Fig-1

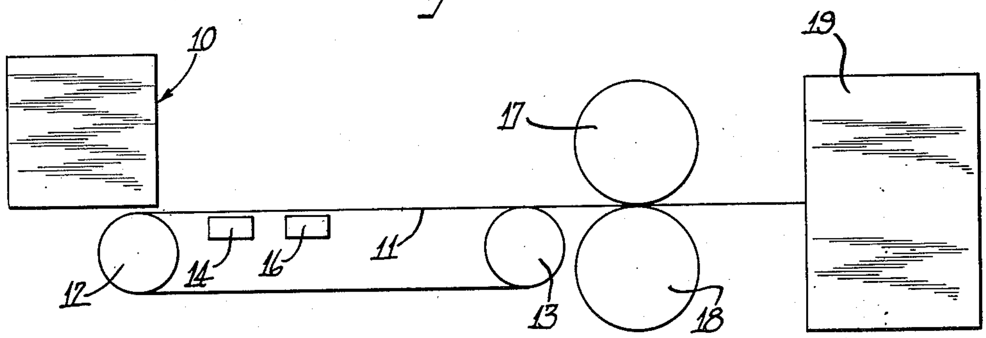


Fig-2

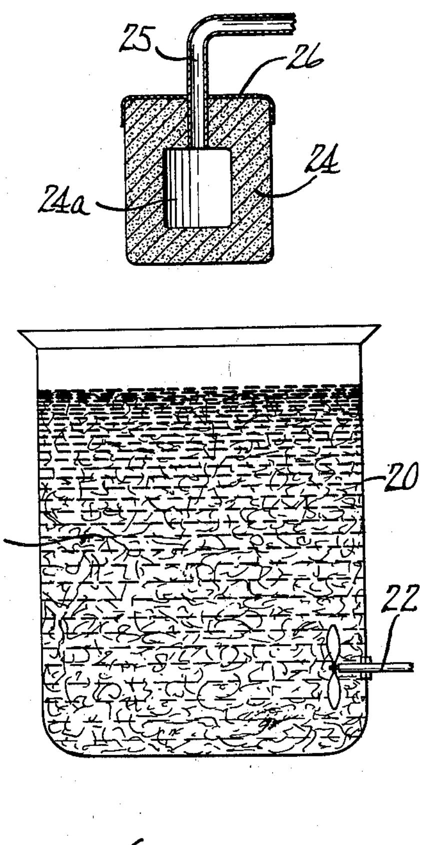


Fig-3

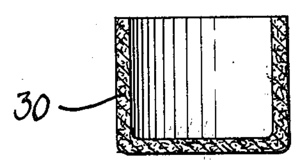
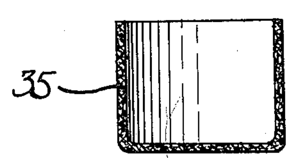


Fig-4



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April 7, 1964 W. C. TROY 3,127,668

