# United States Patent

**Anderson, Jr. et al.**

[15] **3,699,798**

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[54] **METHOD OF INCREASING BERYLLIUM DUCTILITY**


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[52] **U.S. Cl.** .....**72/377**, 72/56, 148/4, 148/11.5 F

[51] **Int. Cl.**.....**C21d 7/00**, B21d 26/08

[58] **Field of Search** .....75/150; 148/11.5 F, 4, 32; 72/56, 377



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[57] **ABSTRACT**

Reorienting by planar compression loading the atomic planes of deformation in a hexagonal close-packed unit cell of a metal crystal, and in particular beryllium, to improve ductility in a bending mode. In particular ductility in the third dimension (short transverse direction) is accomplished by reorientation of existing slip systems by activating twin systems through planar compression loads. Highly textured sheet material, usually cross-rolled from hot pressed block, is of particular interest.


**6 Claims, 8 Drawing Figures**

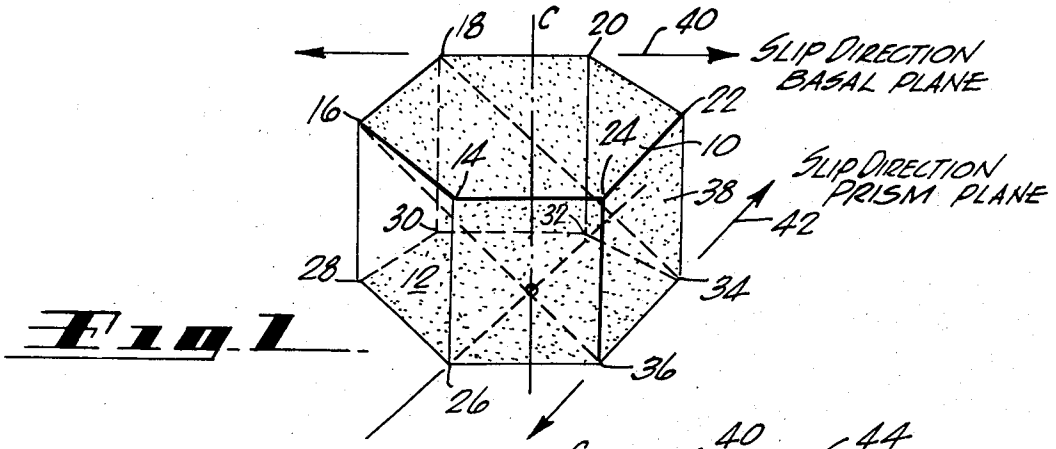



Fig. 1

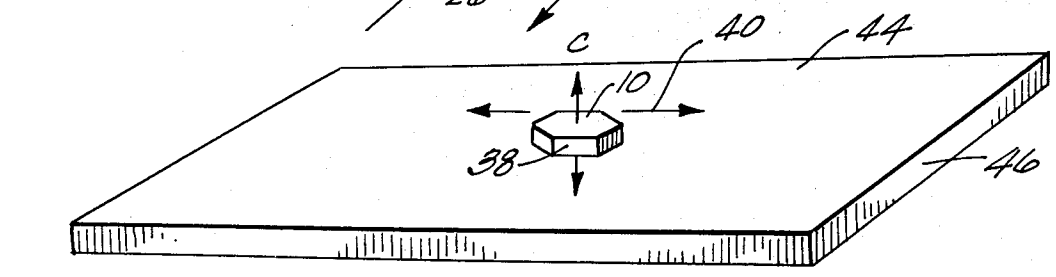



Fig. 2

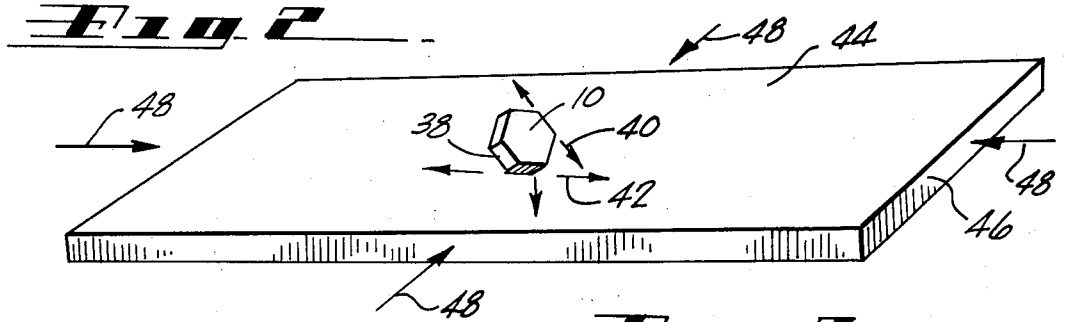



Fig. 3

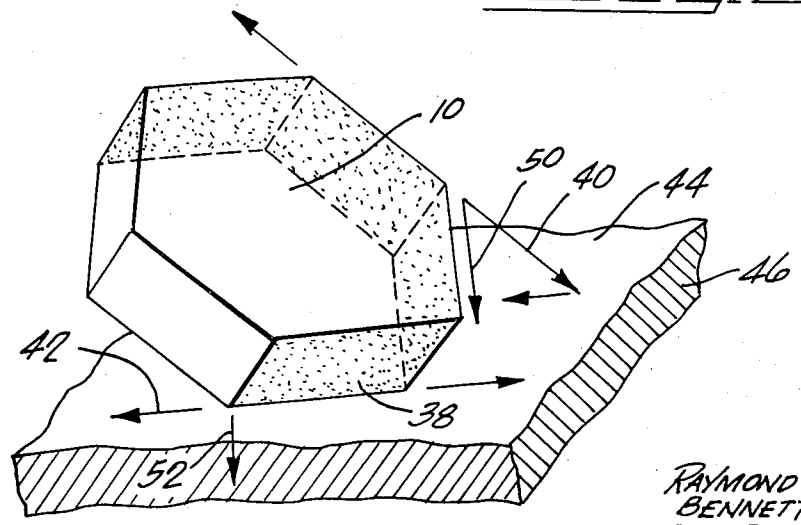



Fig. 4

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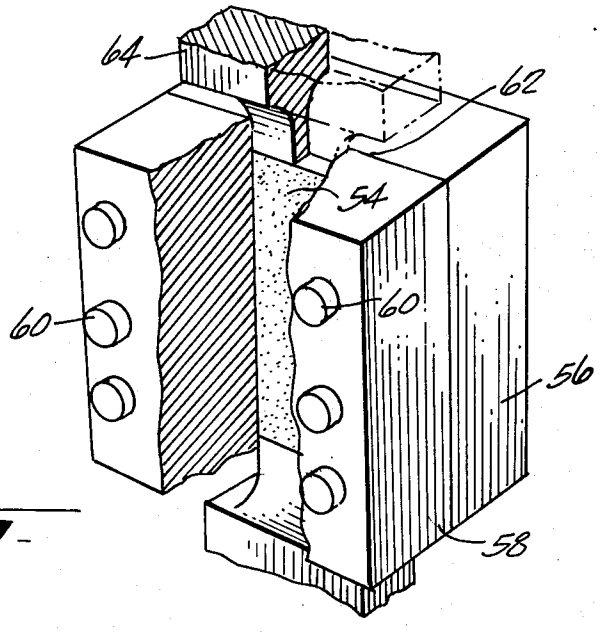



