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(54) METHOD OF JOINING A SUPERCONDUCTOR

VERFAHREN ZUM VERBINDEN EINES SUPERLEITERS

PROCÉDÉ DE LIAISON D’UN SUPRACONDUCTEUR

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Description

Field of the Invention

[0001] The present invention relates to a method of joining a superconductor with another member.

Background to the Invention

[0002] Superconductors are used increasingly in a number of applications, in many cases due to their ability to carry very high current densities which in turn enables their use in extremely powerful magnets. A common application of such materials is in magnetic resonance imaging (MRI) apparatus. A number of different materials are known to possess superconducting behaviour. The most widely used are so called low temperature superconductors (LTS). These have superconducting transition temperatures below about 30 Kelvin in zero magnetic field and are commonly niobium-based. LTS materials are available as "wires" enabling their winding into magnet coils for example. High temperature superconductors (HTS), in contrast, are formed from more exotic materials, typically ceramics. They have a superconducting transition temperature above 77K which is critical technologically since this is a temperature at which liquid nitrogen may be used as a coolant at ambient pressure. HTS materials are, however, very fragile. They are generally produced as "tapes" having a multilayer structure in which a superconducting layer only a few micrometres thick is surrounded by other material layers to protect and stabilise the HTS material and allow it to be joined to other materials.

[0003] In applications which utilise superconductors it is extremely important to be able to join the superconductor to another member so as to form a joint which will bear the operational current of the superconductor reliably and without causing unmanageable resistive heating within the joint. In many applications such a joint is not superconducting, particularly if the member itself is an "ohmic" (resistive) conductor and for this reason it is desired to minimize the electrical impedance presented by the joint. This is achievable by a combination of the electrical resistance of the joint per unit area and the area of the joint in question. A lower resistance per unit area and/or a higher joint area allows a greater current to be used.

[0004] Such joints are conventionally formed by a solder-based process where a metallic material is heated above its melting point and then allowed to cool when in contact with each of the superconductor and the member to which the superconductor is to be joined. Such a process must be performed with great care since the heat applied during the soldering may damage the superconductor or member in question and cause oxidation of the joint surface area which will increase the interface resistance and reduce the 'wettability' or 'solderability' of the joint. Furthermore, whilst aggressive chemical fluxes are used in preparing the surface(s) to be joined, they may also damage the superconductor or member to be joined. If the joining process is not carefully controlled then there may be an impact upon the quality of the joint (corrosion) in terms of its long term viability or its electrical properties.

[0005] In the light of these practical difficulties, there remains a need to provide an improved process for forming an electrically conductive joint with a superconductor.

[0006] JP H10 275641 A provides an example of a soldering process for a superconductor performed at 220 degrees C. US 2005/082343 A1 discloses a method in which a reactive foil and a meltable joining material are disposed between two bodies. The bodies are pressed together and a self-propagating reaction is initiated in the foil to melt the joining material and join the bodies.

Summary of the Invention

[0007] In accordance with a first aspect of the present invention we provide a method according to claim 1.

[0008] We have realised that a superconductor may be joined to another member by the use of a reactive foil. Such foils represent a relatively new technology in which a stable multicomponent nanoscale structure is provided as a foil. Whilst the nanoscale components may be essentially particulate, the structure is typically a multi-layered foil, for example comprising numerous alternating layers according to a sequence (such as aluminium or nickel), each layer having a thickness of less than 1 micrometre. With the application of an appropriate stimulus (such as a localised heat source) these components undergo a rapid exothermic reaction producing an intense localised heat source which is capable of melting adjacent materials, particularly metallic materials. In general, the reaction causes the localised melting of the joining material so as to join the first and second bonding surfaces upon subsequent solidification of the joining material. Depending upon the thickness of the joining material and the heat energy available some melting of the first and/or the second bonding surfaces themselves may occur.

[0009] The joining material itself typically provides the mechanical and electrical connection between the components. The joining material may be provided in a number of different locations and adopt different forms. For example, the joining material may be integral with the reactive foil. Such a foil may be obtained from a supplier already bearing a desired layer of joining material. Alternatively, or in addition, the joining material may be applied to an obtained foil. It will be understood that, advantageously, the reactive foil is generally planar having opposing sides and wherein one or each of the said opposing sides is provided with the joining material. This is a convenient arrangement which ensures that joining material is placed in close proximity to the first and second bonding surfaces at the time of the reaction.

[0010] The joining material may also be integral with one or each of the first superconductor or member. In each use case where the material is integral with a component (superconductor, member, foil) it is preferably applied as a surface layer (either continuous or in regions). Thus it may be applied to the first bonding surface and/or the second bonding surface. Different combinations of joining material locations are contemplated for the joints. Typically more than one layer of joining material is provided. These may be positioned to one side of the foil or to each side. In some examples a joining material is applied to each of the four surfaces to be abutted. In many cases a common material may be used for each instance of the joining material although different joining materials may be provided depending upon their wetting or bonding behaviour with their respective component to which they are attached.

[0011] The joining material is preferably applied by a low thermal input or room temperature process such as an electroplating process. Other processes are contemplated, particularly regarding the foil since this may be placed more readily in coating or deposition equipment for example (e.g. thin film deposition by sputtering or evaporation). Processes which include localised heating may also be used, particularly if the component to be coated has a low thermal mass, such as the foil or a superconducting tape. These thermal processes include the application of the joining material using a hot plate or soldering iron to heat the object in question, although in these cases such processes are performed upon the object separately and prior to being placed within any jointing configuration.

[0012] In addition or as an alternative to providing the joining material attached to another member, it is also contemplated that the joining material may be provided independently in the form of a separate foil or preform. The use of a separate foil of joining material may simplify the method, although in many practical situations it is preferred to provide such a foil in addition to other joining material so as to increase the thickness of the liquid layer of joining material present during the reaction.

[0013] Whilst a number of different objects may be used as the member, including current terminals, in a number of technologically advantageous examples the member comprises a second superconductor. It will be understood that the method applies to superconductors of any type, specifically including low temperature superconductors (LTS) and high temperature superconductors (HTS). High temperature superconductors are typically provided as tapes or cables and these are particularly suitable for use since they have metal clad planar surfaces in the case of HTS and are particularly difficult to join using other methods (due to the use of chemical fluxes for example).

[0014] Furthermore it will be understood that the superconductors discussed herein may include superconductors encapsulated with an outer layer of a "normal" (conventional) conductor such as copper, silver or tin. Likewise the members may be superconductors, and these may also be encapsulated in a similar manner. One or each of the first and second bonding surfaces may therefore be a surface of a superconductor material or, in the case of encapsulation, a surface of conventional conductor material (which encapsulates a superconductor material).

