

(86) Date de dépôt PCT/PCT Filing Date: 2005/04/25
(87) Date publication PCT/PCT Publication Date: 2005/11/03
(45) Date de délivrance/Issue Date: 2013/06/25
(85) Entrée phase nationale/National Entry: 2006/10/17
(86) N° demande PCT/PCT Application No.: EP 2005/004420
(87) N° publication PCT/PCT Publication No.: 2005/104143
(30) Priorité/Priority: 2004/04/23 (EP04009730.5)

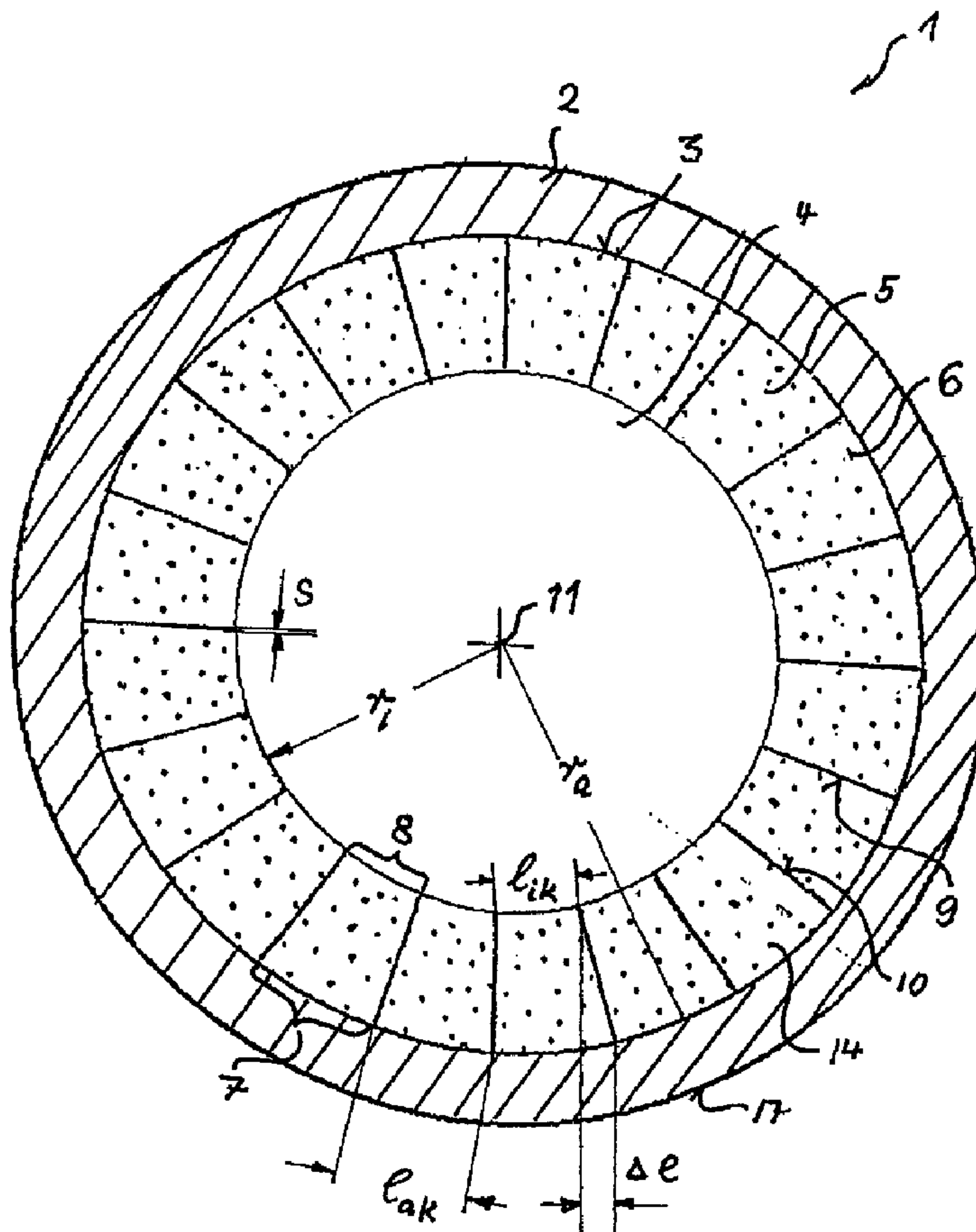
(51) Cl.Int./Int.Cl. *H01B 12/12* (2006.01),
H01B 12/10 (2006.01)

(72) Inventeurs/Inventors:
FISCHER, EGBERT, DE;
KHODGHIBAGIYAN, HAMLET, RU;
KOVALENKO, ALEXANDER, RU;
MORITZ, GEBHARD, DE

(73) Propriétaire/Owner:
GESELLSCHAFT FUER SCHWERIONENFORSCHUNG
MBH, DE

(74) Agent: MACRAE & CO.

(54) Titre : CABLE SUPRACONDUCTEUR ET SON PROCEDE DE PRODUCTION
(54) Title: SUPERCONDUCTIVE CABLE AND METHOD FOR THE PRODUCTION THEREOF



(57) **Abrégé/Abstract:**

The invention relates to a supraconductive hollow cable and to a method for the production thereof. Said supraconductive hollow cable (1) comprises an outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3). The inventive

(57) Abrégé(suite)/Abstract(continued):

supraconductive hollow cable (1) also comprises a central cooling channel (4) having a polygonal or circular cross-section that is, however, smaller than the inner cross-section of the outer tube (2). Profiled supraconductive wires (5) are arranged between the outer tube (2) and the cooling channel (4). Said profiled supraconductive wires (5) have a cross-sectional profile corresponding to that of a keystone such as those used to build roman stone bridges or groined vaults. Furthermore, said cross-sectional profile comprises at least one outer curved section (7) and one inner section (8), said outer curved section (7) being adapted to the inner radius of the outer tube (2), and the inner section (8) being adapted to the cooling channel (4). The lateral edges (12, 13) can either be profiled in a linear manner in the direction of the central point (11) of the cooling channel (4) or staggered in relation to said linearity.

(12) NACH DEM VERTRAG ÜBER DIE INTERNATIONALE ZUSAMMENARBEIT AUF DEM GEBIET DES
PATENTWESENS (PCT) VERÖFFENTLICHTE INTERNATIONALE ANMELDUNG(19) Weltorganisation für geistiges Eigentum
Internationales Büro(43) Internationales Veröffentlichungsdatum
3. November 2005 (03.11.2005)

PCT

(10) Internationale Veröffentlichungsnummer
WO 2005/104143 A1(51) Internationale Patentklassifikation⁷: **H01B 12/12**,
12/10(71) Anmelder (für alle Bestimmungsstaaten mit Ausnahme
von US): **GESELLSCHAFT FUER SCHWERIONEN-
FORSCHUNG MBH** [DE/DE]; Planckstrasse 1, 64291
Darmstadt (DE).

(21) Internationales Aktenzeichen: PCT/EP2005/004420

(22) Internationales Anmeldedatum:
22. April 2005 (22.04.2005)

(72) Erfinder; und

(75) Erfinder/Anmelder (nur für US): **FISCHER, Eg-
bert** [DE/DE]; Planckstrasse 1, 64291 Darmstadt (DE).
KHODGHIBAGIYAN, Hamlet [RU/RU]; Bogolyubov
Avenue 6, apart. 1407., 141980 Dubna, Moscow Region
(RU). **KOVALENKO, Alexander** [RU/RU]; Moskovskaja
Strasse 12, apart. 60, 141980 Dubna, Moscow Region
(RU). **MORITZ, Gebhard** [DE/DE]; Planckstrasse 1,
64291 Darmstadt (DE).

(25) Einreichungssprache: Deutsch

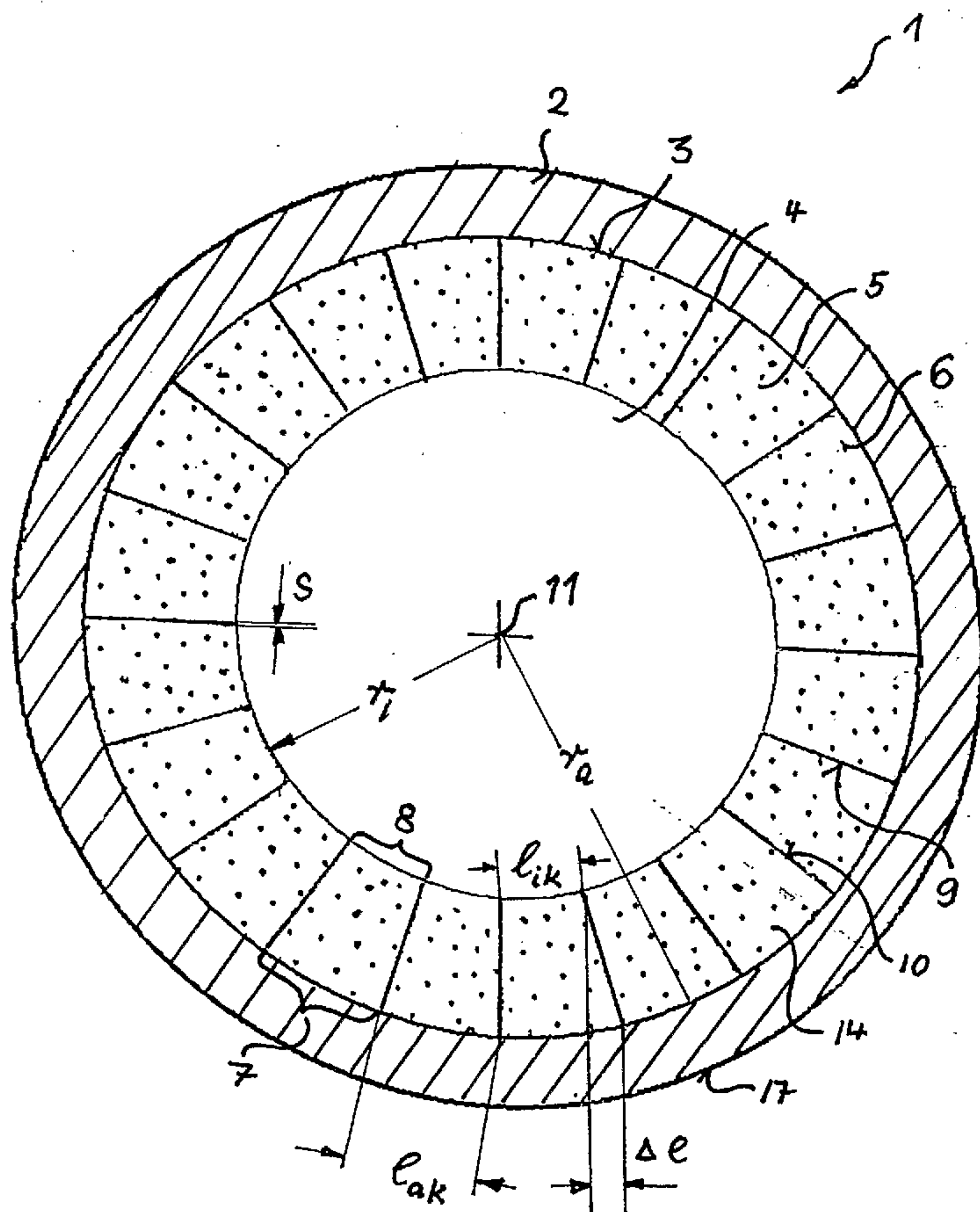
(26) Veröffentlichungssprache: Deutsch

(30) Angaben zur Priorität:
04009730.5 23. April 2004 (23.04.2004) EP

[Fortsetzung auf der nächsten Seite]

