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(54) **METHOD FOR REPAIRING MONOCRYSTALLINE MATERIALS**

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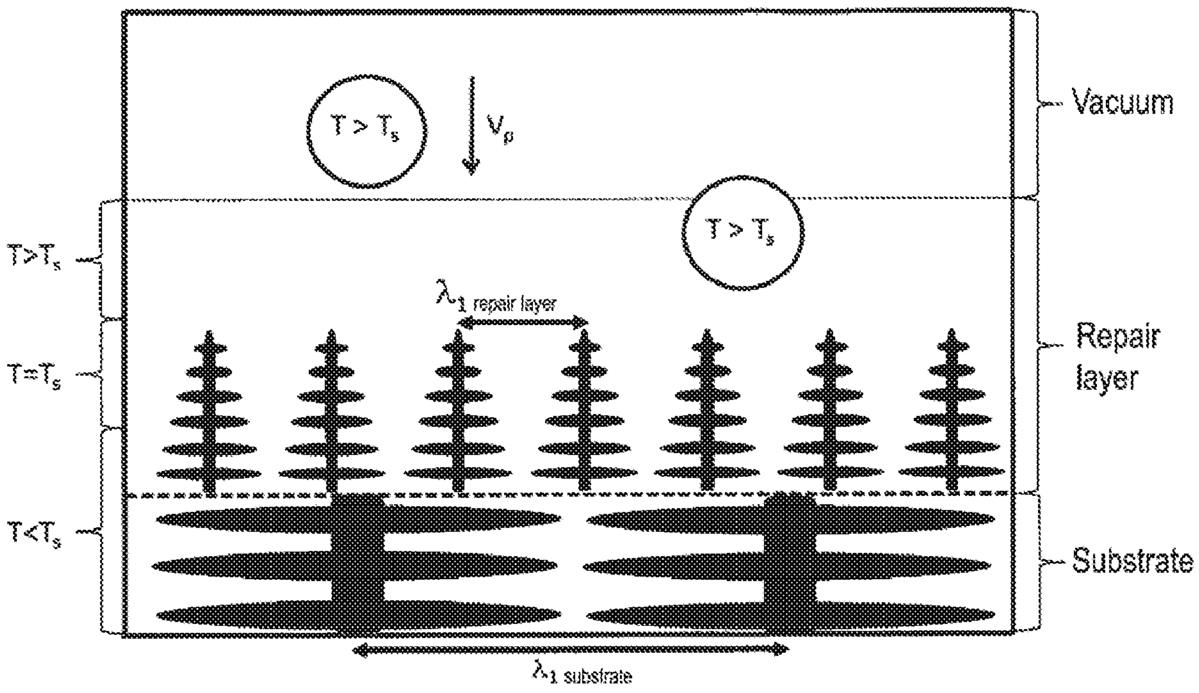
(57) **ABSTRACT**

A method for coating, with a coating material, a monocrystalline substrate surface of a component comprising a monocrystalline alloy includes polishing the monocrystalline substrate surface, transferring the substrate to a vacuum chamber, and heating the entire substrate to a temperature of at least half a melting temperature of the substrate but less than a melting temperature of the substrate. The method further includes applying the coating material in powder form onto the polished monocrystalline substrate surface by vacuum plasma spraying. The powder has a mean particle size in a range of 10 to 200 μm. A pressure in a range of 1 to 200 mbar is set for the vacuum plasma spraying, and an argon atmosphere having a hydrogen content in a range of 10 to 50 vol. % is used as a working gas for the vacuum plasma spraying.