Fig. 5

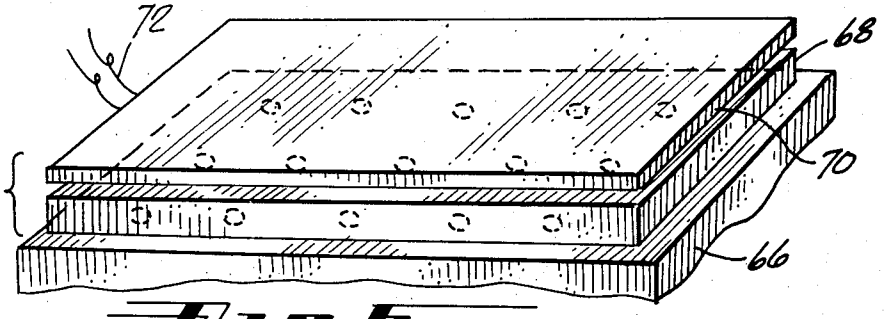



Fig. 6

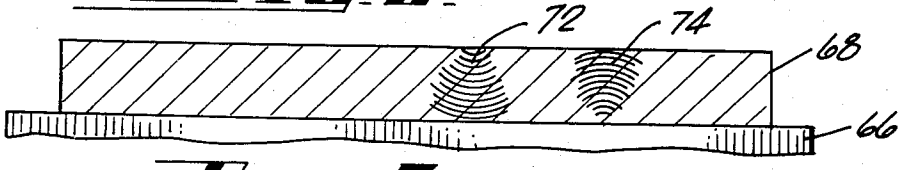



Fig. 7

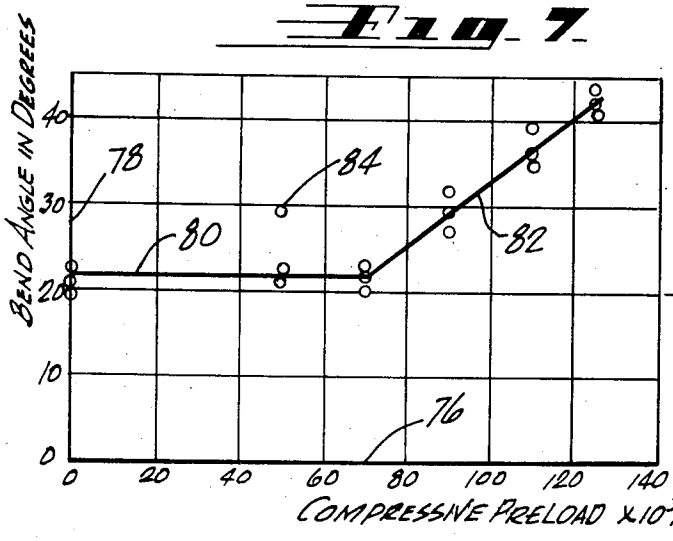



Fig. 8

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# METHOD OF INCREASING BERYLLIUM DUCTILITY

## BACKGROUND OF INVENTION

Commercially available cross-rolled beryllium sheet metal possesses low ductility at room temperature in bending or other complex tension loads. This makes the sheet difficult to deform without failure both in its fabrication into a part and in its use where bending or complex tension load occurs.

The cross-rolling of sheet from powder beryllium block significantly increases the ductility in the plane of the sheet but decreases its ductility in the short transverse direction because the active deformation systems are not properly oriented to permit deformation in that direction. A deformation system may be thought of as a series of atomic planes that will flow under load. This makes the sheet brittle under bending and complex tension loads and causes cracking or breaking at small flow strains. Flow strain is a measure of a material's ability to deform without fracturing. This type of lack of ductility has severely restricted the application of beryllium where complex stresses are developed and limits the materials' usefulness to areas where loads are compressive or low tensile in nature. In addition, forming operations at room temperature are not feasible. This creates a need to form beryllium at elevated temperatures in order to activate additional deformation systems. This operation is expensive.

Attempts to increase ductility in beryllium have concentrated on such diversified approaches as alloy additions, powder preparation, reduction in grain size, texture modifications, and surface preparations.

Beryllium, heretofore, has not been an effective replacement for high strength engineering alloys although it compares favorably on a strength-to-weight ratio. The material is 35 percent lighter than aluminum and possesses a specific heat approximately twice that of aluminum. The materials' elastic modulus is higher than that of any other structural light metal and persists at temperatures where other light metals are no longer operative. The material also possesses useful mechanical properties at temperatures in excess of 800° F. Problems, however, in handling, processing, forming and joining coupled with the high cost and toxicity of the metal have placed severe restrictions on the materials' structural applications. Greater ductility (in bending or complex tension loads) in beryllium would minimize or eliminate some of these restrictions associated with the material. Increased confidence in the materials' usefulness would be a significant result of increased ductility.

## SUMMARY OF THE INVENTION

To increase the ability of highly textured beryllium sheet to bend or deform under load at room temperature, it is necessary to effect rotation of the principal atomic planes into an orientation which is more favorable for flow (yielding). This could be accomplished by the application of compression loads in the plane of the sheet which are less than those required for fracture. These loads should be of sufficient magnitude to cause the material to exceed its compressive yield strength, thus creating significant increases in bend ductility. The application of this compressive load in the plane of the sheet would result in an equivalent tensile force acting normal to the compressive load. The action of this tensile force serves to rotate selected areas of the beryllium crystal in the sheet material. This rotation places the planes in a more favorable orientation for deformation by slip and/or twinning in the thickness direction. Slip is movement of one plane of atoms over another in a manner similar to skidding. Twinning consists of shearing movements of atomic planes over one another, resulting in a uniform tilting of the surface in the twinned region. This new orientation permits a greater amount of bending before the material will fracture and break.



## BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic illustration of the basic crystal structure of beryllium;

FIG. **2** is a pictorial representation of a sheet of beryllium showing the typical orientation of the beryllium crystal with respect to the plane of the sheet;

FIG. **3** is a pictorial representation of the beryllium sheet and the orientation of the crystal when subjected to compression forces acting in the plane of the sheet;

FIG. **4** is an enlarged view of FIG. **3**;

FIG. **5** is an isometric pictorial view of a typical sheet support fixture;

FIG. **6** is a pictorial view showing a method for generating tensile stress waves through the sheet thickness;

FIG. **7** is a schematic illustration showing generation of tensile stress waves in the beryllium sheet following an explosive impact; and

FIG. **8** is a graph showing the effect of compressive pre-load on the bend angle at fracture.

## DETAILED DESCRIPTION OF THE INVENTION

The basic crystal lattice geometry of beryllium is shown in FIG. **1**. It is known as an HCP (hexagonal close-pack) crystal structure. This crystal structure is characterized by two principal active slip systems, basal and prism. The basal system consists of an upper basal plane **10** and a lower basal plane **12**. Basal plane **10** is defined by atom location points **14, 16, 18, 20, 22** and **24**. Basal plane **12** is defined by atom location points **26, 28, 30, 32, 34** and **36**. Prism plane **38** is defined by the atom location points **22, 24, 34** and **36**. This prism plane is typical of five other prism planes intersecting basal planes **10** and **12** and parallel to axis C. The HCP lattice of beryllium is unique, as are other metals of this particular crystallographic system, in that the aforementioned slip planes can only flow in a direction parallel to the basal plane. Typical slip directions for planes **10** and **38** are noted by the arrows **40** and **42** in FIG. **1**. In practical terms this means that no matter what the direction of applied load is on the beryllium crystal, slip can only occur in a direction parallel to the basal plane. If, for instance, loads were applied along the C axis in compression, there would be no available slip systems operable and the beryllium would cleave in a brittle fashion before it would flow in a ductile fashion.

One of the important aspects of the beryllium crystal structure is that compressive loads applied to the crystal along the C axis result in no deformation at all. However, tension loads applied along the C axis activate the principal twinning plane of beryllium

(pyramidal) noted by **16, 18, 34** and **36**. When the twinning plane is activated by tension stresses in the C direction, then localized reorientation takes place in the beryllium crystal which causes a rotation of the crystal with respect to the external applied stress direction. The usefulness of this phenomenon is shown in FIGS. **2, 3** and **4**.

FIG. **2** is an example of the normal orientation taken by the beryllium crystal when the material is hot cross-rolled from beryllium block. (Axis C, arrows **40** and plane **38** are shown for convenience in orientation. Axis C extends in the direction of the sheet thickness). It should be noted that the basal plane **10** lies parallel to the surface **44** of the sheet **46**. This means that no slip directions are available for flow or deformation through the thickness of the sheet. Therefore, when beryllium is loaded in bending or in complex tension stresses that require ductility through the thickness of the material, none exists, and brittle fracture takes place.

When compression stresses (arrows **48** at edge of sheet **46** in FIG. **3**) are applied in the plane of the sheet **46**, resultant tensile stresses are formed acting through the thickness (perpendicular to the applied compressive stresses). The action of this resultant tensile force is shown in FIG. **3** indicating that portions of the beryllium crystals in the sheet are rotated by virtue of the twinning action taking place during the applied compressive loads. The slip direction shown by arrows **40** is no longer parallel to surface **44** of sheet **46**, resulting in a component of slippage across the thickness of the sheet as shown by arrow **50**. This is shown in more detail in FIG. **4** where it can now be seen that the basal and prism planes **10, 38** are oriented in such a manner that some degree of slip or deformation can take place through the thickness as shown by arrows **50** and **52**. This, therefore, increases the ability of the beryllium sheet to be deformed through the thickness direction when bending or complex tension stresses are applied to the sheet, resulting in increased ductility of beryllium at room temperature.

In FIG. **5** there is shown a sheet of beryllium **54** contained between side support plates **56, 58** held together by fasteners **60**. Support plate **56** has a longitudinal channel **62** into which sheet **54** is positioned. End inserts **64** fit within channel **62** and serve to transmit compressive force longitudinally upon the ends of the sheet **54**. Loads greater than the compressive yield strength of the material are thus applied through the plane of the sheet **54** to accomplish the objectives hereinbefore set forth. In addition, the beryllium sheet fits tightly against the side walls of the channel to prevent deformation from occurring transverse to the applied load. There is clearance provided in the thickness direction so that when compressive loads are applied by the end inserts the beryllium sheet can grow in the thickness direction. The tight fitting side wall of the channel restricts lateral flow. Therefore, all plastic flow is forced to be in the thickness direction, which is equivalent to applying a tensile force through the sheet thickness.