[0015] The joining material and operational temperatures of the joint cause the joint to be electrically resistive when in use. Examples of suitable joining materials are those with a material, an alloy, or mixture comprising a material, selected from the group comprising: gold, silver, tin, copper, indium, titanium, a tin-silver eutectic mixture, a tin-lead eutectic mixture, a silver-copper eutectic mixture or a gold-tin eutectic mixture. It will be understood that other metallic joining materials may be used, either in elemental or alloyed form. In case a multielement joining material is used these may be manufactured by depositing a multilayer thin film of the constituents onto the member or superconductor.

[0016] The positioning of the foil with respect to the first and second bonding surfaces is a function of the desired joint configuration and the relative position of the first superconductor and member. In most cases the reactive foil is positioned sandwiched between the first bonding surface and second bonding surface, prior to undergoing the reaction. In order to improve the contact area and the electrical properties of the joint, the method preferably further comprises forcing the reactive foil against each of the first and second bonding surfaces, with the joining material positioned suitably within such a sandwiched structure. To improve the quality of the joint all joint surfaces are preferably flat and parallel.

[0017] A particular advantage of the method is that it is generally performed without any form of pre-heating of the first superconductor or member when in a joining configuration. Thus typically each of the first superconductor and the member is at room temperature at the time of initiating the reaction in the reactive foil. This avoids the need to heat the components and also reduces oxidation. The joint surfaces are typically cleaned and surface oxides removed just prior to forming the joint. Due to the slower reaction speed of the joint surfaces at room temperature the joint can be completed before reoxidation occurs. A further advantage follows in that the use of the reactive foil therefore generally allows the method to be a fluxless joining method. These advantages allow for greater flexibility in the circumstances in which the method may be used. One example is in the joining of a first superconductor to a second superconductor in a "winding pack" of a magnet. Conventionally such a joint, which may be required as part of a repair, requires significant lengths of superconductor to be removed from the winding pack and joined externally. However, the present flux-less room temperature procedure may be performed so as to produce an *in situ* joint between superconductors, with the joining method itself being performed in the winding pack. The improved electrical properties of the joint in comparison with known methods allows physically smaller joints to be produced which may be more easily accommodated within a winding pack of a magnet. For example the dimension of the interface between the first bonding surface and the second bonding surface when joined may be less than 4 mm. Whereas small joint areas may have an advantage for some applications, other applications require larger joint areas. In practice the scaling up of the joint area in conventional soldering processes becomes more difficult whereas the same scaling up process using the present concept is simpler and more reproducible thereby allowing extremely low contact resistance joints to be manufactured (the applicants have demonstrated a reproducibility of +/- 7.3%).

[0018] Such joints are preferably capable of bearing an operational electrical current in excess of the critical current of the superconductor while maintaining a resistance of typically less than less than 150 nanoOhm x cm^2 at 77 Kelvin. Such joints are designed to be operated in a cryogenic environment and typically cycled between room temperature and the cryogenic environment.

[0019] A further advantage of the present invention is the ability to react the joint in any orientation: horizontal, vertical or any other orientation. This is because the reaction to form the joint is completed in typically less than a few milliseconds and the liquid metal solidifies instantly. This is particularly important for large members with a weight of several hundreds of kilogrammes which may be difficult to manipulate and therefore can only be joined in-situ.

Brief Description of the Drawings

[0020] Some examples of a method of joining a superconductor are now described with reference to the accompanying drawings, in which:

Figure 1 is a flow diagram of a first example method;
Figure 2 shows the separated components to be joined according to the first example;
Figure 3 shows the components of the first example prior to the reaction;
Figure 4 shows the resultant joint formed according to the first example;
Figure 5 shows a flow diagram of a second example method;
Figure 6 shows the arrangement of the components of the second example prior to the reaction; and,
Figure 7 shows a joint according to a third example as an extension of the second example.

Description of Preferred Examples

[0021] We now describe a number of examples of methods of forming joints with superconductors, according to the invention. Common to these is the concept of the use of reactive foil which acts as a heat source to bond the superconductor with another member (which may itself be a superconductor). The foil is typically 40 to 120 micrometres thick and, when activated, it creates a self-sustaining exothermic reaction that acts as a rapid and controllable localised heat source to melt adjacent layers (these being typically solder layers) thereby bonding the superconductor to the member in question without the need of either flux or other heat sources.

[0022] In conventional solder-based joining, whilst solder contacts according to known methods are generally good as point contacts for joints, as the joint area is increased, this technique has to be adapted to give satisfactory results. This can be a problem when large contact areas have to be joined, these having a low electrical contact resistance. In the first example below we describe a joint between a copper terminal block with a large thermal mass adapted to carry large currents (typically >500A) and a superconducting HTS tape comprising HTS material sandwiched between copper foils (typically 0.1mm thick, 12mm wide with a joint length of 50-90mm, but in principle this can vary from 1mm up to 1000mm or more. In the conventional process for making such a joint, the components which are to be joined are heated up, treated with flux and tinned with solder. Due to the large thermal mass of the copper terminal this process requires a large heat input which in turn causes surface oxidation of the components and as a result makes wetting with solder difficult even when flux is used or results in flux residue to be incorporated in the joint forming voids. Handling these hot components while aligning them during assembly can also be challenging. The issues which are fundamental to the conventional process have led to a low yield and variability in the joint quality with contact resistance in the range from 80 nanoOhms to 10 microOhms for this type of joint. This increases the risk of hot spots in systems which have multiple joints.

[0023] The first example process is now described in association with the flow diagram of Figure 1. This example process is for joining an HTS tape to an ohmically conductive copper terminal and is illustrated further with reference to Figures 2 to 4. Firstly at step 100 of Figure 1 an electrically conductive member in the form of a copper terminal 1 is obtained. This is then electroplated with a joining layer 5 of tin at step 110, at least in a region which is to form an electrical joint.

[0024] Separately, a length of HTS tape 2 is obtained at step 120. As will be understood HTS tape is a multilayered structure comprising a thin film of superconducting material such as YBCO (Yttrium Barium Copper Oxide) which is supported on a substrate with intervening buffer layers. Whilst other layers may be present, for the purposes of the present discussion it is sufficient to understand that the external layers (upper and lower) are formed from copper. A typical thickness of the tape structure is about 100 micrometres.