(54) Title: SUPRACONDUCTIVE CABLE AND METHOD FOR THE PRODUCTION THEREOF

(54) Bezeichnung: SUPRALEITENDES KABEL UND VERFAHREN ZUR HERSTELLUNG DESSELBEN



(57) **Abstract:** The invention relates to a superconductive hollow cable and to a method for the production thereof. Said superconductive hollow cable (1) comprises an outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3). The inventive superconductive hollow cable (1) also comprises a central cooling channel (4) having a polygonal or circular cross-section that is, however, smaller than the inner cross-section of the outer tube (2). Profiled superconductive wires (5) are arranged between the outer tube (2) and the cooling channel (4). Said profiled superconductive wires (5) have a cross-sectional profile corresponding to that of a keystone such as those used to build roman stone bridges or groined vaults. Furthermore, said cross-sectional profile comprises at least one outer curved section (7) and one inner section (8), said outer curved section (7) being adapted to the inner radius of the outer tube (2), and the inner section (8) being adapted to the cooling channel (4). The lateral edges (12, 13) can either be profiled in a linear manner in the direction of the central point (11) of the cooling channel (4) or staggered in relation to said linearity.

[Fortsetzung auf der nächsten Seite]

WO 2005/104143 A1



(74) **Anwälte:** BOETERS, Hans, D. usw.; Boeters & Lieck, Bereiteranger 15, 81541 München (DE).

(81) **Bestimmungsstaaten** (soweit nicht anders angegeben, für jede verfügbare nationale Schutzrechtsart): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) **Bestimmungsstaaten** (soweit nicht anders angegeben, für jede verfügbare regionale Schutzrechtsart): ARIPO (BW,

GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), eurasisches (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), europäisches (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Veröffentlicht:

— mit internationalem Recherchenbericht

Zur Erklärung der Zweibuchstaben-Codes und der anderen Abkürzungen wird auf die Erklärungen ("Guidance Notes on Codes and Abbreviations") am Anfang jeder regulären Ausgabe der PCT-Gazette verwiesen.

(57) **Zusammenfassung:** Die Erfindung betrifft ein supraleitendes Hohlkabel und ein Verfahren zur Herstellung desselben. Das supraleitende Hohlkabel (1) weist einen Außentubus (2) mit einem kreisförmigen Innenquerschnitt und zylindrischer Innenwand (3) auf. Ferner besitzt das supraleitende Hohlkabel (1) einen zentralen Kühlkanal (4), mit einem polygonalen oder kreisförmigem Querschnitt, der aber kleiner ist als der Innenquerschnitt des Außentubus (2). Zwischen dem Außentubus (2) und dem Kühlkanal (4) sind profilierte supraleitenden Drähte (5) angeordnet. Diese profilierten supraleitenden Drähte (5) haben ein Querschnittsprofil, das einem Schlussstein, bzw. Keystone, wie der für römische Steinbrücken oder für Kreuzgewölbe bekannt ist, entspricht. Dazu weist das Querschnittsprofil mindestens einen äußeren Krümmungsabschnitt (7) und einen inneren Abschnitt (8) auf, wobei der äußere Krümmungsabschnitt (7) dem Innenradius des Außentubus (2) angepasst ist und der innere Abschnitt (8) dem Kühlkanal (4) angepasst ist. Auch die Seitenkanten (12, 13) können entweder geradlinig in Richtung auf den Mittelpunkt (11) des Kühlkanals (4) oder durch einen Versatz gegenüber dieser Geradlinigkeit profiliert sein.

Superconductive cable and method for the production thereof**Field of the Invention**

The invention relates to a superconducting hollow cable having an outer tube which has a circular inner cross-section and, consequently, a cylindrical inner wall. In addition, the superconducting hollow cable has a central cooling channel of a circular cross-section that is smaller than the inner cross-section of the outer tube. Arranged between the inner wall of the outer tube and the cooling channel are profiled superconducting wires. Such profiled superconducting wires comprise at least one superconductor (superconducting filament) and have a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults.

Background of the Invention

Profiled superconducting cables having a cross-sectional profile of a key stone are known from the publication US 6,675,623 B2. Further prior art is US 2003/0024 730. The known key-stone-shaped superconducting cables consist of superconducting wires of round cross-section stranded with one another and, after stranding, they are given a trapezoidal shape with the aid of profiling rollers.

The structure of a superconducting hollow cable of the Nuclotron type having round (standard variant, Figure 16) or profiled (improved Nuclotron cable, Figure 17) superconducting wires is known from the publication "Design and test of new hollow high current NbTi cable for fast ramped synchrotron magnets" Proc. EUCAS 2003, Sorrento, September 2003, H. Khodzhibagiyev *et al.*. In the case of the known hollow cable, first a cooling channel is formed by means of providing a compact metallic inner tube of CuNi. Superconducting wires profiled in the longitudinal direction and having a key-stone-shaped cross-section are placed or wound on the outer wall of the inner tube. In order to fix the superconducting wires on the compact inner tube, NiCr wires are wound around the outside of the superconducting wires radially or in a helical arrangement. A Kapton tape wound over the NiCr wires forms a protective outer jacket. A fibreglass tape wound around the outer jacket ensures that the superconducting hollow cable is electrically insulated.

A superconducting hollow cable that is so structured has the advantage, amongst others, of being able to compensate for high dynamic loads as occur as a result of the Lorentz forces in

- 2 -

fast-pulsed magnets and high magnetic fields. The heat sources brought about by those pulsating fields by means of eddy currents, hysteresis cycles, mechanical stress fields and other external influences (e.g. ion beams) can, in continuous operation, be very effectively cooled by the inner cooling channel by virtue of the compact inner tube. The relatively large cross-section of the compact inner tube, which has a smooth surface, allows a high throughput of coolant with low frictional resistance and, accordingly a low pressure drop in the two-phase helium stream. In addition, all the superconducting wires are arranged absolutely symmetrically and are consequently under identical operating conditions, as a result of which degradation of the critical current of the cable with increasing electromagnetic loading is avoided to a very large extent.

This arrangement of the superconducting wires furthermore results in low cable inductivity and consequently (*inter alia*) also in reduction of the energy stored.

Another cable type is, in general, preferred when the coil system to be produced is not intended to be operated in an extremely fast-pulsed regime but rather has to store a large amount of inductive energy which has to be delivered in high stochastic heat pulses of short duration. In that case, a continuous high cooling performance is secondary whereas the fastest possible heat transfer to the heat capacity of the helium cooling the superconducting wires in the millisecond range is primarily sought. For that task, the known hollow cables of the CICC type as shown in Figure 14 were developed.

However, because those cables also increasingly have to overcome higher mechanical and thermal loads in practical use, further development thereof resulted in a high-current cable of the CICC type having as a result of additional constructional elements, complicated cooling with two basically different cooling circuits with supercritical helium in the outer cooling circuit and with two-phase helium in the central cooling channel.

That complicated structure not only has technical and, therefore, cost-influencing disadvantages but also automatically gives rise to a reduced average current density of the hollow cable. A cable of such a kind in accordance with the present prior art is shown in Figure 15 and is known as a POLO cable (see, for example, "CHATS", FzK, Karlsruhe, September 2002, L. Bottura *et al.*). It represents the starting point for the invention explained hereinbelow.

The problem of the invention is to overcome the disadvantages in the prior art and to provide a superconducting hollow cable which makes possible intensive cooling of the superconducting components and, in addition, makes available a high current density for a hollow cable of the CICC type with a compact and mechanically stable structure for the hollow cable. Solutions are to be provided as to how the disadvantages of the CICC cable with respect to the cable of the Nuclotron type can be overcome to a very large extent and how the advantages of both hollow cable types can be, as far as possible, in a new superconducting hollow cable.

Summary of the Invention

In accordance with the invention, a hollow cable is provided which has an outer tube having a circular inner cross-section and a cylindrical inner wall. In the centre of the superconducting hollow cable there is arranged a central cooling channel of a polygonal or circular cross-section which is smaller than the inner cross-section of the outer tube. Arranged between the inner wall and the cooling channel are profiled superconducting wires. These profiled superconducting wires have at least one superconducting filament (usually in a Cu matrix). Furthermore, the superconducting wires have a cross-sectional profile of a key stone.

The cross-sectional profile of the profiled superconducting wires have an outer region of curvature which is matched to the circular inner cross-section of the outer tube. Furthermore, the cross-section of the profiled superconducting wires have an inner region of curvature which is in turn matched to the circular cross-section of the cooling channel. Finally, the cross-sectional profile has side edges which are oriented profiled towards the centre-point of the cooling channel. The profiled superconducting wires are accordingly arranged on the inner wall of the outer tube and their inner regions form the cooling channel of the superconducting hollow cable.

