] 8.25

[1] Perpendicular to rolling direction of material.
[2] Parallel to rolling direction of material.
[3] Values given are for 300 grade steel.

The data in Table I illustrates the improvement in the fracture toughness of the laminated materials over the continuous homogeneous bar materials. Although only two specific examples have been given, it is not intended to convey that the invention be limited to these specific materials. The remarkable improvement of the fracture toughness characteristic of these laminates over homogeneous bodies of the same dimensions can be analogously achieved in other materials, provided only that the fracture toughness-thickness curve for the material exhibit a maximum and that a suitable binder be employed to join together the laminar composite. Moreover, while the optimum or maximum effects are generally obtained using a laminate comprised only of metal sheets having the specified maximum fracture resistant thicknesses improvement is obtained if even a single such sheet is used with other thickness sheets and with sheets of other materials laminated therewith. The additional benefits obtained in the composite structure generally requires that two or more such sheets or laminae be used. Therefore, the scope of the invention is to be limited only by the following claims.

What is claimed is:

1. A composite structural body of improved fracture toughness, comprising: a plurality of laminar sheets of a titanium alloy consisting essentially of 92.5% by weight of titanium, 5% by weight of aluminum and 2.5% by weight of tin, a combined thickness substantially greater than the thickness range in which the fracture toughness of a homogeneous body of said alloy is at an optimum, said sheets having a thickness in the range of 0.02 and 00.2 inch wherein the sheets individually exhibit an optimum fracture toughness, said laminar sheets being disposed in contiguous face-to-face relation, bonding means joining said laminar sheets in said contiguous face-to-face relation to provide a structural body of improved fracture toughness.

2. The structural body of claim 1 further defined in that said bonding means is a bonding agent layer disposed between and fused to adjacent faces of said laminar sheets.

3. A composite structural body of improved fracture toughness, comprising: a plurality of laminar sheets of maraging steel of a combined thickness substantially greater than the thickness range in which the fracture toughness of said steel is at a maximum, said sheets individually having a thickness in the range of about 0.01 to 0.15 inch wherein said steel exhibits an enhanced fracture toughness, said laminar sheets being disposed in contiguous face-to-face relation and bonding means joining said laminar sheets in said contiguous face-to-face relation to provide a structural body of improved fracture toughness.

4. The structural body of claim 3 further defined in that said bonding means is a bonding agent layer disposed between and fused to adjacent faces of said laminar sheets.

5. The laminate of claim 1 further defined in that said titanium alloy laminar sheets have a thickness in the range of about 0.03 and 0.13 inch.

6. The laminate of claim 2 further defined in that said bonding agent layer is a brazing alloy consisting of 92% by wt. of silver, 7.5% by wt. of copper, and 0.5% by wt. of lithium.

7. The laminate of claim 3 further defined in that said maraging steel sheets have a thickness in the range of about 0.02 and 0.08 inch.

8. The laminate of claim 4 further defined in that said braze joint layer is comprised of a brazing alloy consisting of 63% by wt. of copper, 22% by wt. of manganese, 10% by wt. of cobalt and 5% by wt. of nickel.

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