[0025] Having obtained the HTS at step 120, a region of the external copper "cladding" is exposed and cleaned. A joining layer of tin 6 is then applied at step 130, again, in a region which is to form an electrical joint with the copper terminal 1; this is typically across the full width of the tape and of a predetermined length, such as 60 mm). This layer may be electroplated on to the copper layer of the HTS. An alternative technique is to heat that HTS material to above the melting point of tin and then apply the tin material lightly to the surface to be coated.

[0026] At step 140 the HTS 2 and copper terminal 1 are then arranged in a joining configuration within a mechanical press. In the joining configuration (shown in Figure 2; the mechanical press being omitted) the layers 5 and 6 are arranged to face each other. During this step a length of reactive multilayer foil 3 is positioned "sandwiched" between the opposing layers 5 and 6.

[0027] The reactive multilayer foil 3 is manufactured by a thin film deposition process (sputtering in this case) creating hundreds of thin layers of its constituent metals. When activated by a small electrical, laser or heat pulse the multilayer structure (for example Ni(V):Al foils) transforms to an ordered intermetallic, Ni(V)Al. During the transformation process from the layered metal foil to the ordered structure, energy is released as heat. An example of such a foil 3 is available from Indium Corporation.

[0028] In the present example the foil 3 is supplied in a generally planar or sheet form with each of its parallel surfaces covered with a 10 micrometre thick layer of tin, denoted 7,8 respectively in Figure 2. The foil 3 has a thickness in this case of about 40 micrometres and is pre-cut in its other two dimensions to have dimensions which match the width of the HTS 2 (in this case around 12mm and a length being the desired length of the join, such as 50 mm).

[0029] Once correctly aligned and located, the mechanical press is used to apply a pressure at step 150 so as to compress the copper terminal 1, foil 3 and HTS 2 together. This is illustrated in Figure 3. This brings layer 5 into contact with layer 7, and layer 6 into contact with layer 8. The applied pressure ensures that the HTS 2 and foil 3 are in a flat configuration so as to maximise the contact area between the pairs of layers 5,7 and 6,8. A typical pressure of 2-10 bar (200 kPa to 1MPa) is applied by the pneumatic actuator. Once stabilised and under the applied pressure within the mechanical press the foil reaction is initiated at step 160.

[0030] The reaction of the foil is initiated at an edge of the foil 3 with the use of a spark, provided for example using a small 9 volt battery. The 40 micrometre thick foil 3 releases 23-25 J/cm^2 of energy. At step 170 this energy from the reaction within the foil 3 produces a very high temperature (up to 1500°C) as the foil disintegrates into microscopic reaction products. A further advantage is that the reaction may be initiated at a convenient point or corner of the foil. A chain reaction is initiated at this point and the reaction front propagates with a fast reaction velocity following along the path of the foil in a straight line or even around corners. The reaction is typically complete in a few milliseconds. During this process the two layers of tin 7,8 which are bonded to the foil 3 melt due to the local heating. Similarly the heating is sufficient to melt some or all of the thickness of adjacent layers 5,6. The applied pressure during this step ensures that the intimate contact between the layers remains.

[0031] When in the liquid phase the material from layers 5 and 7 forms a single common liquid layer, as does the material from layers 6 and 8 respectively. The reaction of the foil is near-instantaneous and the microscopic reaction products dissipate into the liquid layers, these layers 5,7 and 6,8 then coalescing so as to form a common layer of liquid tin 10 located between the copper terminal 1 and HTS 2. This is shown in Figure 4. With the reaction finished, at step 180 a brief cooling phase occurs. This is very brief since, whilst the reaction produces very high temperatures, these are very localised (within a few hundred micrometres thickness of material) and the total energy released is modest. Once the resultant structure has cooled the copper terminal-HTS joint structure is removed from the mechanical press at step 190 and subjected to any required further processes. These may include the removal of any remaining foil 3, the cleaning of the joint or the smoothing of the joint edges, for example removing excess tin that has been expelled from the joint while in its molten state and subjected to the pressure exerted onto the joint surface but has then instantly solidified. The process may also include protecting the joint by applying other materials, or other bonding or joining processes.

[0032] The resultant joined structure provides an electrical connection between the copper terminal 1 and the external copper cladding of the HTS 2. This allows the copper terminal 1 to be used for providing the operational current carried by the HTS 2. The current flowing between the copper terminal 1 and the HTS 2 must pass through the tin layer 10 which provides the physical and electrical connection between the copper terminal 1 and the HTS 2. The electrical impedance presented by the layer 10 as a whole and the cross sectional area of the layer 10 within the joint controls the maximum current that may be carried by the layer 10 during use. Since the HTS material must operate at cryogenic temperatures, any ohmic heating caused by the electrical impedance of the tin material should be minimised. The overall electrical impedance of the joint is controlled by the thickness of the layer 10 and the microstructure of the material within the layer 10. Whereas with prior art joining methods a joint of similar dimensions would be expected to have an impedance between hundreds of nanoOhms and several microOhms, in the present case the impedance is found to be between 25 - 200 nanoOhms.

[0033] In the first example described above the copper terminal is electroplated with a layer of tin. Typically this has a thickness of 1 to 20 micrometres. However, alternatively it could be "gold-plated" by electroplating with a nickel layer (about 3 micrometres thick), this being covered by a thin layer of gold (typically <0.4 micrometres thick). The gold-plated finish has the advantage that it contains no surface oxides.

[0034] In a further modification a preform joining material in the form of a foil may be inserted in between one or each of the terminal 1 and HTS 2, the reactive multilayer foil 3. Examples are 50 micrometre thick foils of SnAg, AuSn foils or even foils which are normally used for 'hard solder' or 'braze' joints (such as CuAgInTi). This modification of the technique may be used instead of or in addition to one or more of the joining material layers in the examples discussed herein. More generally, for some applications this technique might be useful as these foils may be utilised to add additional thickness or strength to the "melt interface" during the joining process.

[0035] In a second example, the method is used to provide a lap joint between two lengths of HTS tape. One of the challenges posed by HTS production processes is due to the difficulty in providing long lengths of HTS material. This means that a reliable joining process is required to ensure that longer lengths of HTS tape can be used in practical applications (such as magnet coil windings). The method described in association with Figure 1 may be modified and used for the production of a lap joint between HTS tapes. This is now described in association with the flow diagram of Figure 5.