HIGH STRENGTH-VARIABLE POROSITY SINTERED METAL FIBER ARTICLES AND METHOD OF MAKING THE SAME

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Fig-5

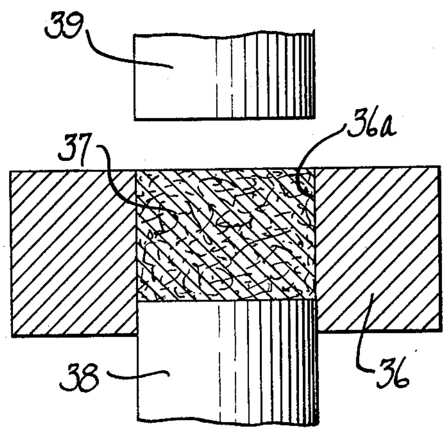


Fig-6

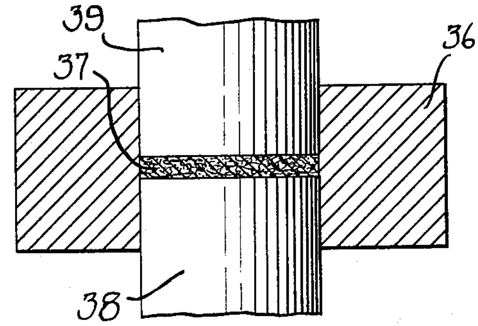


Fig-7

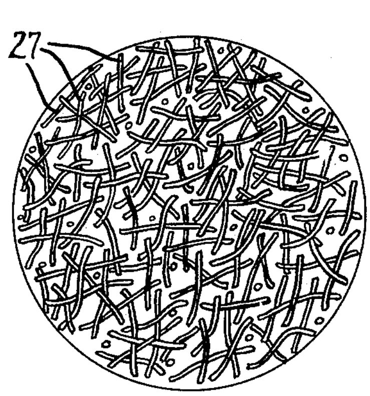


Fig-8

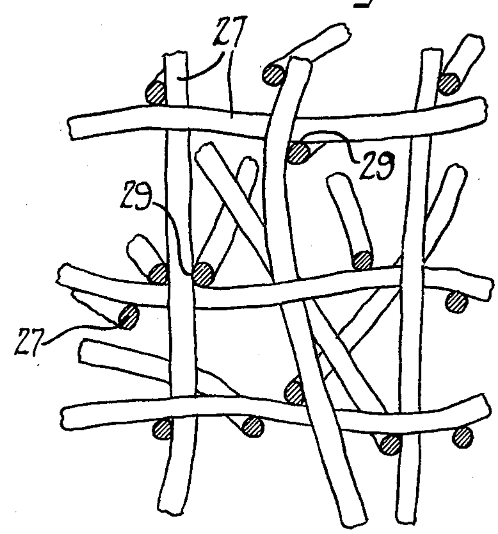
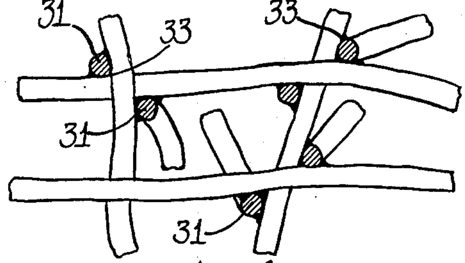


Fig-9



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HIGH STRENGTH-VARIABLE POROSITY SINTERED METAL FIBER ARTICLES AND METHOD OF MAKING THE SAME

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11 Claims. (Cl. 29—182)

The present invention is directed to improvements in the field of metallurgy and has particular application to the manufacture of high strength, variable porosity metal articles.

There is still a significant gap in properties between products produced by powder metallurgy on the one hand and the metallurgy of the more conventional solids on the other. In this gap are products which would find extensive use commercially if some means were devised for their manufacture. Typical of such products are metal articles having a high degree of porosity coupled with sufficient mechanical strength. Powder metallurgy techniques have not been effective to produce acceptable articles of this type because of inherent limitations in the techniques themselves, and the apparently unavoidable lack of sufficient strength in compacts designed to be sufficiently porous. This fact might be explained in several ways. From a theoretical standpoint, the porosity of metal powders necessarily has a theoretical maximum. By "porosity" is meant the percentage voids expressed as a ratio of the volume of voids in the compact to the total volume. In the case of a perfect powder mteallurgy body, that is, one consisting of identical spheres stacked in line, the theoretical maximum porosity is 47.6%. As a practical matter, it is sometimes possible to achieve porosities as high as 70% in powder metallurgy bodies, due to bridging effects which occur due to imperfect packing of the particles, but this degree of porosity is achieved with a substantial loss in strength.

In any process involving compaction of metal powders there is always the problem of lack of strength due essentially to the lack of continuity of the metal powder particles. Expressed in another way, there is no continuity of metal between spaced points in the powder metal compacts even though those points may be bridged by a continuous series of particles which have become joined together at their points of contact by sintering or some other technique. This lack of continuity frequently causes the article to be brittle and incapable of resisting impact effectively even though the tensile strength may be adequate.

In accordance with the present invention, metal compacts having improved physical properties are produced from a starting material consisting of metallic fibers or filaments, that is, relatively elongated metallic bodies of fine diameter. Many of the products produced according to the present invention have the unique combination of extremely high porosity and permeability, as well as adequate mechanical strength, making these products particularly useful in a wide vairety of fields, including use as filtering media, boundary layer control devices, as transpiration cooling elements, heat exchange materials, bearings, electrical brushes, magnetic circuit elements, and in numerous other fields.