There are other techniques that may be applied to meet the objectives of this invention. For instance, it is recognized that constraining a large, thin sheet by the techniques set forth in FIG. **5** would be difficult, as well as requiring massive dies for each thickness and width of material. In addition, massive presses might be required to accomplish the needs of applying sufficiently high compressive stresses in the plane of the sheet to cause tension stresses in the thickness direction which, in turn, result in the reorientation and increased thickness ductility. Another method of accomplishing the same end result would be by the use of explosive shockwaves. The features of this method are shown in FIG. **6**. The device consists simply of a massive rigid steel block **66** upon which is laid the beryllium sheet **68** to be processed. The beryllium sheet is tightly clamped against the steel block by the use of suitable restraining fixtures (not shown) or a vacuum chucking device typical of those used for holding non-magnetic materials against a machine tool bed. In one form a sheet explosive **70** of suitable energy output is placed on top of the beryllium sheet **68** or separated from the beryllium by some stand-off distance using an air or hydraulic medium between the explosive and the sheet. The explosive is suitably connected by leads **72** to an electrical impulse circuit (not shown) so that it might be detonated remotely. The resultant reaction is shown in FIG. **7**.

The initiation of the explosive charge above the beryllium sheet **68** induces an initial compressive stress wave **72** into the beryllium which has little or no effect on the beryllium since it has been heretofore shown that compressive stresses applied through the thickness of beryllium sheet result in no deformation by virtue of the crystallographic orientation. However, when the initial compressive stress wave **72** reaches the tightly bound interface between the beryllium sheet and the steel block **66**, a reflected tensile stress wave **74** is generated, causing tension stresses directly in the thickness direction of the beryllium sheet. It has been heretofore shown that tensile stresses applied through the thickness of cross-rolled beryllium sheet result in twinning action which, in turn, results in the reorientation of many of the beryllium crystals to favor slip through the thickness of the sheet. This increases sheet ductility.

An advantage of this approach is that tensile stresses may be applied directly to a large beryllium sheet using low-cost tools and explosives with the obvious advantage that large sheet sizes or variations in thickness have no effect on the fundamental application of this technique. By careful control of the sheet explosive energy levels, stand-off distances, and shock transmitting medium to the beryllium sheet, sufficient reflected tensile stresses can be applied to the thickness to promote twinning but not so severe as to cause delamination or fracture to the sheet.

Reference is now made to the graph in FIG. **8** wherein compressive pre-loading in pounds per square inch is shown along the abscissa line **76** and bend angle in degrees is shown along the ordinate axis **78**. Application to beryllium sheet at room temperature of compressive loads of zero to 70,000 psi along the plane of the sheet had no effect on the materials' bend angle and the sheet failed when bent at an angle of approximately 20° to 25° as shown by line **80**. 70,000 psi is approximately the compressive yield strength of the beryllium sheet used. Thereafter the bend angle increases linearly with increased loads up to 125,000 psi as shown by line

82. At the upper limit bend angles of 40° to 45° were possible before fracture was experienced. The round dots **84** in the graph are data points from performed experiments.

Having thus described an illustrative embodiment of the present invention, it is to be understood that modifications thereof will become apparent to those skilled in the art and it is to be understood that these deviations are to be construed as part of the present invention.

We claim:

**1**. Method of increasing bending ductility in beryllium sheet metal comprising the step of:

tensile loading said metal across its thickness, wherein said tensile loading is accomplished by applying a compression loading along the plane of said sheet metal, the magnitude of said compression loading being sufficient to cause said material to exceed its compressive yield strength.

**2**. The method as set forth in claim **1** wherein compression loads are applied longitudinally while restricting lateral movement and permitting expansion in the thickness of said sheet metal.

**3**. The method as set forth in claim **1** wherein the beryllium sheet metal is first cross-rolled, resulting in the C-axis of the beryllium crystal being approximately perpendicular to the plane of said sheet metal.

**4**. The method as set forth in claim **1** wherein compressive shock waves are sent through the thickness of said sheet metal.

**5**. The method as set forth in claim **4** wherein said sheet metal is first secured to a rigid backing whereby said compression shock waves are reflected back as tensile shock waves to thus apply said tensile loading.

**6**. The method as set forth in claim **5** wherein said compressive shock waves are initiated through an explosive charge.

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