In summary it can be mentioned that the superconducting cable has three main elements, which have the following advantages. First, the superconducting filaments are minimised, as a result of which the Meissner effect and the alternating current losses are minimised. Second, as large a number of filaments as possible is embedded in a metallic matrix which mechanically stabilises the filaments and ensures a high degree of heat conduction. Third, a number of superconducting wires are combined and mechanically stabilised in the

- 4 -

superconducting cable and contact with the coolant is brought about. Electrically insulated from one another, the superconducting wires according to the invention, with a resistance barrier, form the basic material for producing actual coil elements. Because the wires are not fused with one another, the coils and/or cables are extremely flexible.

Such a superconducting hollow cable according to the invention has, amongst others, the following advantages:

The profiled superconducting wires are so arranged tightly against one another and matched to the inner wall of the outer tube that they can hold themselves in position by means of a shape-based and force-based fit without the inner tube known from the prior art and they result in a cylindrical body, the space within which forms the cooling channel. This is to say that inner structural elements are no longer required for mechanically fixing the superconducting wires in place. In addition to the material saving resulting from dispensing with a component, this superconducting hollow cable has the further advantage that the larger cross-section of the cooling channel brings about a reduction in resistance to the flow of the cooling medium. As a result, a greater effect can be achieved. Alternatively, that additional free volume can also be utilised for larger superconducting wires and, consequently, for a higher average current density.

Finally, the cooling medium, or cooling channel, is in direct contact with the profiled superconducting wires. Even though that contact is also present in the above-described CICC cables, the resistance to flow in the cooling strands therein is considerable and the heat capacity of the small amount of supercritical helium is limited so that the cooling effects achievable with the hollow cable according to the invention are much greater in all time intervals (short heat pulses and continuous loading). The symmetrical arrangement of all superconducting wires ensures that the cable as a whole has additional stability against thermal pulses, as described above for the Nuclotron cable. From the cryotechnical point of view, the now dramatically simplified cooling, compared to the starting point, constitutes a decisive advantage because this means that two cooling circuits, and indeed two qualitatively different cooling circuits, are no longer required and cooling performance is improved by orders of magnitude in all time scales (pulse operation to constant continuous operation).

The profiled superconducting wires are arranged so tightly on the inner wall of the outer tube of the superconducting hollow cable by means of their outer regions of curvature and with their radially oriented side edges adjacent to one another that at all operating temperatures of the

- 5 -

superconducting hollow cable they maintain a central cooling channel with their inner regions of curvature. Because such a superconducting hollow cable undergoes extreme temperature differences from room temperature to a few degrees kelvin in its operation, the tight structure of the key-stone-shaped profiled superconducting wires means that the central cooling channel is maintained despite the different operating temperatures. For that purpose, the sum of gap widths that possibly form between the profiled superconductors during operation is, at all operating temperatures of the superconducting hollow cable, smaller than the difference in length Δl between the outer and inner regions of curvature of an individual profiled superconductor. In this context,

$$\Delta l = 2\pi (r_a - r_i)/n,$$

n being the number of profiled superconductors distributed on the inner wall of the outer tube, r_a being the inner radius of the outer tube and r_i being the inner radius of the flow channel. Because the length l_{ak} of an outer curvature radius

$$l_{ak} = 2\pi r_a/n$$

and the length l_{ik} of the inner region of curvature of a profiled superconductor

$$l_{ik} = 2\pi r_i,$$

the following conditions must be satisfied at all operating temperatures of the superconducting hollow cable:

$$n \cdot s < \Delta l \text{ or}$$

$$n \cdot s < l_{ak} - l_{ik}$$

and accordingly the condition is to be met

$$s < 2\pi (r_a - r_i)/n^2.$$

- 6 -

so that the central cooling channel is maintained. Accordingly the number of profiled superconducting wires is dependent on the manufacturing tolerance and must, where necessary, be kept as small as possible in order that the resulting gap width s can be allowed in the case of large tolerances. In general, in order to reduce the influence of eddy currents, the two main dimensions of the cross-section of the profiled superconducting wires should not differ too greatly from one another. The likewise undesirable heat production due to mechanical stress and deformation fields can be minimised by means of manufacture with a shape-based fit, where appropriate with biasing.

In a further embodiment of the invention, the profiled superconducting wires have intermeshing profiled side edges. Whereas the above observations are provided and deduced for the formation of a central cooling channel from profiled superconductors having rectilinear side edges of the cross-section of the profiled superconductors, those side edges pointing in towards the centre of the hollow cable, a further possibility is provided by this further embodiment of the invention, in which the side edges too are profiled and do not extend in a straight line towards the centre-point, of increasing the safety margin for maintaining the central cooling channel, especially as - in addition to the above-mentioned difference in length Δl for the sum $s \cdot n$ of all gap widths s - the offset due to the profiled side edges also comes into play. As a condition for the allowable gap width s , that offset, of a magnitude v , results in the value

$$s < (\Delta l + v)/n.$$

The accompanying Figures 2 and 4 show two embodiments of profiled superconductors having profiled side edges and the respective offset of magnitude v .

In a further embodiment of the invention, the outer tube is of two layers. A first layer comprises one or more tensioning wires wound in a helical arrangement around a bundle of superconducting profiled wires. A second layer comprises an electrically insulating and hermetically sealing outer layer. This tensioning wire solution has the advantage that superconducting hollow cables of any desired length can be produced continuously.

In a further embodiment of the invention, the profiled superconducting wires comprise stranded or twisted superconducting filaments. Examples of embodiments of such profiled

- 7 -

superconducting wires are shown in the further Figures 6, 7 and 8 and are explained later. The superconducting filaments are provided with a ductile metallic core and a ductile metallic jacket so that the superconducting wires are accessible to profiling shaping. For the purpose, the profiled superconducting wires comprise a metallic matrix (having a metallic core or centre, usually of Cu) and, for reducing eddy currents, optionally additional high-resistance intermediate layers, for example of CuNi alloys. The superconducting filaments consist of, for example, NbTi wires, which are twisted or stranded with one another. The jacket likewise preferably comprises a CuNi alloy.

In a further embodiment of the invention, the profiled superconducting wires are ceramic or high-temperature superconductors. Such HTSC's have the advantage that their critical temperature is substantially higher than in the case of metallic superconductors. The critical temperature in the case of metallic superconductors is below 20 degrees kelvin. With the HTSC's, the critical temperatures are in some cases above 80 degrees kelvin, associated with which is the advantage that substantially cheaper coolants can be used or higher magnetic fields can be achieved at lower temperatures. Even if the processing of HTSC's into profiled superconducting wires is more difficult, it is nevertheless to be foreseen that the so-called YBCO-based ceramic superconductors based on Y_3O_3 , $BaCO_3$ and CuO with admixtures of silver oxide, platinum oxide or cerium oxide can certainly be processed into profiled superconducting wires by means of appropriate melting and annealing processes. Even the so-called BSCCO superconductors, which consist of bismuth oxides, strontium oxides, calcium oxides and copper oxides and may comprise additions of lead oxides, comprise up to 90 % superconducting orthorhombic material, which can be processed into profiled superconducting wires.

The outer tube of the superconducting hollow cable is made from a metallic or non-metallic material, such as a CuNi alloy, stainless steel, GFRP or organic material and can have a circular, square or trapezoidal external contour or any other shape required. The outer tube in question can be wound in appropriate Kapton tapes and/or fibreglass tapes for electrical insulation. The square external contour has the advantage that cooling channels can be incorporated within the outer tube in the longitudinal direction so that not only are the profiled key-stone-shaped superconducting wires cooled by the central cooling channel, which is in direct contact with the superconductors, but also, in addition, they can additionally be cooled by the outer tube or the cooling channel running through the outer tube in the longitudinal

- 8 -

direction. The same also applies to trapezoidal external contours because, in that case too, for example, four additional cooling channels can be provided directly in the outer tube material. The outer cooling channels can be open along the inner wall of the outer tube over a finite width $\sim l_{ak}$.

The twisted profiled superconducting wires cross those channels at an angle that is not too acute and accordingly after each quarter turn of the helical displacement are additionally cooled from the outside in direct contact with the coolant.

Accordingly, in this variant too, all the wires are subject to identical electromagnetic, mechanical and thermal conditions.

Depending on the production technology (with or without mechanical biasing) and conditions of use, it is possible to provide, as the material for the outer tube, a material which has a higher or lower coefficient of thermal expansion than the material of the profiled superconducting wires. Where appropriate, the properties of the material of the outer tube are matched to the properties of the superconducting material in order to ensure that the shape and integrity of the central cooling channel are preserved. A further crucial material selection criterion for the outer tube is high electrical resistance to eddy currents whilst having sufficiently high mechanical strength.

Methods of producing a superconducting hollow cable can comprise a plurality of method steps in different orders. Furthermore, the method of producing a superconducting hollow cable according to the invention is also dependent on the possibilities for producing profiled superconducting wires.

One of the methods, according to the invention, of producing a superconducting hollow cable comprises the following method steps. First, a compact outer tube having a circular inner cross-section and a cylindrical inner wall that is as smooth as possible is produced. Aside therefrom, profiled superconducting wires having a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults are produced. For the purpose, the cross-sectional profile of the profiled superconducting wires have an outer region of curvature which is matched to the circular inner cross-section of the outer tube. Furthermore, the cross-sectional profile has an inner region of curvature which is matched to the circular cross-section of the cooling channel.

- 9 -

Finally, the cross-sectional profile has side edges which are oriented profiled towards the centre-point of a cooling channel to be formed.

After those two main components of the hollow cable according to the invention have been produced, the profiled superconducting wires are first brought together to form a longitudinally extended circular bundle around a central cooling channel. In the course of that bringing together, aids such as adhesive substances can also be used in order to ensure a material-based connection between the profiled superconducting wires. That circular bundle comprising profiled superconducting wires is then drawn into the compact outer tube of the superconducting hollow cable. This method has the advantage that the hollow cable can be assembled from two components which can be produced independently of one another.

In a further method variant, the outer tube is not produced in the form of a compact component but rather is fabricated in two half-shells. On assembly of the superconducting hollow cable, the profiled superconducting wires produced are then placed inside the half-shells. The half-shells are subsequently brought together with profiled superconductors lying inside and welded together. This method has the advantage that, after the welding process, contraction of the outer tube can occur which simultaneously brings about compressive compaction of the profiled superconducting wires lying inside.