[0036] At step 200 a first length of HTS tape 11 is obtained, with a target region for joining being exposed and cleaned. Similarly at step 210 a second length of HTS tape 12, to be joined with the first length 11, is obtained, with a similar target region for joining being exposed and cleaned. At step 220 a piece of reactive multilayer foil 13 having at least the dimensions of the target regions of the tapes 11,12 is obtained. In the present case the foil 13 is not provided with any surface coating and is instead in its "raw" form (unlike the foil 3 in the previous example). Instead, in this case the foil is electroplated (or coated) on each of its surfaces at step 230 with a layer of joining material, this being a eutectic mixture or an alloy containing silver as one of the constituents. A deposited layer of 1-20 micrometres in thickness may be used for each surface for example. A silver-containing material is used in the present example since it firstly has excellent electrical conductivity properties and, secondly, is a material which is very compatible with the HTS tapes 11,12.

[0037] At step 240 the two tapes 11,12 having exposed clean copper surfaces facing one another are positioned within the mechanical press. The plated foil 13 is located between these surfaces. This arrangement is shown in Figure 6. As can be seen the electroplated layers denoted 14 face the corresponding exposed copper surfaces of the HTS tapes 11,12. The pressure is then applied using the mechanical press at step 250 and the reaction is then initiated in the foil 13 at step 260. At step 270 the reaction proceeds by melting the adjacent layers of electroplated material 14. The liquid metal immediately wets the surface of the corresponding copper of the tapes and the reaction products from the foil disperse into the liquid. Once the reaction is completed a unitary melted layer of the plated joining material exists between the opposed surfaces of the HTS tapes 11,12. This then solidifies at step 280 so as to form the desired mechanically and electrically joined structure. The joined tapes 11,12 may then be subjected to further processes.

[0038] In one example of such processes the method of Figure 5 may be repeated one or more further times at step 290, subject to some modifications to the Figure 5 method. For example, if the HTS tape 11 is replaced with a copper member, then upon reaching step 280, the method of Figure 5 forms a joint between the member and the HTS 12. A further HTS tape 16 may be joined upon the opposite side of the member. Thus in Figure 6, if the region indicated at 15 is then treated so as to expose a region of copper to be joined, then steps 210 onwards may be repeated to add the further HTS tape 16. This results in a structure indicated in Figure 7, namely a joint between a copper member and two HTS tapes with intervening layers of joining material 13 providing the physical and electrical connections between the components. This process can be used to build stacks of multiple joints as each new joint will not re-melt the previous joint because the 'heat penetration' of the released energy is less than a hundred micrometres into the surrounding materials. A similar method may be applied to the first example of Figure 1 also.

[0039] It will be understood that the above method of joining HTS materials may be modified by pre-coating the exposed surfaces of the HTS tapes in a similar manner to the previous example. Furthermore, it is not essential that the joining material layers are formed from the same material; this might be the case where particular materials exhibit improved wetting of certain types of surface.

[0040] The methods described above each assume that the superconductor and member to be joined are freely moveable with respect to one another. However, the physically smaller joints now enabled by the method and the low heat input used in the joining process, allow the fabrication of such joints in situations where the superconductor in particular is *in situ* within a magnet. A join may be produced without deconstructing a wound magnet using this method. This is because the reactive multilayer foil is thin and neither additional heating nor fluxes are required. Provided the surfaces to be joined are sufficiently accessible to allow exposure and cleaning, a foil may be inserted between such surfaces. It is advantageous practically if it is not required for the surfaces themselves to be pre-coated with a joining layer of solder, with such a layer instead being provided upon the reactive foil surfaces.

[0041] Another example which has been successfully tested is the use of the idea to manufacture current leads whereby an HTS tape is joined onto a brass member. In this configuration the role of the brass is to provide a relatively low thermally static heat load (compared with copper) during cool down and once the current lead is cooled below the transition temperature of the HTS tape the role of the HTS tape is to carry the current during the operation of the device. This combination reduces both static and ohmic heat loads of the system. Using the current method to join the HTS tape to the brass member makes this process more convenient and reliable avoiding damage to the HTS tape by overheating or by chemical attack due to flux used in conventional soldering processes.

[0042] The above examples have discussed the joining of HTS tapes in particular, either to a conductive member such as a copper terminal, or indeed to another tape. These examples are provided since the joining of HTS tapes is a particular technological area of interest at present. However, it will be understood that the method may be applied also to low temperature superconductor materials.

[0043] With this method, the amount of energy released is easily controllable by selecting a specific reactive foil thickness and defining the joint surface area, example energies being: 40 micrometre foil = 23-25 J/cm^2; 60 micrometre foil = 35-38 J/cm^2; 80 micrometre foil = 47-51 J/cm^2; that is 1050 -1250 J/g.

[0044] Depending on the specific nature of the joint with the superconductor in question (where considerations include: electrical resistance, mechanical strength, joint ductility, joint brittleness) it is possible to select different joining materials depending on their material and surface properties, in particular their ability to 'wet' solder (oxygen free surface or ability to remove oxides) these materials include (by way of example):

1) Tin (Sn) melting point Fp= 232°C; Tensile Strength 1,900psi (13 MPa);
2) Tin-Silver eutectic (96.5Sn-3.5Ag : classic lead-free solder); melting point Fp= 232°C; Tensile Strength 5,620psi (39 MPa);
3) Tin-lead eutectic (63Sn-37Pb : classic lead solder); melting point Fp= 183°C; Tensile Strength 7,500psi (52MPa) or
4) Gold -Tin eutectic (80Au-20Sn); melting point Fp= 280°C; Tensile Strength 40,000psi (276 MPa).

[0045] The reproducibility and quality of the joints using this method are significantly improved over conventional methods and the assembly risk is reduced. At the same time the assembly process itself becomes much easier and manufacturing is simplified.

Practical Advantages of the Invention

[0046] The use of the reactive multilayer foil opens up numerous new process and assembly possibilities in comparison with known joining techniques for superconductors, including those encapsulated with an outer layer of a normal conductor, such as used in cryogenic applications, these increasing the flexibility and efficiency of manufacturing.

[0047] As will be understood from the examples given below, the processes are extremely simple, reliable, repeatable and efficient. They produce strong joints with exceptional electrical properties that are of high quality and reliability. The extremely localised melting of joining material (such as solder) minimises the exposure of nearby materials (particularly HTS materials) to heat damage. Thus the heating is only provided where it is required, this for example only penetrating less than a hundred micrometres away from the bond line. Thermal stresses are also avoided for similar reasons. The process advantageously provides "millisecond soldering" in air and at room temperature meaning that no special environment is required. Critically the process is "flux-free" which eliminates the creation of any voids within the joined material caused by flux residues and subsequent cleaning operations. Flux and flux residues each lead to an increased probability of joint failure in the medium to long term due to the aggressive chemical nature of fluxes. This fluxless process offers long term stability to the bond, for example after repeated thermal cycling. The process also offers flexibility in the choice of joining material (solder) and the sequence of assembly.