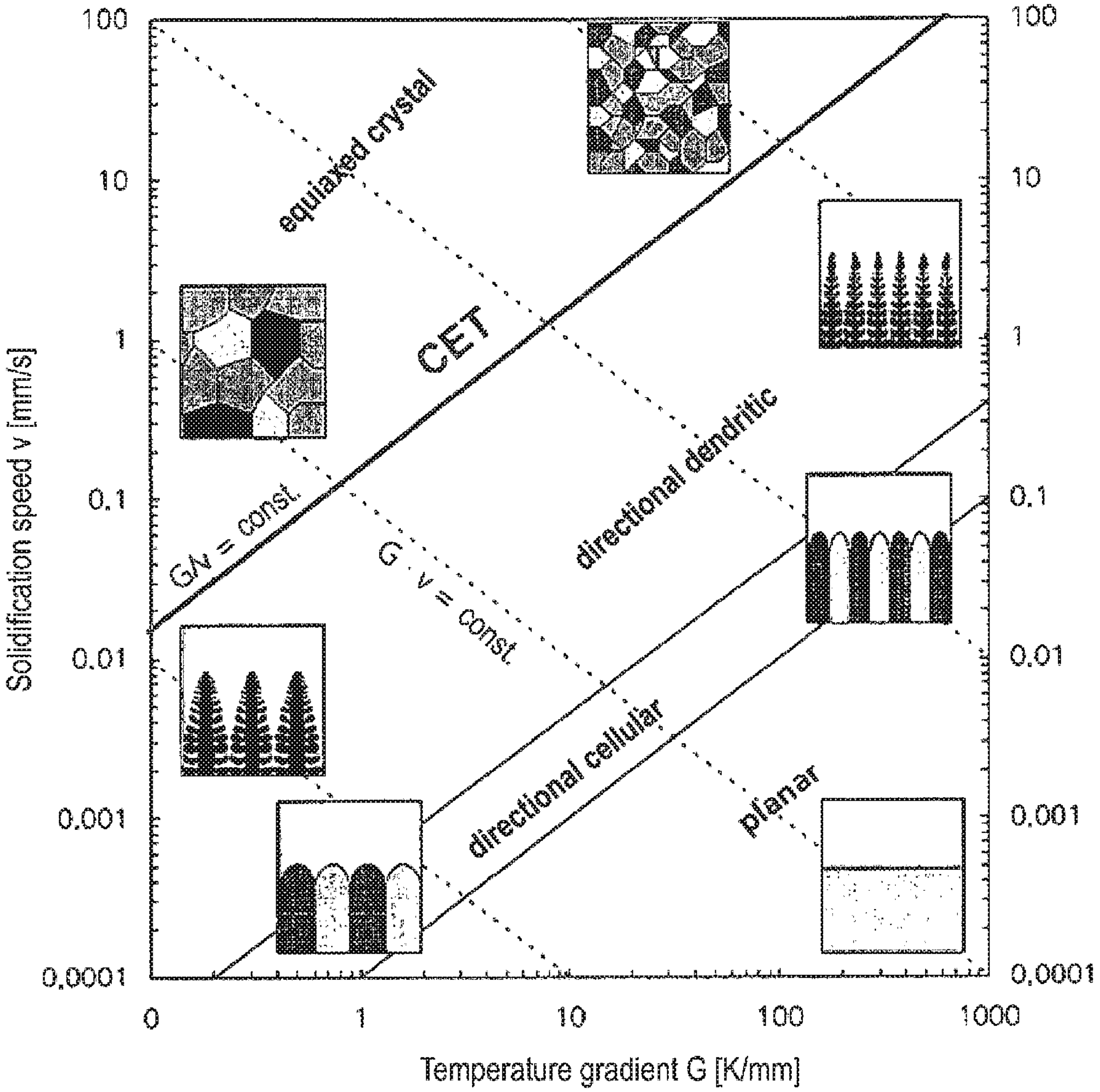
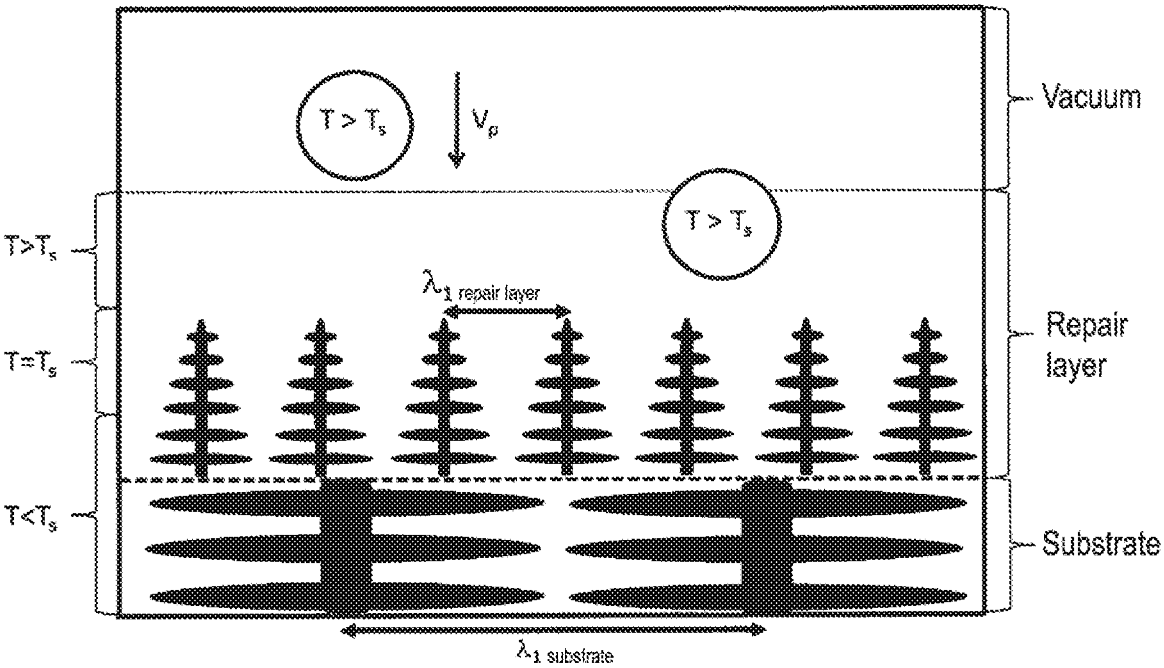