In a further method variant, tensioning wires are wound in a helical arrangement around a bundle of profiled superconducting wires, preferably contrary to the twist direction of the superconducting wires. An electrically insulating and hermetically sealing outer layer is subsequently applied over the tensioning wires. This method variant has the advantage that unlimitedly long superconducting hollow cables comprising profiled superconducting wires can be continuously produced.

A further method variant provides the possibility of heating the outer tube in the form of a compact component and cooling a bundle of profiled superconducting wires having a central cooling channel. The two components are then pushed one into the other. Afterwards the outer tube shrinks onto the circular bundle of longitudinally extended profiled superconducting wires and causes the superconducting wires to press against one another whilst forming a central cooling channel. This method has the advantage that drawing-in of the circular bundle of superconducting wires having a central cooling channel into the compact outer tube is made

- 10 -

easier. In this context it is also possible for only the solidly constructed outer tube to be heated or for only the bundle of profiled superconducting wires to be cooled.

A preferred method of producing profiled superconducting wires comprises the following method steps. First, in the standard method, superconducting multifilament wires of round cross-section are produced which, in accordance with the intended conditions of use, have an optimum microstructure, where appropriate with additional resistive barriers. Subsequently, the round superconducting wires are profiled to form profiled superconducting wires. That profiling can be carried out in a great variety of ways.

On the one hand it is possible to use appropriate profile rollers, which produce the inner region of curvature and the outer region of curvature as well as the key stone shape of the side faces. It is furthermore possible also to use profile rollers for the side edges in order to provide an offset in the side edges, so that the profiled superconducting wires intermesh to a greater extent on assembly into a bundle having a central cooling channel. Instead of profile rollers it is also possible to provide profile drawing through an appropriate profile block, through which the prepared wire is drawn and by means of which, in the process, the shape of its cross-sectional profile is modified. A further possibility lies in so-called reshaping forging, in which the desired profile is produced by means of appropriate forging procedures.

Instead of a solidly constructed outer tube, jacketing of the profiled superconducting wires can also be accomplished using helically wound tensioning wire, for example made of NiCr, Figure 13: The electrically insulating, hermetically tight outer layer is subsequently produced, for example by means of polymerisation.

In accordance with one embodiment, the invention accordingly relates to a superconducting hollow cable having the following features:

- an outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3);
- a central cooling channel (4) having a polygonal or circular cross-section which is smaller than the inner cross-section of the outer tube (2), there being arranged between the inner wall (3) and the cooling channel (4) profiled superconducting wires (5);

- 11 -

- profiled superconducting wires (5) which comprise at least one superconducting filament (6) and which have a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults, characterised in that the cross-sectional profile of the profiled superconducting wires (5) has an outer region (7) of curvature which is matched to the polygonal or circular inner cross-section of the outer tube (2) and an inner region (8) of curvature which is matched to the circular cross-section of the cooling channel (4), and the cross-sectional profile has side edges (9, 10) which are oriented profiled towards the centre-point (11) of the cooling channel (4), the profiled superconducting wires (5) being arranged on the inner wall (3) of the outer tube (2), and the inner regions (8) of the profiled superconducting wires (5) forming the cooling channel (4) of the superconducting hollow cable (1).

The superconducting hollow cable can be characterised in that the profiled superconducting wires (5) are arranged so tightly on the inner wall (3) of the outer tube (2) of the superconducting hollow cable (1) by means of their outer regions (7) of curvature and with their radially oriented side edges (9, 10) adjacent to one another that at all operating temperatures of the superconducting hollow cable (1) they maintain a central cooling channel (4) with their inner regions (8) of curvature.

This superconducting hollow cable can be characterised in that the sum of gap widths (s) of possible radial gap formations between the profiled superconducting wires (5) is, at all operating temperatures of the superconducting hollow cable (1), smaller than the difference in length (Δl) between the outer (7) and inner (8) regions of curvature of an individual profiled superconducting wire.

Furthermore, the superconducting hollow cable can be characterised in that the profiled superconducting wires (5) have intermeshing profiled side edges (12, 13).

Furthermore, the superconducting hollow cable can be characterised in that the profiled superconducting wires (5) have special surface coatings or partial high-resistance jacketing means in order to reduce eddy current effects and thermal losses.

- 12 -

Furthermore, the superconducting hollow cable can be characterised in that the profiled superconducting wires (5) are twisted around the central cooling channel.

Furthermore, the superconducting hollow cable can be characterised in that the profiled superconducting wires (5) have ceramic superconductors or high-temperature superconductors.

Furthermore, the superconducting hollow cable can be characterised in that the outer tube (2) has a circular, square or trapezoidal external contour (17).

Furthermore, the superconducting hollow cable can be characterised in that the outer tube (2) comprises cooling channels (18) in its longitudinal direction.

Furthermore, the superconducting hollow cable can be characterised in that the coefficient of thermal expansion of the material of a compact outer tube (2) is greater than the coefficient of thermal expansion of the profiled superconductors (5).

In accordance with a further embodiment, the invention relates also to a method of producing a superconducting hollow cable (1), which comprises the following method steps:

- producing an outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3);
- producing profiled superconducting wires (5) having a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults, the cross-sectional profile of the profiled superconducting wires (5) having an outer region (7) of curvature which is matched to the circular inner cross-section of the outer tube (2) and having an inner region (8) which is matched to the polygonal or circular cross-section of a central cooling channel (4), and the cross-sectional profile having side edges (9, 10) which are oriented profiled towards the centre-point (11) of a cooling channel (4) to be formed;
- bringing together the profiled superconducting wires (5) to form a longitudinally extended circular bundle (28) around a central cooling channel (4);
- drawing the circular bundle (28) having a central cooling channel (4) into the outer tube (2).

In accordance with a further embodiment, the invention relates also to a method of producing a superconducting hollow cable (1), which comprises the following method steps:

- producing profiled superconducting wires (5) having a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults, the cross-sectional profile of the profiled superconducting wires (5) having an outer region (7) of curvature which is matched to the circular inner cross-section of the outer tube (2) and having an inner region (8) which is matched to the polygonal or circular cross-section of a central cooling channel (4), and the cross-sectional profile having side edges (9, 10) which are oriented profiled towards the centre-point (11) of a cooling channel (4) to be formed;
- bringing together the profiled superconducting wires (5) to form a longitudinally extended circular bundle (28) around a central cooling channel (4);
- winding at least one tensioning wire around the bundle in a helical arrangement;
- covering the wound-around tensioning wire with an electrically insulating and hermetically sealing outer layer of the superconducting hollow cable.

In accordance with a further embodiment, the invention relates also to a method of producing a superconducting hollow cable (1), which comprises the following method steps:

- producing two half-shells of a compact outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3);
- producing profiled superconducting wires (5) having a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults, the cross-sectional profile of the profiled superconducting wires (5) having an outer region (7) of curvature which is matched to the circular inner cross-section of the outer tube (2) and having an inner region (8) which is matched to the polygonal or circular cross-section of a central cooling channel (4), and the cross-sectional profile having side edges (9, 10) which are oriented profiled towards the centre-point (11) of a cooling channel (4) to be formed;
- bringing together the profiled superconducting wires (5) to form a longitudinally extended circular bundle (28) around a central cooling channel (4);

- 14 -

- bringing together the half-shells, with the bundle lying inside, to form a compact outer tube of the superconducting hollow cable.

Those methods of producing profiled superconducting wires for a superconducting hollow cable can comprise the following method step:

- profiling the round standard shape of superconducting wires (5).

Profiling of the wire can be accomplished by means of profile rollers.

Furthermore, profiling of the wire can be accomplished by means of a profile block.

Furthermore, profiling of the wire can be accomplished by means of reshaping forging.

Furthermore, an additional partial jacketing of the profiled superconducting wires by means of metal coating can be provided.

Brief Description of the Drawings

The invention will now be explained in greater detail with reference to the accompanying Figures.

Figure 1 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to a first embodiment of the invention;

Figure 2 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to a second embodiment of the invention;

Figure 3 shows a cross-section, in diagrammatic form, through a detail of the superconducting hollow cable according to Figure 2;

Figure 4 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to a third embodiment of the invention;

Figure 5 shows a cross-section, in diagrammatic form, through the initial form of a superconducting wire before being provided with profiling;

- 15 -

- Figure 6 shows a cross-section, in diagrammatic form, through a profiled superconducting wire after being provided with a profiled shape for a superconducting hollow cable of the first embodiment of the invention according to Figure 1;
- Figure 7 shows a cross-section, in diagrammatic form, through a profiled superconducting wire after being provided with a profiled shape for a superconducting cable of the second embodiment of the invention according to Figure 2;
- Figure 8 shows a cross-section, in diagrammatic form, through a profiled superconductor after being provided with a profiled shape for a superconducting hollow conductor cable of the third embodiment of the invention;
- Figure 9 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to a fourth embodiment of the invention;
- Figure 10 shows the cross-section, in diagrammatic form, through two variants of a superconducting hollow cable according to a fifth embodiment of the invention;
- Figure 11 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to a sixth embodiment of the invention;
- Figure 12 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to a seventh embodiment of the invention;
- Figure 13 shows a cross-section, in diagrammatic form, through a superconducting hollow cable according to an eighth embodiment of the invention;
- Figure 14 shows, as Figure 14a, a photograph and, as Figure 14 b, a drawing, in diagrammatic form, of a superconducting hollow cable of the CICC type in a standard arrangement
- Figure 15 shows, as Figure 15 a, a photograph and, as Figure 15 b, a cross-section, in diagrammatic form, through a superconducting hollow cable of the CICC type according to the prior art (POLO cable).

- 16 -

Figure 16 shows, as Figure 16 a, a photograph and, as Figure 16 b, a drawing, in diagrammatic form, of a superconducting cable of the Nuclotron type in a standard arrangement.

Figure 17 shows a cross-section, in diagrammatic form, through a superconducting hollow cable of the Nuclotron type in an improved arrangement.

Detailed Description of Preferred Embodiments

Figure 1 shows a cross-section, in diagrammatic form, through a superconducting hollow cable 1 according to a first embodiment of the invention. This hollow cable 1 has a central cooling channel 4, which is surrounded by profiled superconducting wires 5, which are usually twisted multifilament wires. In the cross-section shown here, these profiled superconducting wires 5 form a ring directly surrounding the central cooling channel 4 so that those profiled superconducting wires can be intensively cooled by the coolant stream. The profiled superconducting wires 5 are held together by a solidly constructed outer tube 2, which has an inner wall 3, against which the profiled superconducting wires 5 are in close abutment. The profiled superconducting wires 5 have a cross-section which corresponds to a key stone of a Roman bridge and/or of a Gothic vault.