[0048] Since the components are assembled at room temperature their surfaces can be prepared as 'wettable' surfaces by removing any oxide layers thereby eliminating the need for flux. Because the assembly as a whole remains at room temperature re-oxidation of the surfaces is largely reduced or slowed down. Such joints are superior to conventional joints because they have a significantly lower fraction of voids and contain only a mixture of metals as opposed to organic residues and so on. Electrical measurements have confirmed that the methods described produce joints which are reproducible (100% success rate has been demonstrated on more than 100 joints for example) and have low contact resistance and in some cases lower contact resistance compared with joints made by conventional techniques. Assembly and handling of the joint is much simpler because it can take place while all components are at room temperature. These key differences result in joints with lower void volume compared with traditional techniques making them superior as contact resistance joints for high current terminals.

Claims

1. A method of forming an electrically conductive joint between a first superconductor (2, 12) and a member (1, 11), the method comprising the steps of:

providing (120, 200) a first superconductor (2, 12) having a first bonding surface;
providing (100, 210) a member (1, 11) having a second bonding surface, **characterised by**:

positioning (140, 240) a reactive foil (3, 13) between the first superconductor and the member and adjacent to each of the first and second bonding surfaces;
positioning (130, 230) a joining material (5-8, 14) between the reactive foil and each

of the first and second bonding surfaces;
applying pressure (150, 250) so as to compress the member (1, 11), the reactive foil (3, 13) and the first superconductor (2, 12) together; and,
initiating (160, 260) a reaction in the reactive foil so as to join the first and second bonding surfaces together.

2. A method according to claim 1, wherein said reactive foil (3, 13) is a reactive multilayer foil comprising numerous layers of materials in an alternating sequence, each layer having a thickness of less than 1 micrometre.

3. A method according to claim 1 or claim 2, wherein the said reaction causes the localised melting of the joining material (5-8, 14) so as to join the first and second bonding surfaces upon subsequent solidification of the joining material.

4. A method according to any of the preceding claims, wherein the joining material (7, 8, 14) is integral with the reactive foil.

5. A method according to claim 4, wherein the reactive foil (3, 13) is generally planar having opposing sides and wherein one or each of the said opposing sides is provided with said joining material (7, 8, 14).

6. A method according to any of the preceding claims, wherein the joining material (5, 6) is integral with one or each of the first superconductor or member.

7. A method according to claim 4 or claim 5, wherein the joining material (7, 8, 14) is integral in the sense of being provided as one or more layers upon a surface.

8. A method according to any of the preceding claims, wherein the joining material (5-8, 14) is applied by an electroplating process.

9. A method according to any of the preceding claims, wherein the joining material is provided as a foil.

10. A method according to any of the preceding claims, wherein the member (11) is a second superconductor.

11. A method according to claim 10, wherein one or each of the first and second superconductors (11, 12) is a high temperature superconductor, provided in the form of a tape.

12. A method according to any of the preceding claims, wherein the method is a fluxless joining method.

13. A method according to any of the preceding claims, wherein the member (11) is a second superconductor and wherein the first superconductor and the second superconductor (11, 12) are each located within a winding pack and wherein the joining is performed in situ within the winding pack.

Patentansprüche

1. Verfahren zur Herstellung einer elektrisch leitenden Verbindung zwischen einem ersten Supraleiter (2, 12) und einem Element (1, 11), umfassend die folgenden Schritte:

die Bereitstellung (120, 200) eines ersten Supraleiters (2, 12) mit einer ersten Verbindungsfläche;
die Bereitstellung (100, 210) eines Elements (1, 11) mit einer zweiten Verbindungsfläche,
gekennzeichnet durch:

das Positionieren (140, 240) einer reaktionsfähigen Folie (3, 13) zwischen dem ersten Supraleiter und dem Element und benachbart zur ersten und zur zweiten Verbindungsfläche;
das Positionieren (130, 230) eines Verbindungsmaterials (5-8, 14) zwischen der reaktionsfähigen Folie und der ersten und der zweiten Verbindungsfläche;
das Aufbringen von Druck (150, 250) zum Zusammendrücken des Elements (1, 11), der reaktionsfähigen Folie (3, 13) und des ersten Supraleiters (2, 12); und das Einleiten (160, 260) einer Reaktion in der reaktionsfähigen Folie zur Verbindung der ersten und der zweiten Verbindungsfläche.

2. Verfahren nach Anspruch 1, wobei die besagte reaktionsfähige Folie (3, 13) eine reaktionsfähige Mehrlagenfolie mit zahlreichen Materiallagen in abwechselnder Reihenfolge, jeweils mit einer Dicke von weniger als 1 Mikrometer, ist.

3. Verfahren nach Anspruch 1 oder 2, wobei die besagte Reaktion das örtliche Schmelzen des Verbindungsmaterials (5-8, 14) veranlasst, so dass die erste und die zweite Verbindungsfläche nach der darauffolgenden Verfestigung des Verbindungsmaterials miteinander verbunden sind.

4. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Verbindungsmaterial (7, 8, 14) mit der reaktionsfähigen Folie integriert ist.

5. Verfahren nach Anspruch 4, wobei die reaktionsfähige Folie (3, 13) im Allgemeinen flach ist und einander gegenüberliegende Seiten aufweist, und wobei eine oder beide der besagten einander gegenüberliegenden Seiten mit dem besagten Verbindungsmaterial (7, 8, 14) versehen ist/sind.

6. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Verbindungsmaterial (5, 6) mit dem ersten Supraleiter und/oder mit dem Element integriert ist.

7. Verfahren nach Anspruch 4 oder 5, wobei das Verbindungsmaterial (7, 8, 14) in dem Sinne integriert ist, dass es in der Form von einer Lage oder mehreren Lagen auf einer Oberfläche vorgesehen ist.

8. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Verbindungsmaterial (5-8, 14) in einem Galvanisierverfahren aufgetragen wird.

9. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Verbindungsmaterial in Form einer Folie vorliegt.

10. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Element (11) ein zweiter Supraleiter ist.

11. Verfahren nach Anspruch 10, wobei der erste und der zweite Supraleiter (11, 12) jeweils ein Hochtemperatur-Supraleiter in der Form eines Bandes ist.

12. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Verfahren ein flussmittelfreies Verbindungsverfahren ist.

13. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Element (11) ein zweiter Supraleiter ist und wobei der erste und der zweite Supraleiter (11, 12) jeweils in einem Wickelpaket angeordnet ist und wobei die Verbindung vor Ort im Wickelpaket erfolgt.

Revendications

1. Un procédé de formation d’un joint conducteur sur le plan électrique entre un premier supraconducteur (2, 12) et un élément (1, 11), procédé se composant des phases suivantes :

la fourniture (120, 200) d’un premier supraconducteur (2, 12) qui a une première surface de liaison ;
la fourniture (100, 210) d’un élément (1, 11) qui a une deuxième surface de liaison **se caractérisant par** :

le positionnement (140, 240) d’un feuillard réactif (3, 13) entre le premier supraconducteur et l’élément et adjacent à la première surface de liaison et également à la deuxième surface de liaison ;
le positionnement (130, 230) d’un matériau de liaison (5-8, 14) entre le feuillard réactif et la première surface de liaison et également la deuxième surface de liaison ;
l’application de la pression (150, 250) de façon à comprimer l’élément (1, 11), le feuillard réactif (3, 13) et le premier supraconducteur (2, 12) les uns contre les autres et le lancement (160, 260) d’une réaction dans le feuillard réactif de façon à lier la première surface de liaison à la deuxième surface de liaison.

2. Le procédé décrit dans la revendication 1, si ce n’est que ledit feuillard réactif (3, 13) est un feuillard réactif multicouche qui comporte de nombreuses couches de matériaux superposés en alternance et chaque couche a une épaisseur inférieure à 1 micromètre.

3. Le procédé décrit dans la revendication 1 ou 2, si ce n’est que ladite réaction provoque la fusion localisée du matériau de liaison (5-8, 14) de façon à lier la première surface de liaison et la deuxième surface de liaison lors de la solidification ultérieure du matériau de liaison.

4. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que le matériau de liaison (7, 8, 14) fait partie intégrante du feuillard réactif.

5. Le procédé décrit dans la revendication 4, si ce n’est que le feuillard réactif (3, 13) est en général plan et à des côtés opposés et si ce n’est que l’un desdits côtés opposés ou les deux côtés opposés est ou sont composés dudit matériau de liaison (7, 8, 14).

6. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que le matériau de liaison (5, 6) fait partie intégrante du premier supraconducteur et (ou) du premier élément.

7. Le procédé décrit dans la revendication 4 ou 5, si ce n’est que le matériau de liaison (7, 8, 14) fait partie intégrante, c’est-à-dire qu’il est fourni sous la forme d’une ou plusieurs couches sur une surface.

8. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que le matériau de liaison (5-8, 14) s’applique par électroplacage.

9. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que le matériau de liaison est fourni sous la forme d’un feuillard.

10. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que l’élément (11) constitue un deuxième supraconducteur.

11. Le procédé décrit dans la revendication 10, si ce n’est que le premier et (ou) le deuxième supraconducteur(s) (11, 12) est un ou sont des supraconducteur(s) fourni(s) sous la forme de rouleau.

12. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que ce procédé est une méthode de liaison sans fondant.

13. Le procédé décrit dans l’une des revendications précédentes, si ce n’est que l’élément (11) constitue un deuxième supraconducteur et si ce n’est que le premier supraconducteur et le deuxième supraconducteur (11, 12) sont tous deux implantés dans un groupe d’enroulement et si ce n’est que la liaison s’effectue sur place à l’intérieur de ce groupe d’enroulement.

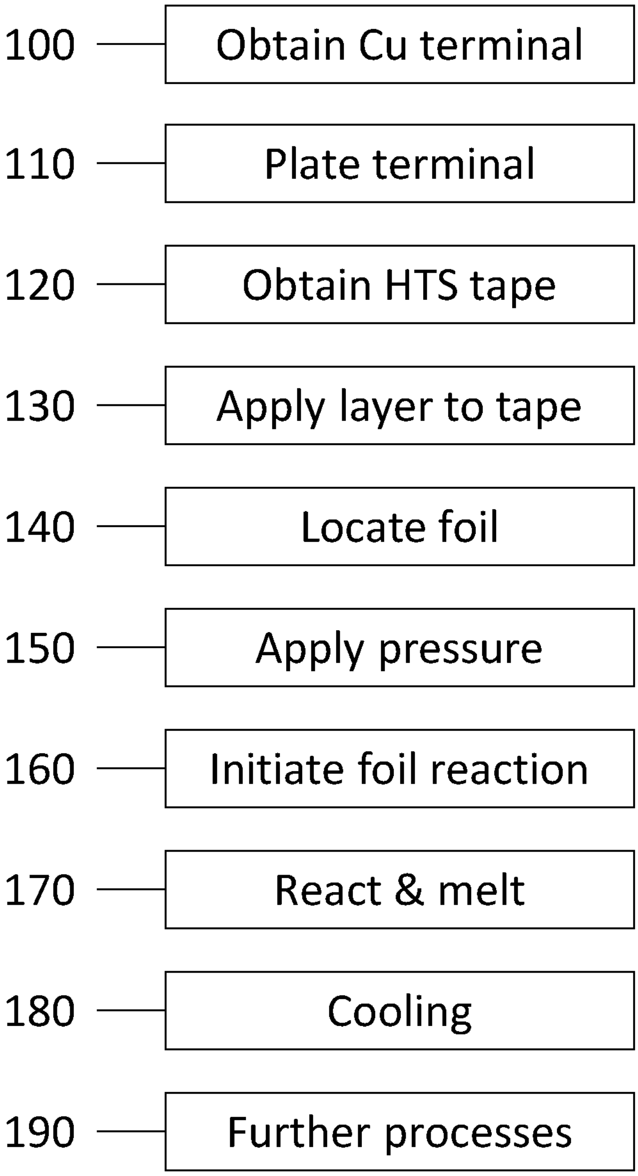
100
Obtain Cu terminal
110
Plate terminal
120
Obtain HTS tape
130
Apply layer to tape
140
Locate foil
150
Apply pressure
160
Initiate foil reaction
170
React & melt
180
Cooling
190
Further processes