Figure 1 from prior art [6]



T > T_s
V_p
Vacuum
T > T_s
T>T_s
λ_1 repair layer
Repair layer
T=T_s
T<T_s
Substrate
λ_1 substrate

Figure 2

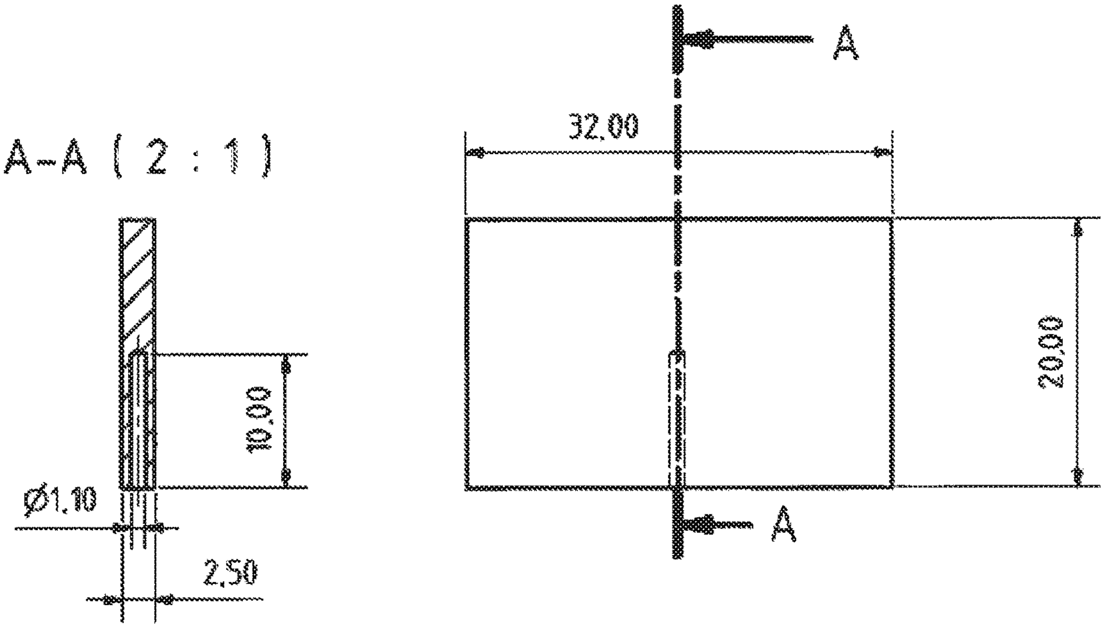


Figure 3

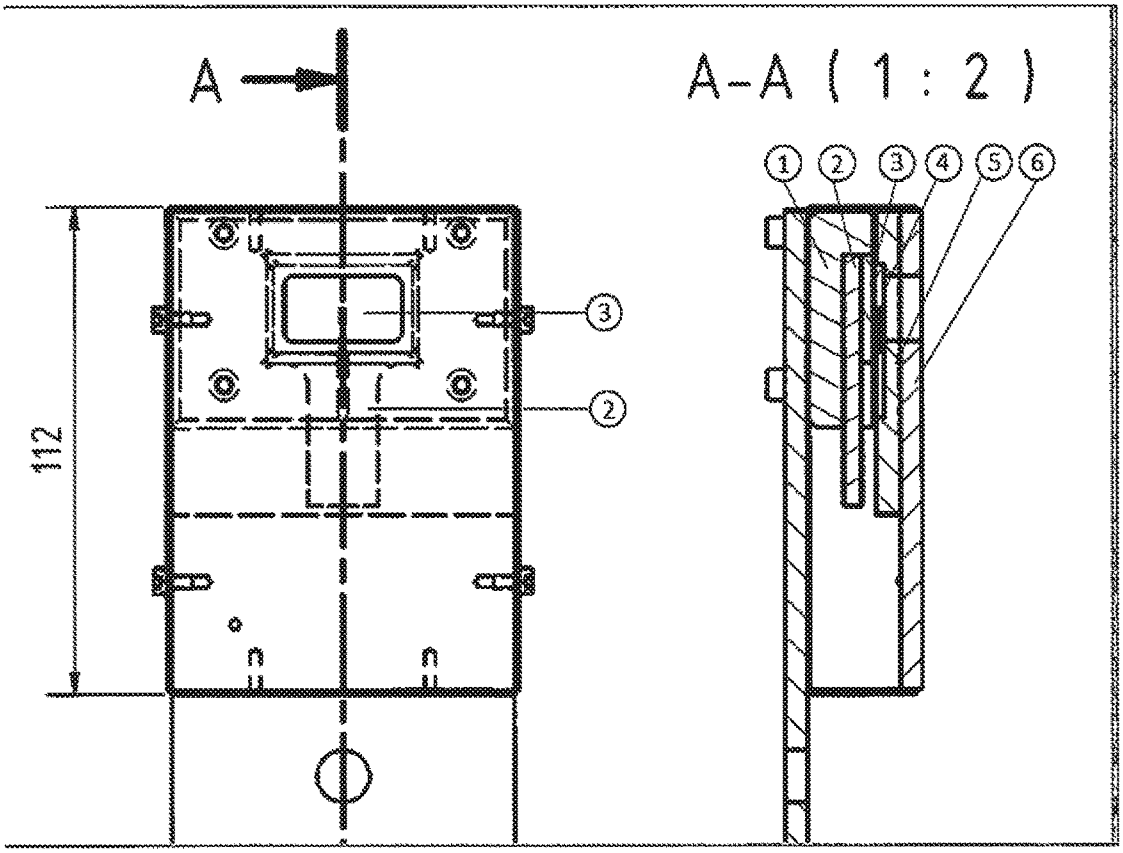


Figure 4

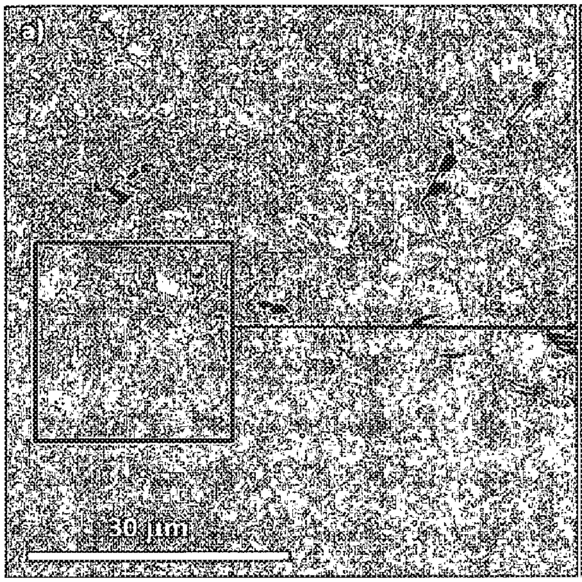


Figure 5a

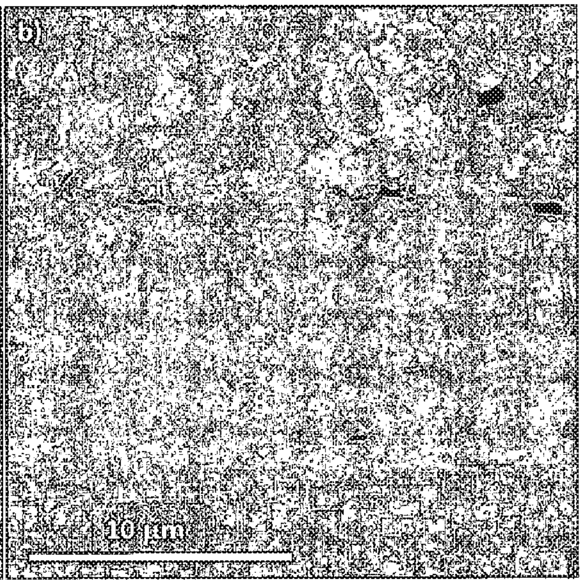


Figure 5b

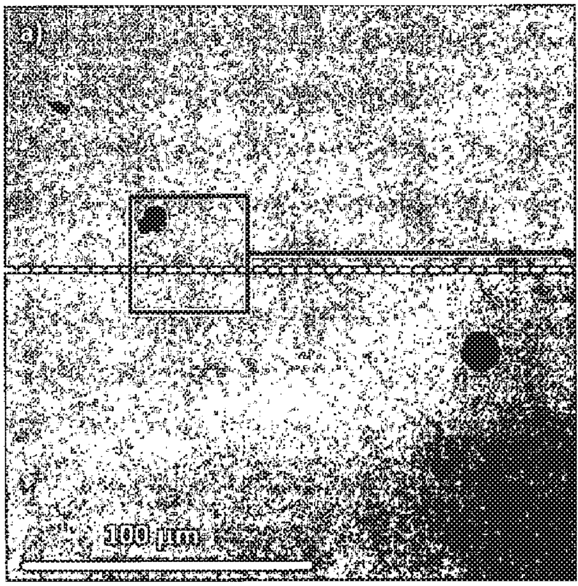


Figure 6a

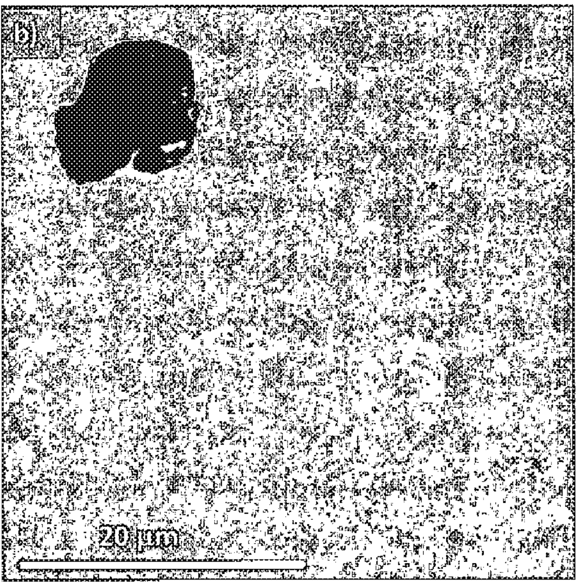


Figure 6b

METHOD FOR REPAIRING MONOCRYSTALLINE MATERIALS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a U.S. National Phase Application under 35 U.S.C. § 371 of International Application No. PCT/DE2018/000281, filed on Oct. 4, 2018, and claims benefit to German Patent Application No. DE 10 2017 009 948.0, filed on Oct. 26, 2017. The International Application was published in German on May 2, 2019 as WO 2019/080951 under PCT Article 21(2).

FIELD

[0002] The invention relates to the field of metals and alloys, and specifically, to the field of nickel alloys. The invention relates in particular to a method for repairing monocrystalline materials which are frequently used for components subjected to high temperatures, for example, the blades of stationary gas turbines or of aircraft turbines.

BACKGROUND

[0003] It is known from the literature that the production of monocrystalline blades of stationary gas turbines and/or of aircraft turbines is very expensive and complex due to the directional solidification and special casting processes. The orientation of the microstructure produced in the components is effected along the direction of the axial tension. During operation, the blades are regularly exposed to a high thermal load and also to a corrosive atmosphere, as a result of which the blades wear strongly.

[0004] This is why, for example, there is great interest in repairing instead of remanufacturing monocrystalline turbine blades. Some repair methods from the prior art are also already known for this purpose, wherein a distinction is made between methods for repairing, for example, turbine blades via a thermal spraying method, also repair methods using welding and laser cladding and finally methods where epitaxial growth of ceramic materials takes place during a thermal spraying process.