This profile has an outer region 7 of curvature which is matched to the curvature of the inner wall 3 of the outer tube 2. Furthermore, the cross-section of the profiled superconducting wires 5 has an inner region 8 of curvature which is matched to the curvature of the central cooling channel 4. In this first embodiment of the invention, the profiled superconducting wires 5 have smooth side edges 9 and 10 which are oriented towards the centre-point 11 of the central cooling channel 4. The gap width s between side edges of adjacent superconducting wires 5 cannot be as large as may be desired because otherwise the annular structure of the profiled superconducting wires 5 and, as a result, the cooling channel 4 in operation is destroyed. The sum $n \cdot s$ of all gap widths s must therefore be less than the difference in length Δl of the curvature length l_{ak} of the outer region 7 of curvature minus the curvature length l_{ik} of the inner region 8 of curvature of the profile of the profiled superconducting wires 5.

Because twenty profiled superconducting wires 5 are provided in this first embodiment of the invention, the gap width s that can be tolerated between the side edges of adjacent superconducting wires 5 is extremely limited. Also, this limitation is not least dependent on the

- 17 -

difference between the inner radius r_a of the outer tube 2 and the inner radius r_i of the cooling channel 4, as explained in the formulae hereinbefore. A superconducting hollow cable 1 of such a kind has the advantage that the resistance to flow within the cooling channel 4 is extremely low and, as a result, a high cooling rate and high mechanical stability can be achieved. It furthermore has the advantage that the cooling medium directly contacts the profiled superconducting wires 5 and, accordingly, intensive cooling is ensured even for short heat pulses. Finally, this hollow cable has the advantage that it is made up of substantially only two layers or components: namely the concentric bundle of key-stone-shaped profiled superconducting wires 5 and the solidly constructed outer tube 2. Further thereto, for the purpose of (additional) electrical insulation, this superconducting hollow cable 1 according to the invention can have a Kapton tape wound around the external contour 17 of the outer tube 2 and, if necessary, further electrically insulating layers, for example of fibreglass tapes. This applies to all the variants corresponding to Figs. 1, 2, 4, 9, 10, 11 and 12.

The hollow cable 1 of the second embodiment differs from the hollow cable 1 of the first embodiment in the profiling of the profiled superconducting wires 5. In addition to the key stone shape, these profiled superconducting wires 5 have an offset of magnitude v , which additionally improves the intermeshing of the profiled superconducting wires 5 and allows larger gap widths s between the adjacent profiled side edges 12 and 13 of these profiled superconducting wires 5. The relationship between the possible gap width s and the difference in length Δl between the outer and inner regions of curvature and the magnitude v of the offset has already been discussed in detail hereinbefore.

Figure 3 shows a cross-section, in diagrammatic form, through a detail of the superconducting hollow cable 1 according to Figure 2. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. Figure 3 shows, to an enlarged scale, the intermeshing of the profiled superconducting wires 5 by means of the offset 19 of adjacent profiled side edges 12 and 13.

Figure 4 shows a cross-section, in diagrammatic form, through a superconducting hollow cable 1 according to a third embodiment of the invention. This third embodiment of the invention differs from the preceding embodiments in that the number of profiled superconducting wires 5 has been reduced from twenty in Figures 1 and 2 to ten in Figure 4. The intermeshing of the profiled superconducting wires 5 is enhanced by means of the fact that the superconducting

- 18 -

wires 5 have pointed profiles 20 on their profiled side edges 12 and 13. These pointed profiles 20 form an offset of magnitude v , which in co-operation with the difference in length Δl between the outer and inner regions 7 and 8 of curvature of the cross-sections of the profiled superconducting wires 5 increases the tolerance for the gap width s , so that a higher tolerance with respect to gap widths s that are formed can be permitted without the structure of the superconducting wires 5 arranged inside the outer tube 2 collapsing.

Figure 5 shows a cross-section, in diagrammatic form, through a superconducting multifilament wire in a standard arrangement. Such wires have a circular cross-section and comprise, as described hereinbefore, twisted superconducting filaments in a more or less complex Cu matrix.

Figure 6 shows a cross-section, in diagrammatic form, through a profiled superconducting wire 5 after being provided with a profiled shape for a superconducting hollow cable 1 of the first embodiment of the invention according to Figure 1. In the course of being provided with that shape, a wire according to Figure 5 is rolled, using different roller profiles, so that there are formed, on the one hand, an outer region 7 of curvature and, on the other hand, an inner region 8 of curvature. Furthermore, the side edges 9 and 10 are rolled by means of rollers set at an appropriate angle to one another. Instead of a rolling mechanism, drawing through an appropriate shape-providing drawing die can also be employed. In the case of this method, the round wire shown in Figure 5 is re-shaped into a profiled superconducting wire 5 having a cross-section governed by the drawing die.

Figure 7 shows a cross-section, in diagrammatic form, through a profiled superconducting wire 5 after being provided with a profiled shape for a superconducting cable 1 of the second embodiment of the invention according to Figure 2. Instead of smooth side edges as are still shown in Figure 6, in the case of this profiling profiled side edges 12 and 13 are shaped or drawn through a drawing block. In the process there are formed stepped shoulders 19, which make possible intermeshing of the profiled superconducting wires 5 when the hollow cable is assembled.

Figure 8 shows a cross-section, in diagrammatic form, through a profiled superconducting wire 5 after being provided with a profiled shape for a superconducting hollow cable 1 of the third embodiment of the invention according to Figure 4. This profile too, which has a profile

- 19 -

point 20 on the side edge 12, can be obtained by appropriate shaping of an initially circular cross-section as shown in Figure 5. For the purpose, either four differently shaping profile rollers or a drawing orifice of appropriate shape can be used in order to produce the four profile edges of the cross-section of the profiled superconducting wires 5. An advantage of these profiled superconducting wires 5 of Figure 8 over Figure 7 is that an outwardly bulging pointed profile 20 of the profiled side edge 12 is easier to produce by means of profile rollers than is possible for the profile having a stepped shoulder 19 of Figure 7 and that the intermeshing of those shapes contributes to the profiled superconducting wires' orienting themselves around the cooling channel.

Figure 9 shows a cross-section, in diagrammatic form, through a superconducting hollow conductor cable 1 according to a fourth embodiment of the invention. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. The difference from the preceding embodiments lies in the fact that, as the solidly constructed outer tube 2, there is selected an outer tube which, although having a cylindrical inner wall 3, has a square external contour 17, as a result of which, on the one hand, the strength of the outer tube 2 is increased and, on the other hand, the production of compact coils can be substantially simplified.

Figure 10 shows cross-sections, in diagrammatic form, through two variants of a superconducting hollow conductor cable 1 according to a fifth embodiment of the invention. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. The difference of this fifth embodiment of the invention differs from the preceding embodiments in that the outer tube 2 having a square external contour 17 has, in the corners of the square outer tube 2, additional cooling channels 18 in the longitudinal direction of the hollow cable 1. As a result, the cooling action can, as already described hereinbefore, be further intensified for this hollow cable 1.

Figure 11 shows a cross-section, in diagrammatic form, through a superconducting hollow conductor cable 1 according to a sixth embodiment of the invention, reference numeral 5 denoting profiled superconducting wires, reference numeral 2 denoting the outer tube and reference numeral 18 denoting cooling channels in the outer tube 2 in the longitudinal direction of the latter. By virtue of these outer cooling channels 18, which extend along the inner wall of the outer tube and which have an opening to the bundle of profiled superconducting wires, the

- 20 -

twisted profiled superconducting wires are accordingly additionally cooled from the outside in direct contact with the coolant after each quarter-turn of the helical displacement. In this variant too, all the wires are subject to absolutely identical electromagnetic, mechanical and thermal conditions.

Figure 12 shows a cross-section, in diagrammatic form, through a superconducting hollow conductor cable 1 according to a sixth embodiment of the invention. The sixth embodiment of the invention differs from the preceding embodiments in that the outer tube 2 has a trapezoidal external contour 17. This trapezoidal external contour 17 can be advantageous when a plurality of these superconducting hollow cables 1 are assembled into a circular coil or when specific coil geometries have to be produced in a mechanically compact manner and in as stable a manner as possible.

Figure 13 shows a cross-section, in diagrammatic form, through a superconducting hollow cable 1 according to an eighth embodiment of the invention. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. The outer tube in this case is formed from two layers: a first layer having a tensioning wire 33, for example of NiCr, wound in a helical arrangement, and an electrically insulating, hermetically sealing outer layer 34, for example produced by means of polymerisation. As already described hereinbefore, this eighth embodiment of the invention differs from the preceding embodiments in that, instead of a solidly constructed outer tube, jacketing of the profiled superconducting wires is accomplished by means of tensioning wire wound in a helical arrangement, to which an electrically insulating, hermetically tight outer layer is subsequently applied.

Figure 14 shows, as Figure 14a, a photograph and, as Figure 14 b, a drawing, in diagrammatic form, of a superconducting hollow cable of the CICC type in a standard arrangement. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. Figure 14 shows a bundle of twisted superconducting wires 30 running inside a hermetically tight tube 32.

Figure 15 shows, as Figure 15 a, a photograph and, as Figure 15 b, a cross-section, in diagrammatic form, through a superconducting hollow cable of the CICC type according to the prior art (POLO cable). Components having the same functions as in the preceding Figures are

- 21 -

identified by the same reference symbols and not separately discussed. In this case, superconducting wires 30 are arranged on a solidly constructed inner tube 21 as an inner supporting tube, the inner cooling channel being provided for a two-phase helium stream and the direct passage of supercritical helium between the superconducting wires 30 being possible with a high resistance to flow.

Figure 16 shows, as Figure 16 a, a photograph and, as Figure 16 b, a drawing, in diagrammatic form, of a superconducting cable of the Nuclotron type in a standard arrangement. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. Figure 16 shows, in a central cooling channel formed by a compact inner tube 21 of CuNi, two-phase helium 35 that is passed through therein. On the inner tube 21 there are wound superconducting wires 30, which are held together by an NiCr tensioning wire 33. A Kapton tape 24 forms electrical insulation and a fibreglass tape 25 serves for thermal insulation of the superconducting hollow cable.