While the processes described herein have particular merit in the production of high porosity articles, the processes also have applicability to the manufacture of more dense materials, including compacts having a density approaching the theoretical density of the metal involved.

An object of the present invention is to provide an improved metallic mass from a starting material consisting of metal fibers.

Another object of the present invention is to provide improved metal compacts of controllable porosity and high strength from metallic fibers.

Still another object of the invention is to provide mechanical elements suitable for use as filters, and the like, from a readily available starting material.

Another object of the invention is to provide an improved process for forming metal fibers into compacted masses.

Still another object of the invention is to provide an improved process for felting metal fibers into a coherent metallic sheet.

Another object of the invention is to provide an improved molding process for forming metal fibers into shapes of substantial depth.

The present invention is applicable to the treatment of metal fibers generally. The only requirements for the metal fibers are that they (1) be capable of being formed into fibers of suitable length and shape and (2) that they be capable of being consolidated into a reasonably strong compact by a sintering process or similar treatment.

As employed in this specification and claims, the term "fibers" is intended to denote an elongated metallic filament having a long dimension substantially greater than its mean dimension in cross-section. As a general rule, a fiber should have a length of at least about 10 times its mean dimension in cross-section. The term "mean dimension in cross-section" is related to the shape of the fiber or filament in cross-section and refers to the diameter of the cross-section in the case of a circular filament, or in the case of a rectangular ribbon, denotes one-half the sum of the short side and the long side of the rectangle.

Particularly good results have been achieved in the described process by the use of metal fibers having a diameter of .00025 inch to .010 inch, and lengths varying from about 0.002 inch to two inches or more.

The fiber metal bodies are considerably superior in physical characteristics and porosity to their powder metal counterparts for several reasons. For one, the continuity possessed by the fibers during the formation permits kinking or bending of the fibers thereby facilitating mechanical interlocking or felting of the fibers. Hence, highly porous materials can be produced with little pressure because the unsintered compact is frequently strong enough due to mechanical interlocking of the fibers to be self-sustaining.

Additionally, compacts made from powder and those made from fiber exhibit different oxidation properties, due to this difference in continuity of the material making up the compact. For example, oxidation of molybdenum base powder metal compacts results in rapid failure of the compact due to the combined effects of oxidation and rupture of the bonds produced during sintering. In corresponding compacts produced from molybdenum fibers, however, it was observed that whatever damage occurred during oxidation progressed along a flat interface rather than by a distintegration mechanism.

In addition to the increased porosity and the improved oxidation properties of the compact, the compacts produced from metal fibers also have substantially improved strength properties. This can be explained by the fact that there are a large number of bonds produced between the adjoining fibers per unit of length. In addition, the metal fibers are capable of mechanically interlocking with each other to form an intertwined, laced network which has inherent mechanical strength even apart from the strength given to it by the subsequent sintering operation. Experimentally, it has been determined the strength of the compacts produced from the metal fibers according to the present invention is such that the number of bonds multiplied by the strength of the bonds per unit length is greater than the strength of the fibers themselves in tension.

Another interesting characteristic of the fiber compacts is their "fail-safe" feature which is also attributable to the fact that the fibers have a unidirectional continuity which metal powder compacts do not have. Thus, structural elements produced from the metal fiber compacts tend to fail progressively rather than fracture all at once due to brittleness, a characteristic of many powder metal compacts.

Besides the production of structural elements and the like, the present invention has applicability to the manufacture of metal fiber sheets of low density. These sheets are unique as compared to anything produced by powder metallurgy processes or from metal foil. Their most noteworthy characteristic is a high sectional modulus for a given mass.

The compositions of the present invention, when examined under a microscope, appear to be characterized by a large number of bonds between the adjoining fibers, and interlacing between the fibers. It appears that substantially all of the fibers making up the compact are bonded at a plurality of points to adjoining fibers, giving the resulting compact a strength which is considerably greater than that which may be achieved by ordinary sintering of metal powder compacts.

The strengthening of the metal fiber compacts is preferably accomplished by sintering the compacts at appropriate temperatures and at appropriate times to cause an autogenous bond to be produced at the points of contact between the adjoining fibers. Other means of joining the fibers, however, can be employed such as by coating the fibers with a brazing compound prior to their formation into the desired shape, followed by a heat treatment of sufficient intensity and duration to cause flow of the brazing compound around the junctures between the fibers.