Fig. 1

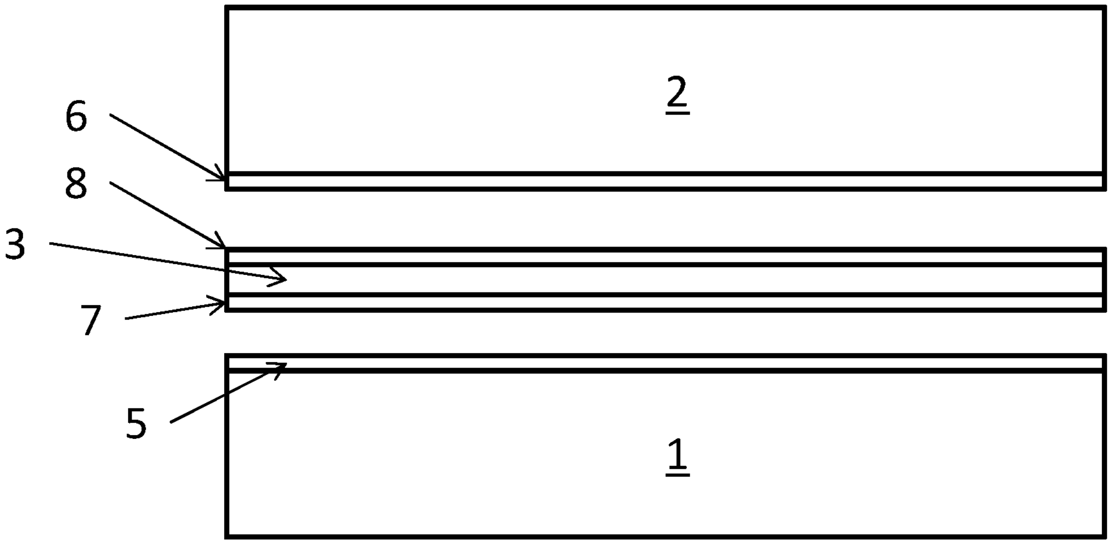

Fig. 2

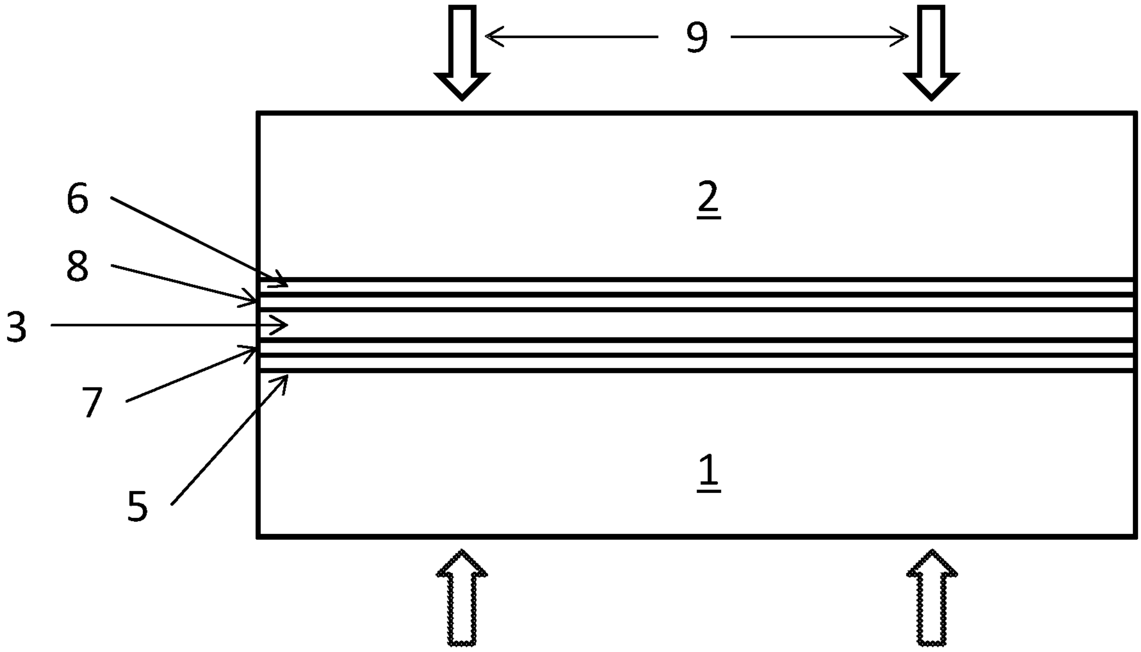

Fig. 3

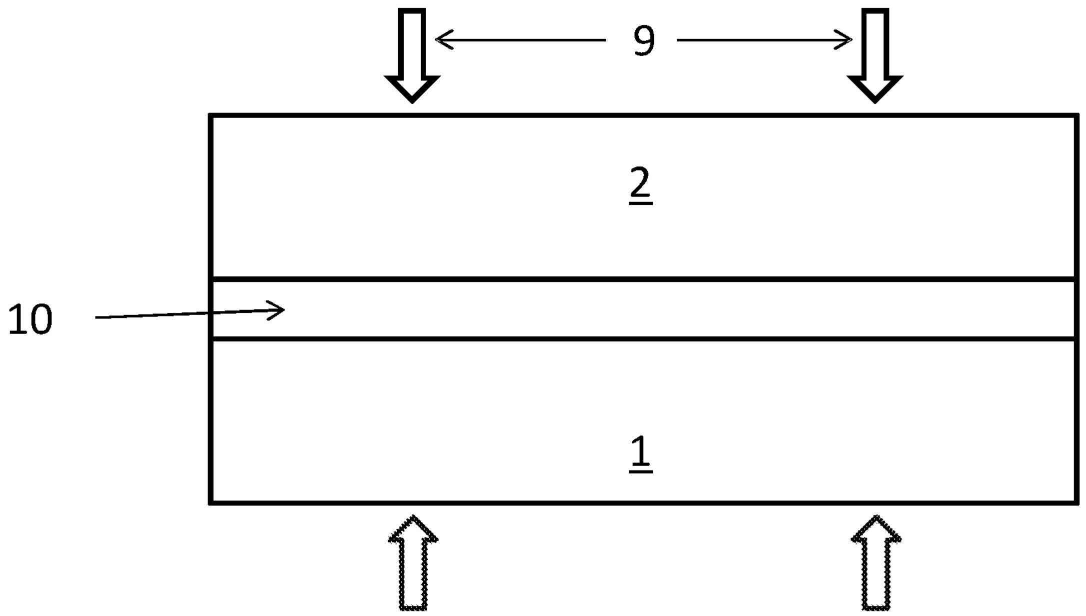

Fig. 4

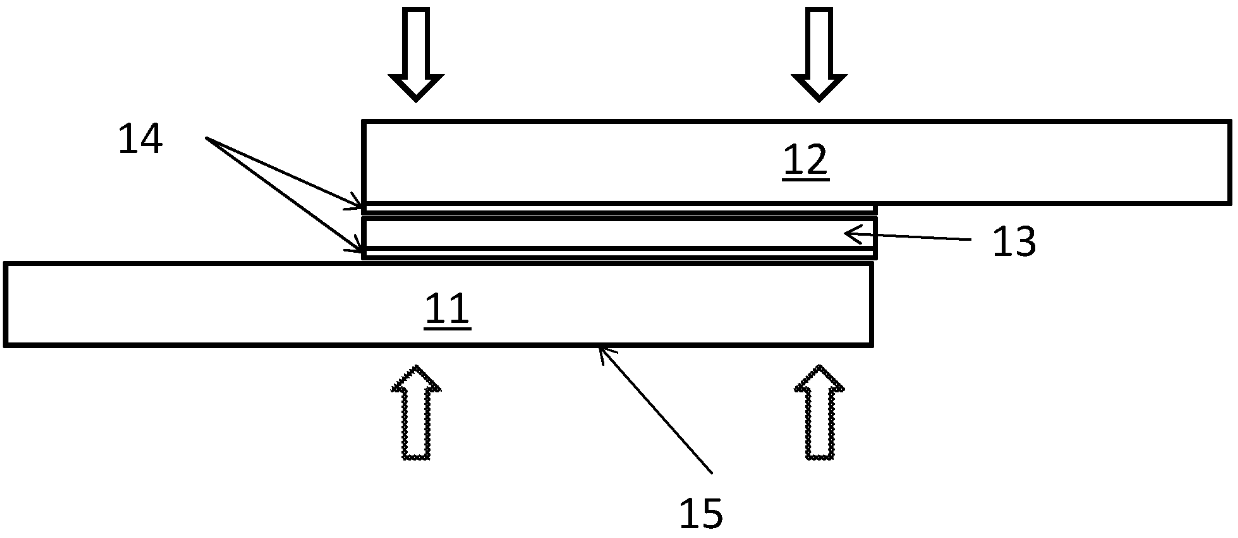

Fig. 6

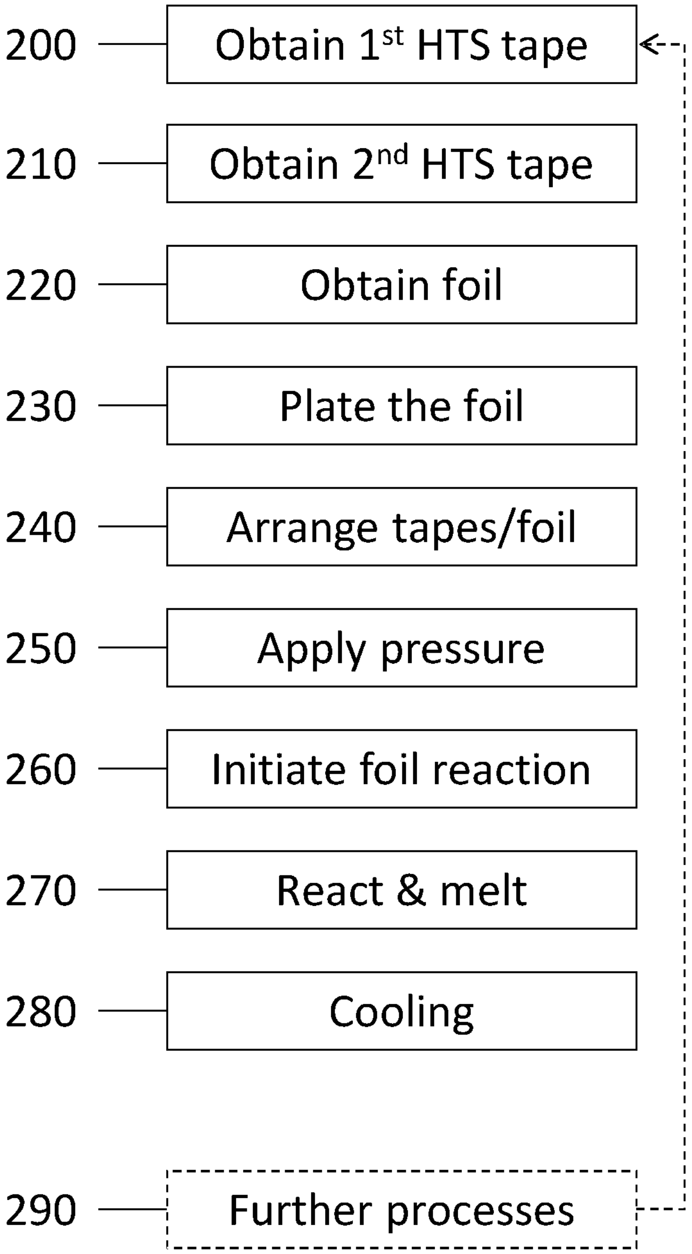
200
Obtain 1st HTS tape
210
Obtain 2nd HTS tape
220
Obtain foil