Figure 17 shows a cross-section, in diagrammatic form, through a superconducting hollow cable 1 of the Nuclotron type in an improved arrangement. Components having the same functions as in the preceding Figures are identified by the same reference symbols and not separately discussed. Figure 17 shows a central cooling channel 4 formed by a compact inner tube 21 of CuNi. On the inner tube 21 there are wound profiled superconducting wires 5, which are held together by an NiCr tensioning wire. An electrically insulating, hermetically tight outer layer 34 is arranged on the tensioning wire 33.

List of reference symbols

1	superconducting hollow cable
2	outer tube
3	inner wall of outer tube
4	central cooling channel
5	profiled superconducting wire
6	superconducting filament
7	outer region of curvature
8	inner region of curvature
9	smooth side edge
10	smooth side edge
11	centre-point of cooling channel
12	profiled side edge
13	profiled side edge
14	superconducting filament
15	metallic core or centre of stabilising matrix of a superconducting multifilament conductor
16	jacket of the stabilising matrix of a superconducting multifilament conductor of a profiled wire
17	external contour of outer tube
18	cooling channels of the outer tube in a longitudinal direction
19	stepped shoulder (stepped profile)
20	pointed profile of a side edge
21	compact inner tube
24	Kapton tape
25	fibreglass tape
26	outer jacket of inner tube
27	inner wall of inner tube
28	bundle comprising superconducting filaments
29	wire from a bundle comprising superconducting filaments and stabilising matrix
30	superconducting wires
31	bundle of twisted superconducting wires

- 23 -

32	hermetically tight tube
33	tensioning wire wound in a helical arrangement
34	electrically insulating, hermetically sealing outer layer
35	two-phase helium
l_{ak}	length of outer region of curvature
l_{ik}	length of inner region of curvature
Δl	difference in length
s	gap width
v	magnitude of offset
n	number of profiled superconducting wires per superconducting hollow cable
r_a	inner radius of outer tube
r_i	radius of central cooling channel

Patent claims

1. Superconducting hollow cable (1) having the following features:

an outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3);

a central cooling channel (4) having a polygonal or circular cross-section which is smaller than the inner cross-section of the outer tube (2);

profiled superconducting wires (5) which are arranged between the inner wall (3) and the cooling channel (4) and which comprise at least one superconducting filament (6) and which have a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults,

the cross-sectional profile of the profiled superconducting wires (5) having an outer region (7) of curvature which is matched to the polygonal or circular inner cross-section of the outer tube (2), and the cross-sectional profile of the profiled superconducting wires (5) having side edges (9, 10) which are oriented towards the centre-point (11) of the cooling channel (4);

characterised in that

the profiled superconducting wires (5) are arranged on the inner wall (3) of the outer tube (2);

the cross-sectional profile of the profiled superconducting wires (5) has an inner region (8) of curvature which is matched to the circular cross-section of the cooling channel (4);

the profiled superconducting wires (5) form, by means of their inner regions (8) of curvature, the cylindrical cooling channel (4) of the superconducting hollow cable (1), said wires being arranged with their radially oriented side edges (9, 10) so tightly against one another and with their outer regions (7) of curvature so tightly on the inner wall of the outer tube (2) that they can hold themselves in position by means of a shape-based and force-based fit and maintain the cooling channel (4) at all operating temperatures of the superconducting hollow cable (1).

2. The superconducting hollow cable according to claim 1,

characterised in that

the sum of gap widths of radial gap formations between the profiled superconducting wires (5) is, at all operating temperatures of the superconducting hollow cable (1), smaller than the difference in length (Δl) between the outer (7) and inner (8) regions of curvature of an individual profiled superconducting wire.

- 25 -

3. The superconducting hollow cable according to claim 1,
characterised in that
the profiled superconducting wires (5) have intermeshing profiled side edges (12, 13).
4. The superconducting hollow cable according to claim 1 or 2,
characterised in that
the profiled superconducting wires (5) have special surface coatings or partial high-resistance jacketing means in order to reduce eddy current effects and thermal losses.
5. The superconducting hollow cable according to any one of claims 1 to 4,
characterised in that
the profiled superconducting wires (5) are twisted around the central cooling channel.
6. The superconducting hollow cable according to any one of claims 1 to 5,
characterised in that
the profiled superconducting wires (5) have ceramic superconductors or high-temperature superconductors.
7. The superconducting hollow cable according to any one of claims 1 to 6,
characterised in that
the outer tube (2) has a circular, square or trapezoidal external contour (17).
8. The superconducting hollow cable according to any one of claims 1 to 7,
characterised in that
the outer tube (2) comprises cooling channels (18) in its longitudinal direction.
9. The superconducting hollow cable according to any one of claims 1 to 8,
characterised in that
the coefficient of thermal expansion of the material of a compact outer tube (2) is greater than the coefficient of thermal expansion of the profiled superconductors (5).

- 26 -

10. Method of producing a superconducting hollow cable (1), which comprises the following method steps:

producing profiled superconducting wires (5) having a cross-sectional profile of a key stone as known for Roman stone bridges or for groin vaults, the cross-sectional profile of the profiled superconducting wires (5) having an outer region (7) of curvature and having an inner region (8) which is matched to a polygonal or circular cross-section of a central cooling channel (4), and the cross-sectional profile having side edges (9, 10) which are oriented towards the centre-point (11) of a cooling channel (4) to be formed by the inner regions (8);

bringing together the profiled superconducting wires (5) to form a longitudinally extended circular bundle (28), the side edges (9, 10) of the adjacent profiled superconducting wires (5) lying against one another and the inner regions (8) thereof forming a central cooling channel (4);

and, alternatively:

drawing the circular bundle (28) having the central cooling channel (4) into an outer tube (2)

or

bringing together two half-shells of a compact outer tube (2) having a circular inner cross-section and a cylindrical inner wall (3), with the bundle (28) lying inside, to form a compact outer tube of the superconducting hollow cable.

11. The method according to claim 10,

characterised in that

at least one tensioning wire is wound around the bundle (28) in a helical arrangement and the wound-around tensioning wire is covered with an electrically insulating and hermetically sealing outer layer of the superconducting hollow cable before bringing together the half-shells forming the outer tube.

12. The method of producing profiled superconducting wires for a superconducting hollow cable, according to claim 10 or 11, which comprises the following method step:

profiling the round standard shape of superconducting wires (5).

13. The method according to claim 12,

characterised in that

profiling of the wire is accomplished by means of profile rollers.

- 27 -

14. The method according to claim 12,
characterised in that
profiling of the wire is accomplished by means of a profile block.
15. The method according to claim 12,
characterised in that
profiling of the wire is accomplished by means of reshaping forging.
16. The method according to any one of claims 10 to 15,
characterised in that
an additional partial jacketing of the profiled superconducting wires is accomplished by
means of metal coating.

Application number / numéro de demande: EP0504420

Figures: 3, 5, 6, 7, 8, 9, 10, 11, 14A, 15A-B, 16A-B,

Pages: _____

Unscannable item(s)

received with this application

To inquire if you can order a copy of the unscannable items, please visit the
CIPO WebSite at [HTTP://CIPO.GC.CA](http://CIPO.GC.CA)

Item(s) ne pouvant être balayés

Documents reçus avec cette demande ne pouvant être balayés.

Pour vous renseigner si vous pouvez commander une copie des items ne
pouvant être balayés, veuillez visiter le site web de l'OPIC au [HTTP://CIPO.GC.CA](http://CIPO.GC.CA)