[0005] A method is known for example from Kazuhoro et al. HI that can be used to repair a defective turbine blade. In this case, however, there is no epitaxial growth on the monocrystalline substrate, so that as a result a polycrystalline microstructure is produced which regularly does not have the mechanical properties of the original substrate.

[0006] Furthermore, U.S. Pat. No. 5,732,467 A1 describes a method for repairing cracks in the outside surfaces of components which have a superalloy with a directional microstructure. The method described therein coats and seals the outside surfaces of directionally solidified and monocrystalline structures by coating the defective region using a high velocity oxy-fuel method (also referred to herein as HVOF) followed by hot isostatic pressing of the corresponding component. This is to produce a crack-free repaired region without adversely affecting the monocrystalline microstructure of the remaining component. However, in this case too, a polycrystalline microstructure having the above-mentioned disadvantages is produced in the repair region.

[0007] From prior art we also know a welding method by Boris Rottwinkel et al. [2], where breaking points are provided in a time-saving and material-saving manner for repairing a crack below the tip region of a monocrystalline component, e.g. a turbine blade, in order to first eliminate the damaged area concerned. The breaking point must be suitable for being welded and at the same time for allowing an orientation direction of the newly applied material having the same orientation as the remaining material. A temperature gradient is required for this purpose which supports the orientation alignment. Due to its specific process parameters, such as low local energy input and controlled material input, the laser beam application welding described herein is in principle a suitable method for welding such breaking points accordingly. However, the challenges with this method are to achieve a perfect monocrystalline crack-free region since only polycrystalline regions can be regularly produced due to low unstable energy distribution.

[0008] Automatic welding methods for the industrial production of gas turbines are known from Henderson et al. [3]. The welding of highly alloyed nickel alloys is very complex and often it can be applied satisfactorily only with great difficulty. For example, special alloy wires have been used for filling in welding attempts to repair blade wheels. This was followed by a standard baking and aging procedure in which, however, microcracks occurred.

[0009] A welding method is also proposed to repair damages to monocrystalline materials that occur, for example, in the blades of gas turbines [3]. When performing repairs by laser metal forming (LMF) or laser cladding, it is basically possible to produce monocrystalline structures on a monocrystalline substrate. This method is characterized by minimum heat input into the component during construction which prevents further cracks or recrystallization of the monocrystalline material.

[0010] Moreover, by using this method it is possible to maintain the orientation of the monocrystalline starting material across the interface and into the newly applied material. Moreover, optimized process parameters can lead to a consistent epitaxial growth on a monocrystalline substrate, for example in which the ratio between the temperature gradient in the welding zone and the solidification speed is higher than a material-dependent threshold value.

[0011] However, a targeted repair of cracks has not been possible so far. The repair of larger regions is regularly accompanied by increased tensions due to thermal expansion. Furthermore, literature does not provide results on the repair of regions by this method where cooling holes or lines run. A complex solidification system is produced by cooling holes, like in a notch. Directional crystalline solidification will regularly occur only if the heat flow is constant and if it is not disturbed. However, such constant heat flow is typically disturbed in the presence of cooling holes which will result in cracks and/or in an unwanted polycrystallinity in this region. A repair in such a region below the turbine tip is thus generally not possible with these methods.

[0012] With the already existing repair methods, it is thus not yet possible to restore the microstructure of the monocrystalline base material at each region of the component to be repaired, e.g. a turbine blade. This means that although it is possible to repair the blades, they regularly still will not have the mechanical properties of new blades.

[0013] Studies on epitaxial growth during the solidification of plasma-spayed molten TiO_2 have been carried out by Shu-Wie Yao et al. [4] in the field of ceramic processing. It has been found that a plurality of parameters, such as application temperature, crystallographic alignment and supercooling of the melt, have a significant impact on epitaxial growth. In particular, the temperature of the melt decides whether heterogeneous nucleation or epitaxial growth will occur. The printed publication shows that directional solidification was also observed already in plasma spraying.