230
Plate the foil
240
Arrange tapes/foil
250
Apply pressure
260
Initiate foil reaction
270
React & melt
280
Cooling
290
Further processes

Fig. 5

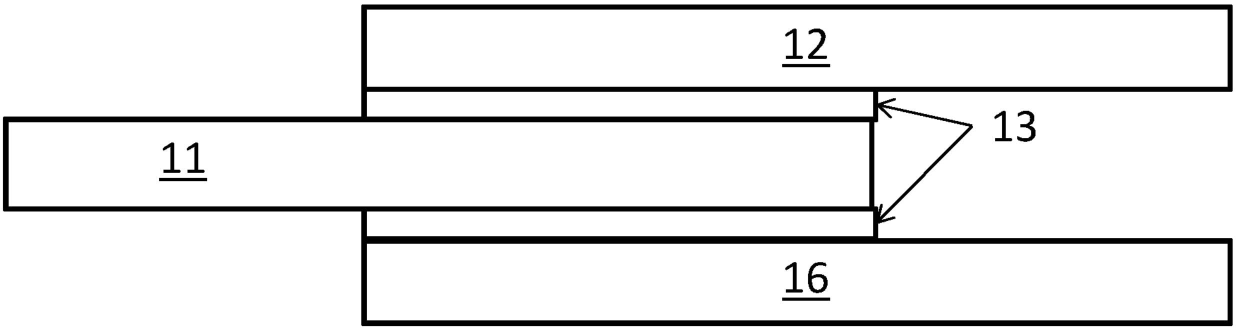

Fig. 7

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- JP H10275641 A **[0006]**
- US 2005082343 A1 **[0006]**