FIG 1

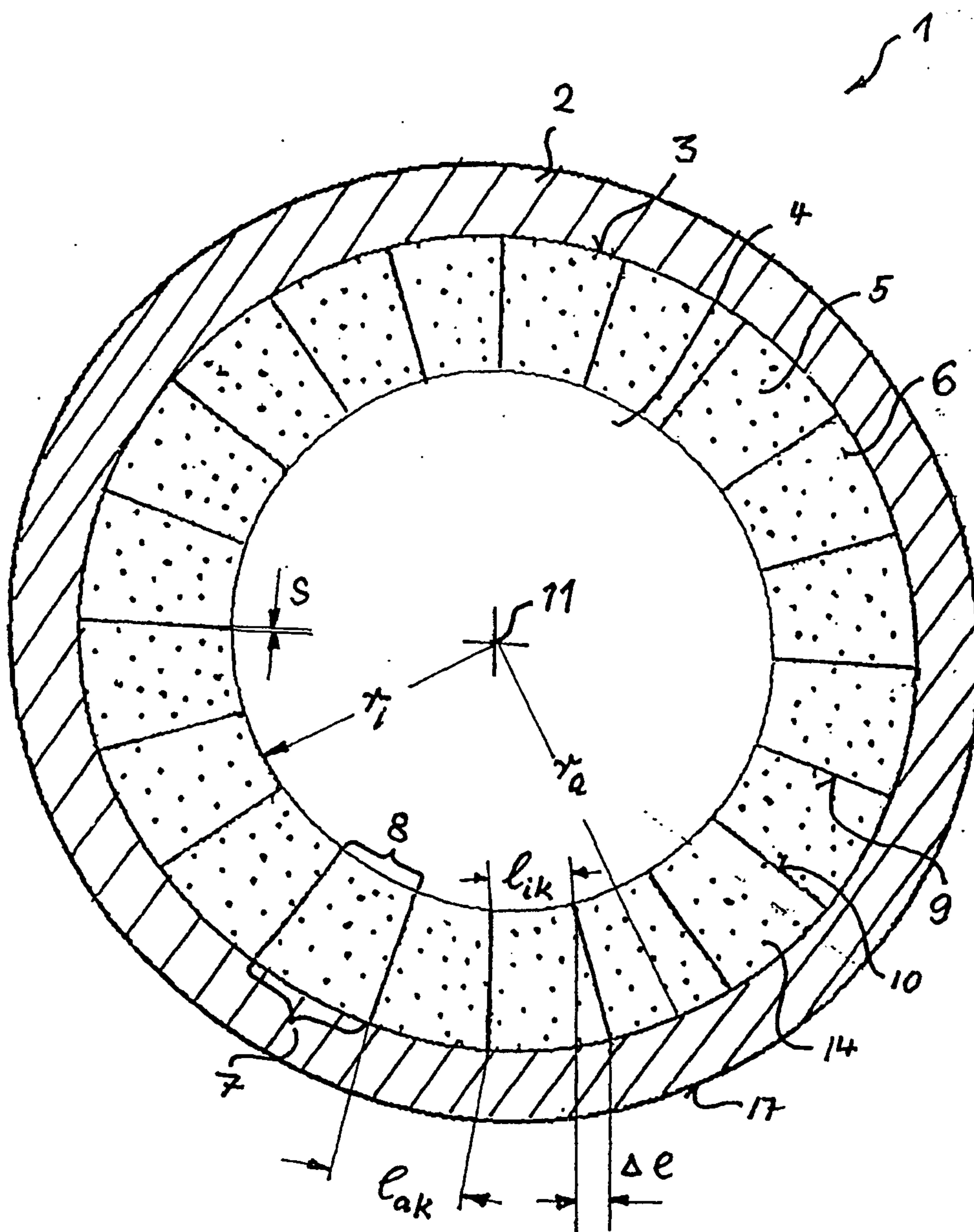


FIG 2

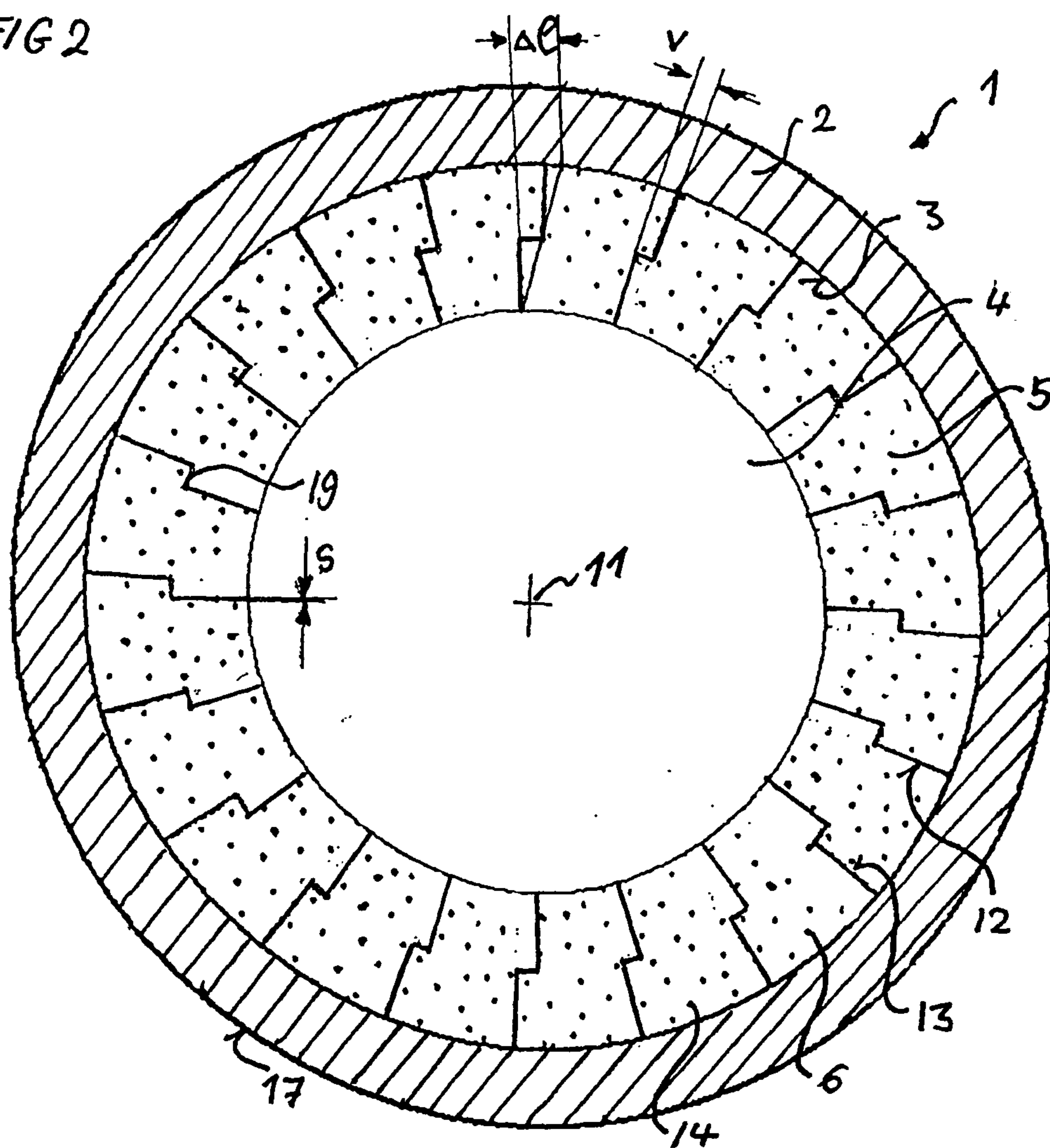


FIG 4

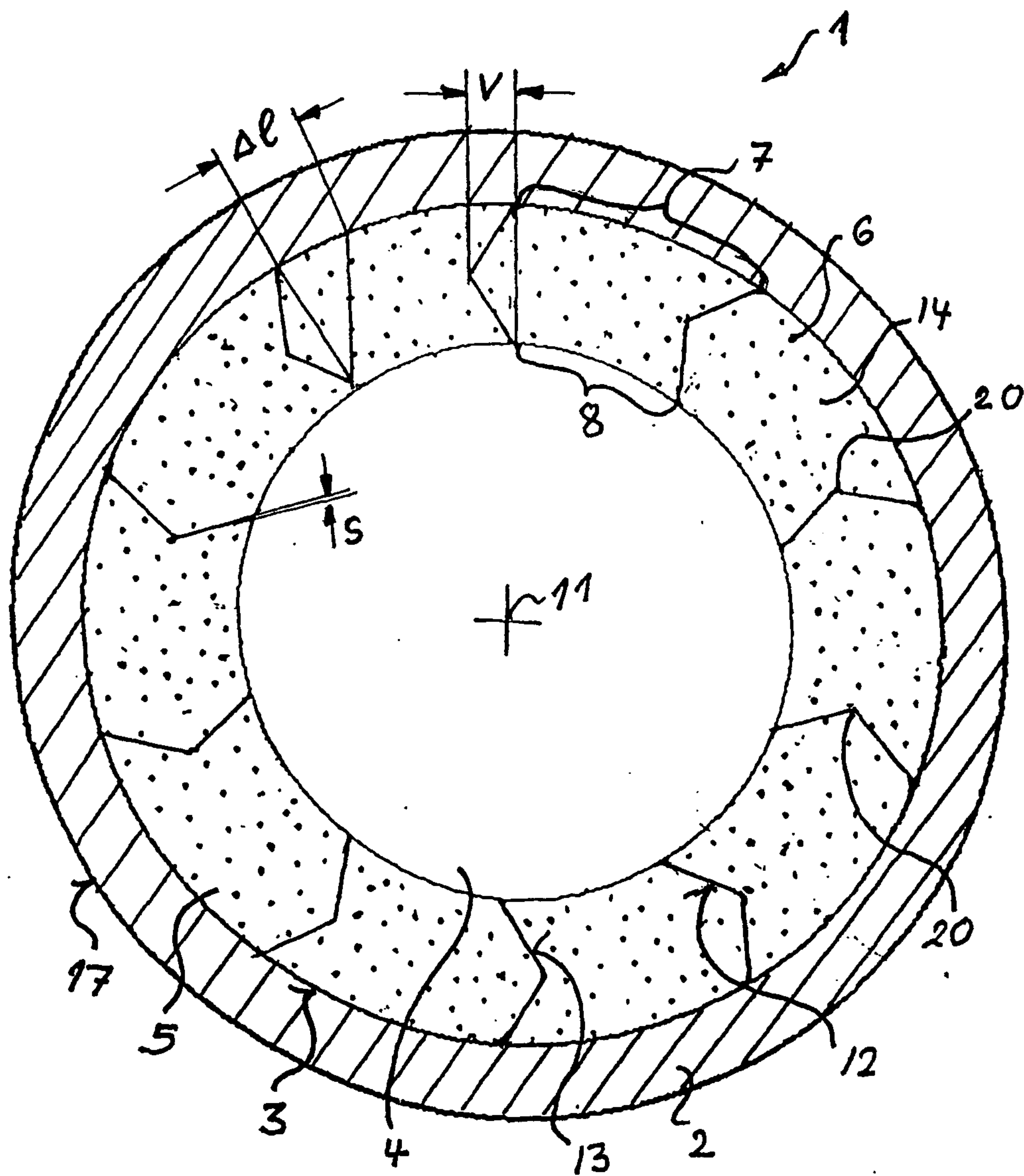
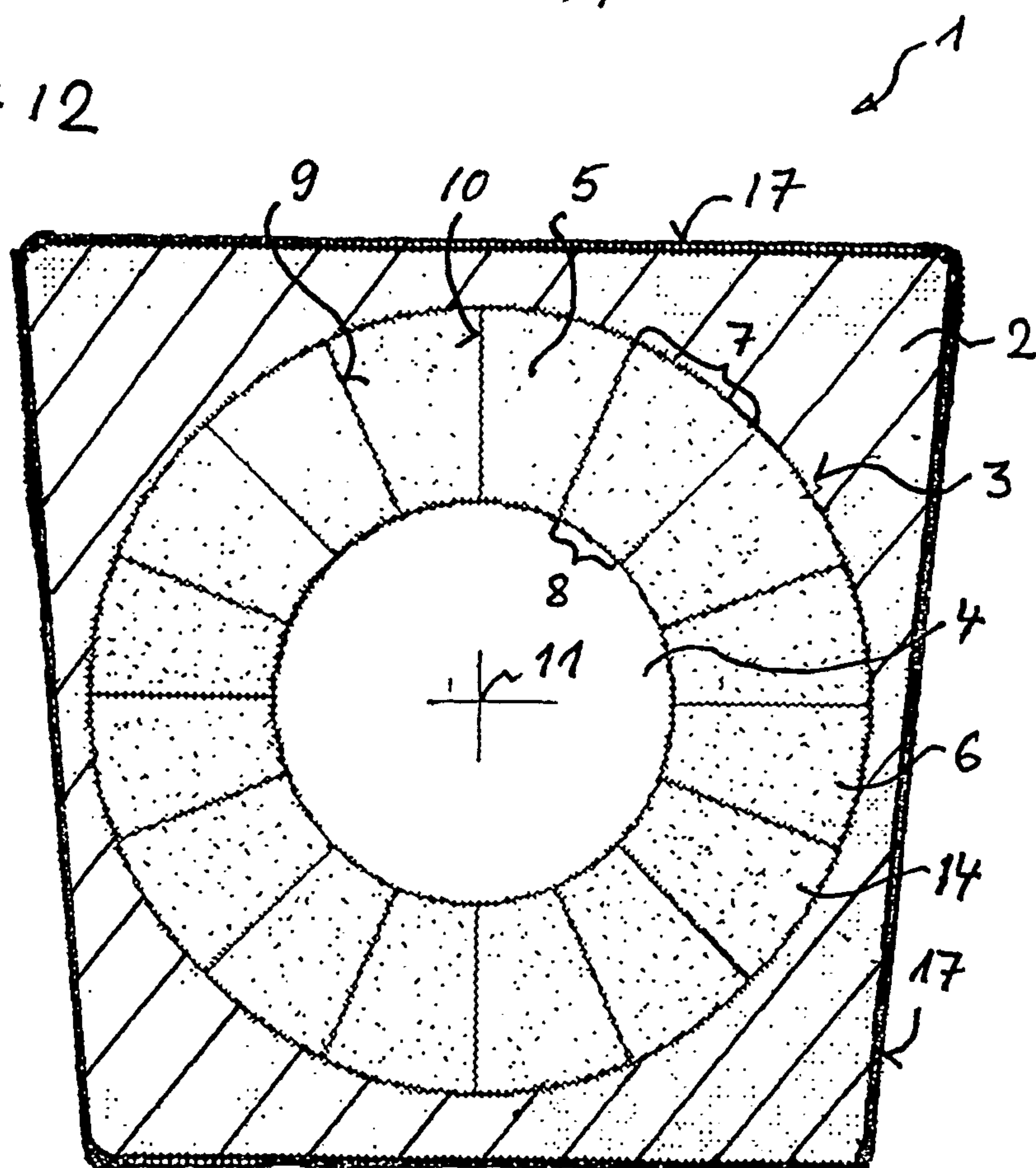