A number of different processes may be employed in the manufacture of the improved products of the present invention, depending upon the characteristics desired in the final article. For example, a thin web or sheet of metal fibers may be produced by forming a suspension of the metal fibers in a suitable liquid suspending medium, and then depositing the suspension onto a foraminous surface such as a moving or vibrating screen. Upon drainage of the liquid suspending medium, the metal fibers settle into an interlaced, matted sheet which can be subsequently pressed and sintered to provide an extremely low density material having a high sectional modulus.

The procedure given above can likewise be used to build up successive layers of the fiber sheets into a blanket of metal fibers of substantially greater thickness.

In another modified form of the invention, the fibers can be suspended as a slurry in a suitable liquid suspending medium and introduced into a mold having porous walls, the mold including a cavity of the shape desired in the final article. As the slurry is introduced into the molding cavity, the metal fibers are retained within the cavity and the suspending liquid is removed by filtration or absorption through the porous walls. The compact which remains can then be pressed, if desired, and finally sintered to achieve the desired physical characteristics.

The features of the described processes and articles can best be observed by reference to the following attached sheet of drawings which illustrate several preferred embodiments of the invention.

In the drawings:

FIGURE 1 is a schematic view of an assembly of apparatus arranged to form a sheet of metal fibers;

FIGURE 2 is a view of a molding arrangement for forming a molded cup of metal fibers;

FIGURE 3 is a view in perspective of the "green" mass produced by the apparatus illustrated in FIGURE 2;

FIGURE 4 is a view in perspective of the mass of FIGURE 3 after compression;

FIGURE 5 is a somewhat schematic view of a cold pressing assembly which may be employed for manufacturing the compacts;

FIGURE 6 is a view similar to FIGURE 5, but illustrating the closed position of the assembly;

FIGURE 7 is a very highly magnified view of the finished article, illustrating the interlacing of the fibers;

FIGURE 8 is a view even more highly magnified than FIGURE 7, illustrating the manner in which the fibers are bonded together in the finished article; and

FIGURE 9 is a view similar to FIGURE 8, but illustrating a modified form of the invention.

FIGURE 1, reference numeral **10** indicates generally a feeding tank, or head box in which a suspension of metal fibers is received. The suspending medium for the fibers will depend to a large extent upon the density of the fibers, their size, and their reaction with the proposed suspending medium. For example, metal fibers such as stainless steel, nickel and the like which are relatively inactive toward oxidation, may be suspended, in suitable particle sizes, in water. However, fibers such as iron or the like which should be protected from oxidation should be suspended in non-aqueous liquids such as glycerine, petroleum oils, and the like.

Generally, the suspension employed in the feed tank **10** should be relatively dilute and typically may consist of about 5 to 10% by weight of the fibers. The fibers themselves can be formed in any fashion such as by grinding, milling, and the like. In order to provide a uniform dispersion of the fibers, it is desirable to agitate the suspending medium with the fibers by means of a suitable beater. If the finished article is to have a fiber arrangement of more or less uniform size, the agitation can be followed by a process of levigation which at least roughly classifies the fibers into different size ranges.

The suspension of metal fibers flows out of the flow tank **10** as a uniform dispersion onto a foraminous forming member **11** which, in the illustrated form of the invention, may consist of a fine mesh forming wire which moves as an endless loop between the pair of spaced rollers **12** and **13**. Alternatively, a layer of porous paper or the like can be laid on top of the forming wire **11** for the reception of the particle suspension. In either case, the forming surface should permit passage of the liquid suspending medium through the surface, but should retain the metal fibers.

To assist in removing the suspending medium as the web of metal fibers is being formed, the forming wire **11** carries the suspension over a pair of suction boxes **14** and **16** where a reduced pressure is applied to the web during its formation.

After the initial formation of the sheet, the sheet may be consolidated by passing the same into the nip of a pair of cooperating pressure rollers **17** and **18** which receive the formed sheet from the forming wire **11**. Pressure on the sheet aids in securing the mechanical interlocking between the felted fibers in producing a self-sustaining sheet.

Finally, the formed web may be passed directly into a sintering furnace 19 to produce metal-to-metal bonds at the points of contact in the fiber mass.

The conditions for sintering metal fibers are similar to those employed for sintering the corresponding powder metal particles, except that it may be desirable to raise the temperature by a matter of 100 or 200° F., above those employed for sintering powders of the same composition, and then to hold the sheet in the sintering furnace for a slightly longer time than would be practiced with metal powders. A non-oxidizing atmosphere is also required in the sintering furnace to prevent oxidation.

The sintered sheet leaving the sintering furnace 19 contains a network of interlaced, securely bonded fibers in which substantially all of the fibers are bonded to adjoining fibers at a plurality of points along their length. This type of structure provides a remarkably strong sheet of an extremely porous nature.

If desired, the thickness of the web can be built up by successive depositions of the metal fibers on the forming wire. For example, a second forming tank can be located following the suction box 16 to deposit a second web of the fibers over the initially deposited web. In some applications, it is desirable to avoid excessive orientation of the metal fibers in the direction of travel of the web, i.e., in the "machine direction" of the formed web. To do this, a magnetic field may be employed in conjunction with the second deposition of fibers onto the sheet to orient the second web of fibers in a direction at right angles or at a given angle to the predominating direction of fiber lay in the first formed web. This orientation is possible because the magnetic field has little or no effect upon the previously matted and interlaced fibers of the first web once they have become matted, but is effective upon those later deposited fibers which are still in suspension in the suspending medium.

For manufacturing fiber compacts of intricate shape, a molding system of the type illustrated in FIGURE 2 may be employed. This assembly may include a container 20 filled with a slurry 21 of metal fibers in an appropriate suspending medium. An agitator 22 is provided to prevent settling of the metal fibers from the suspension. A porous core 24 having an internal cavity 24*a* connected to a source of vacuum by a line 25 is arranged to be immersed into the slurry 21 to receive a deposit of fibers from the slurry 21. An impervious sealing cap 26 is included to seal off the core 24 from atmospheric pressure when the core 24 is immersed in the slurry 21 to the level of the cap 26. When the core 24 is immersed in the slurry 21, a buildup of metal fibers occurs on the immersed portion of the core 24 due to the application of the vacuum through the porous walls of the core 24. The suspending medium may be recovered in a suitable trap in the vacuum system and reused.

The appearance of the "green" matted mass after removal from the core shown in FIGURE 2 is illustrated in FIGURE 3 of the drawings. This compact may consist of a loosely formed cup 30 of the metal fibers 27 having an extremely high porosity. For some applications, particularly for use as filtering media, such high porosity is desirably retained in the final article, so that the cup 30 may be passed directly into a sintering furnace where the mass is strengthened by the production of autogenous metal-to-metal bonds between the interlaced fibers.

In some instances, however, it will be desirable to compress the green compact prior to sintering in order to densify the same while still retaining a substantial degree of its porosity. Generally, the most desirable products produced by the described process have a porosity in the range of from about 50% to about 95%. For filtering elements, this porosity may be in the range from about 70 to about 90%. At such high porosities, there is a very low loss in head in the fluid stream being passed through the filter.

The condition of the green compact after compression in a coining die or the like is illustrated in FIGURE 4 of the drawings. The cup 35 illustrated in FIGURE 4 has been compressed hydrostatically to achieve the desired density prior to sintering. The compressed cup 35 is then sintered. In some cases additional advantages may be gained by repressing and resintering the compact.

Another apparatus for preparing the green compact has been illustrated somewhat schematically in FIGURES 5 and 6 of the drawings. The apparatus there shown includes a floating die member 36 providing a molding cavity 36*a* into which dry metal fibers 37 are introduced directly. A lower punch member 38 and an upper punch member 39 are moveable relative to each other, as best seen in FIGURE 6 to compress the fibers 37 to the density desired in the final compact. This density may approach the theoretical density of the metal involved, or it may be only a small fraction of the theoretical density depending on the use to which the compact is ultimately put.

The structure of the sintered compact is best illustrated in FIGURES 7 and 8 of the drawings. As evident from these two figures, the fibers 27 are mechanically interlaced with adjoining fibers which assists in preventing relative movement between the fibers. The bonding between the fibers 27, as illustrated in FIGURE 8 of the drawings, occurs along relatively wide areas of contact 29 and consists in an autogenous welded bond caused by holding the compact at the sintering temperature until adequate sintering of the metal occurs. The extended area bonding made possible by the employment of metal fibers, coupled with the mechanical interlocking effect previously mentioned, is believed to be primarily responsible for the improved physical properties of the compacts produced according to this invention.