FIG 12



8/12

FIG 13

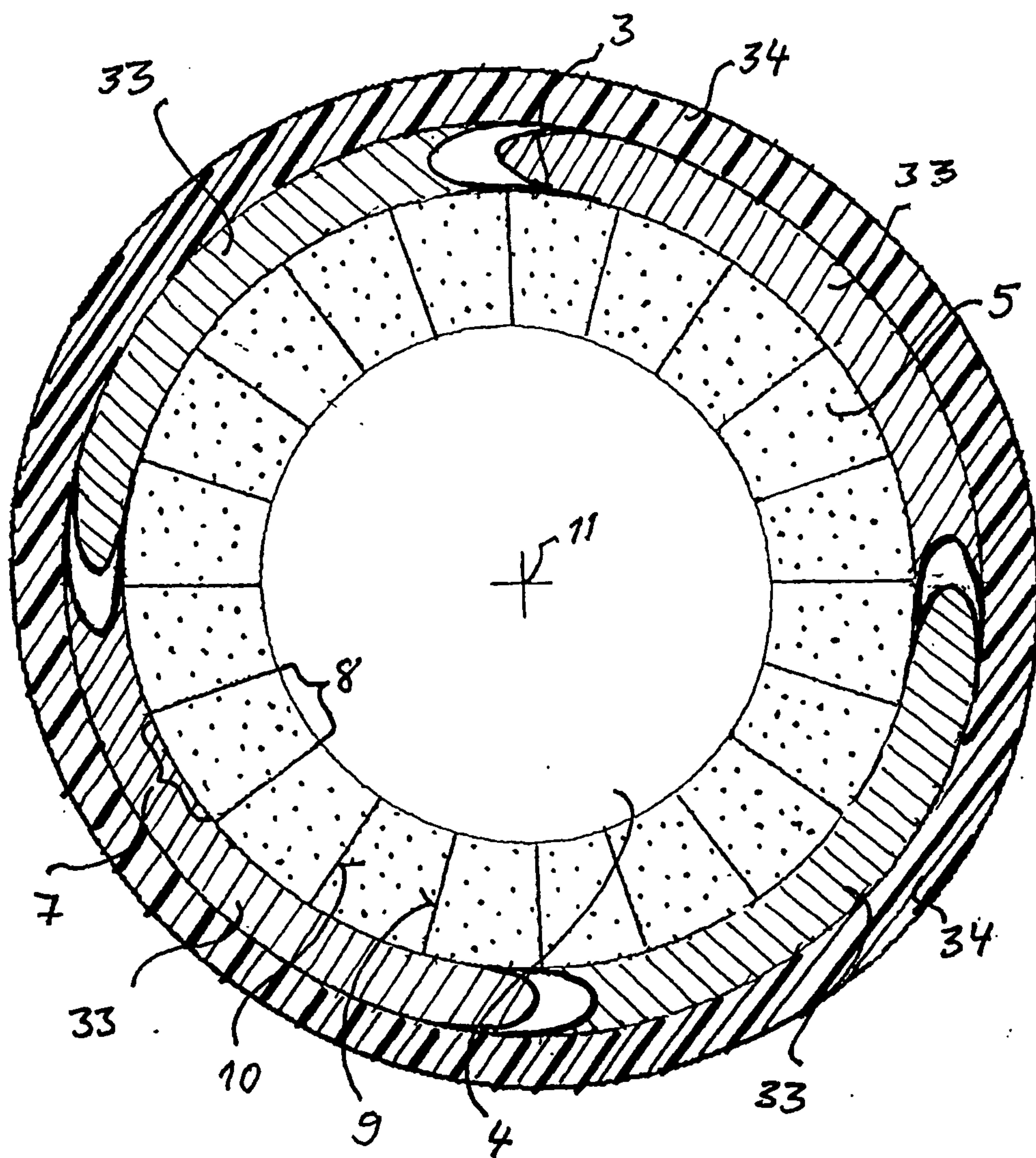
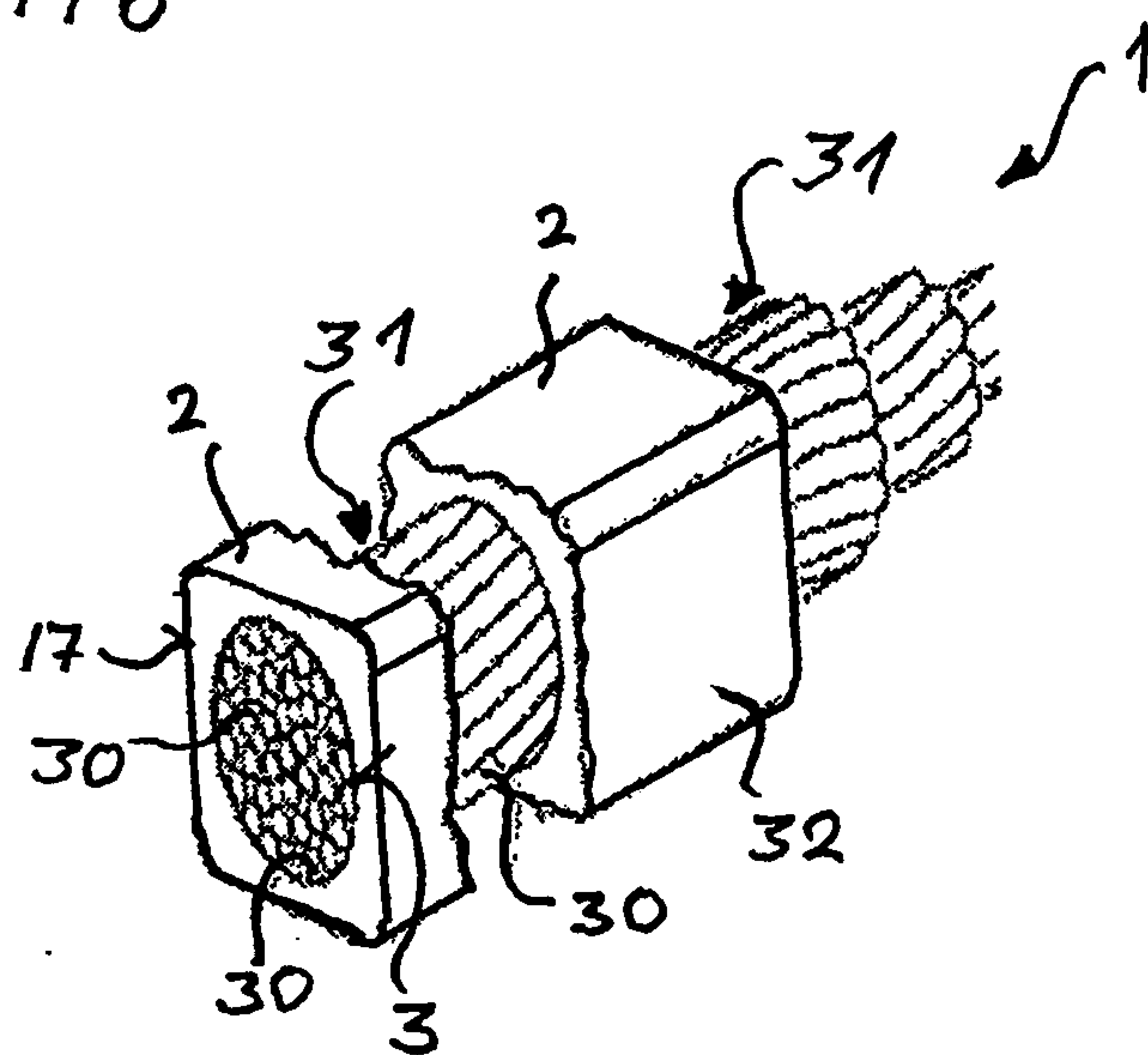


FIG 14b



12/12

FIG 17