In a modified form of the invention, as illustrated in FIGURE 9, the individual fibers 31 may each be given a surface coating of a brazing compound such as copper. The compact is then passed into the heat treating furnace, where the temperature employed is sufficient to melt or at least soften the brazing compound causing it to flow into the junctions between the fibers. Upon cooling of the compact, the brazing composition solidifies to form deposits 33 of the brazing metal which hold the fibers of the mat together into a coherent mass.

Tests have indicated that for a given porosity, a compact produced from a metal fiber composition is considerably stronger in tensile strength than a compact produced from metal powders of the same chemical composition. For example, the following table indicates the comparative tensile properties of iron powder and iron fiber bodies, each of which had a maximum carbon content of 0.10%.

TABLE I

Comparative Tensile Properties of (0.10% C Max) Iron Powder and Iron Fiber Bodies

Tensile Strength, p.s.i.	Porosity in percent	
	Powder Body	Fiber Body
7,500	32	50
11,000	29	40
15,000	23	30

The impact properties of the fiber metal bodies were markedly superior to compacts employing powdered metal. The test specimens used in the impact test were unnotched bars each 0.490 by 0.200 inch. These specimens were broken in a 25 foot pound Baldwin Sonntag Impact Testing Machine with the following results:

TABLE II

Comparative Impact Properties of Iron Powder and Iron Fiber Bodies

Impact Strength, ft. lb.	All Powder Body	Porosity in percent	
		Powder and Fiber Body	All Fiber Body
1	30		(85)
2	22	35	(70)
4	(17)		45
6			27
Over 25			[1] 18

[1] Specimen did not break.
( ) Extrapolated values.

It was interesting to note in connection with the impact test, that the type of fracture which the compacts underwent was considerably different. In a case of the metal fiber compacts, the failure occurred largely through the fiber rather than through the inter-fiber bonds. In the case of the powdered metal compacts, the failure occurred as a brittle fracture at the point of impact.

The following data illustrates the manner of preparing the compacts and some of their physical properties.

Two grades of stainless steel (Type 430) wool were employed as starting materials. The finer grade had an average fiber cross-sectional area of 4×10^{-6} sq. in. and the coarser grade had an average fiber cross-sectional area of 10.5×10^{-6} sq. inch. The fine fibers were cut to a length of 5/16", so that the ratio of length to diameter of the fibers was about 150. The coarse fibers were cut to a length of ½", so that their length to diameter ratio was about 120.

The fine and coarse fibers were dispersed separately in a Waring blender. The fibers were deposited from suspension onto a porous forming surface in a vacuum filter. The disks which results were removed and cold pressed, the fine fibers being pressed at a pressure of 10 to 50 tons per square inch, and the coarse fibers at 30 to 70 tons per square inch. All disks were sintered at 2400° F., for one hour in pure hydrogen. Some of the disks were coined under the same conditions given for cold pressing, followed by resintering at 2400° F., for one hour.

The physical and mechanical properties of the resulting disks were given below.

TABLE III

Physical and Mechanical Properties of Stainless Steel Fiber Metal Disks

Fiber Type	Porosity, percent	Tensile Strength, p.s.i.	Permeability coefficient (Darcy's Law)
Fine	32.2	12,250	14.7×10^{-10} in.^{2}
Do	29.0	22,800	5.0×10^{-10} in.^{2}
Do	37.7	15,300	26.1×10^{-10} in.^{2}
Coarse	27.6	19,800	37.2×10^{-10} in.^{2}
Do	29.7	17,500	34.2×10^{-10} in.^{2}
Do	15.7	23,300	9.8×10^{-10} in.^{2}
Do	11.7	28,800	2.4×10^{-10} in.^{2}

Numerous modifications can be made to the procedures described above, as will be evident to those skilled in the art. For example, in order to increase the degree of mechanical interlocking between the fibers, the fiber surfaces may be roughened to provide tiny barb-like projections along the length of the fibers. As another alternative, compacts can be made using different types of metals in the compact and the union between the fibers produced by surface alloying under the appropriate heat treatment conditions. As a further alternative, the compacts may be built up from metal fibers of different sizes

where a body is to be produced which has a variation in porosity from one end to the other.

It will be understood that modifications and variations may be effected without departing from the scope of the novel concepts of the present invention.

I claim as my invention:

1. A fiber metal skeleton consisting essentially of a bonded mass of metal fibers each of sufficiently short length to be suspendible in a fluid as discrete fibers, the lengths of said fibers being in the range from 0.002 to 2 inches, said fibers being arranged at random in said skeleton and being bonded at points of contact with adjoining fibers to provide a skeleton having a porosity in the range from about 50% to about 95%.

2. A fiber metal skeleton consisting essentially of a bonded mass of metal fibers each of sufficiently short length to be suspendible in a fluid as discrete fibers, the lengths of said fibers being in the range from 0.002 to 2 inches, said fibers being arranged at random in said skeleton and being bonded at points of contact by means of solidified deposits of a brazing composition to provide thereby a skeleton of appreciable porosity and substantial tensile strength.

3. The method of making a fiber metal article which comprises suspending short, discrete metal fibers in a fluid medium, agitating said fluid medium to keep said fibers in suspension, rapidly withdrawing the fluid suspending medium from such suspension to thereby leave a felted mass of discrete metal fibers, compressing said mass, and sintering said mass to produce a self-sustaining fiber metal article.

4. The method of making a fiber metal article which comprises suspending short, discrete metal fibers in a liquid medium, agitating said liquid medium to keep said fibers in suspension, applying suction to the resulting suspension to withdraw the suspended liquid rapidly and leave a felted mass of fibers, compressing said mass and sintering said mass to produce a self-sustaining fiber metal article.

5. The method of making a fiber metal article which comprises suspending short, discrete metal fibers in a liquid medium, maintaining said fibers in suspension, applying the resulting suspension to a foraminous surface, applying suction through said foraminous surface to withdraw the suspending medium rapidly and thereby leave a felted mass of metal fibers, compressing said felted mass and sintering said mass to produce a compact having metal-to-metal bonds therethrough.

6. The method of making a fieber metal sheet which comprises suspending short discrete metal fibers in a liquid medium, maintaining said fibers in suspension, depositing the resulting suspension on a moving screen, applying suction through said screen to withdraw the suspending medium rapidly and thereby leave a felted mass of metal fibers, compressing said felted mass and sintering said mass to produce a fiber metal sheet having metal-to-metal bonds therethrough.

7. A fiber metal skeleton consisting essentially of a bonded mass of metal fibers each of sufficiently short length to be suspendible in a fluid as a feltable dispersion, the lengths of said fibers being at least ten times their mean dimension in cross-section, and being in the range from 0.002 to 2 inches, said fibers being arranged at random in said skeleton and being bonded at points of contact with adjoining fibers with metallic bonds to provide a skeleton of appreciable porosity and substantial tensile strength.

8. A fiber metal skeleton consisting essentially of a bonded mass of metal fibers each of sufficiently short length to be suspendible in a fluid as a feltable dispersion, the lengths of said fibers being at least ten times their mean dimension in cross-section, and being in the range from 0.002 to 2 inches, said fibers being arranged at random in said skeleton and being bonded at points of contact with adjoining fibers by autogenous metal-to-

metal bonds to provide a skeleton of appreciable porosity and substantial tensile strength.

9. The method of making a fiber metal article which comprises suspending short, discrete metal fibers in a liquid medium, maintaining said fibers in suspension, applying the resulting suspension to a permeable surface, applying suction through said permeable surface to withdraw the suspending medium rapidly and thereby leave a felted mass of metal fibers, compressing said felted mass and sintering said mass to produce a compact having metal-to-metal bonds therethrough.

10. A method of continuously making a conductive strip material which comprises continuously suction depositing metal fibers from a fluid suspension thereof to form a porous mat and continuously integrally bonding the fibers at their conductive junctures to improve the electrical conductivity therebetween.

11. A method for continuously making a reinforced conductive fibrous strip which comprises suction-depositing metal conductive fibers from fluid suspension onto a reinforcing porous base made from nonconductive fibers to form a porous laminated mat, and integrally bonding the metal fibers at their conductive junctures.

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