SUMMARY

[0014] In an embodiment, the present invention provides a method for coating, with a coating material, a monocrystalline substrate surface of a component comprising a monocrystalline alloy. The method includes polishing the monocrystalline substrate surface, transferring the substrate to a vacuum chamber, and heating the entire substrate to a temperature of at least half a melting temperature of the substrate but less than a melting temperature of the substrate. The method further includes applying the coating material in powder form onto the polished monocrystalline substrate surface by vacuum plasma spraying. The powder has a mean particle size in a range of 10 to 200 μm. A pressure in a range of 1 to 200 mbar is set for the vacuum plasma spraying, and an argon atmosphere having a hydrogen content in a range of 10 to 50 vol. % is used as a working gas for the vacuum plasma spraying. The method finally includes thereby generating at least one region directly at an interface of the coating material and the polished monocrystalline substrate surface having a same single-crystalline orientation as the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The present invention will be described in even greater detail below based on the exemplary figures. The invention is not limited to the exemplary embodiments. All features described and/or illustrated herein can be used alone or combined in different combinations in embodiments of the invention. The features and advantages of various embodiments of the present invention will become apparent by reading the following detailed description with reference to the attached drawings which illustrate the following:

[0016] FIG. **1** illustrates a prior art diagram for CMSX-4® material;

[0017] FIG. **2** schematically shows a solidification model for a method according to an embodiment;

[0018] FIG. **3** illustrates a substrate sample geometry;

[0019] FIG. **4** is a technical drawing illustrating a configuration of a polished sample incorporated into a heated sample holder; and

[0020] FIGS. **5***a* and **5***b* show scanning electron micrographs of transverse grinds of treated samples showing directional solidification on a monocrystalline substrate; and

[0021] FIGS. **6***a* and **6***b* show scanning electron micrographs of transverse grinds of the same samples which, after coating, were first solution annealed and then precipitation annealed.

DETAILED DESCRIPTION

[0022] Embodiments described herein provide a repair method for monocrystalline materials, in particular for monocrystalline blades of stationary gas turbines and/or of aircraft turbines where the added material has mostly the same microstructure and crystal orientation as the material to be repaired.

[0023] It has been found, within the scope of the invention, that epitaxial growth on a monocrystalline material (substrate) can be generated via the method of vacuum plasma spraying.

[0024] In the context of this invention, the material to be repaired, which is hereinafter referred to as substrate material, typically comprises a metallic alloy, in particular a nickel-based alloy or also a cobalt-based alloy.

[0025] The term plasma spraying is understood to mean a coating method which is carried out using a plasma and is not based on plasma polymerization.

[0026] Unlike atmospheric plasma spraying, vacuum plasma spraying is understood to be a coating method which is carried out in a vacuum chamber at a pressure of 1 to 200 mbar in order to avoid oxidation of the coating material by atmospheric oxygen.

[0027] Ideally, the same material of which the substrate material is made is used as the coating material. Since the components to be repaired, such as the blades of stationary gas turbines and/or aircraft turbine blades, are generally highly temperature-loaded materials, in particular all metallic high-temperature alloys or superalloys are suitable as coating materials.

[0028] Known high-temperature alloys currently include predominantly solid and high-strength nickel-based alloys or cobalt-based alloys. Metallic materials of complex composition (iron, nickel, platinum, chromium or cobalt base with the addition of the elements Co, Ni, Fe, Cr, Mo, W, Re, Ru, Ta, Nb, AI, Ti, Mn, Zr, C and B) for high-temperature applications are generally referred to as superalloys. They are mostly scaling-resistant and highly heat-resistant. They can be produced both by a melt metallurgy method and a powder metallurgy method.

[0029] The polycrystallinity of thermally sprayed metallic layers can be suppressed by spaying an at least similar alloy, such as the monocrystalline substrate material, onto the heated and polished substrate surface at a greatly reduced pressure and in an argon atmosphere. As described herein, the term “similar” is understood to mean that the proportion of the alloying elements of substrate and layer differ only slightly and that they have a virtually identical microstructure after a heat treatment.

[0030] A low solidification rate favors the directional monocrystalline growth of the applied material. The rate of solidification within the applied layer regularly decreases as the substrate temperature increases.

[0031] According to embodiments, the temperatures of the substrate are so high that the solidification speed of the molten powder particles is greatly reduced but the melting temperature of the substrate is not reached. Substrate temperatures between 700° C. and temperatures just below the melting temperature of the substrate used, i.e. for example 50° C. below the melting temperature of the substrate, are typically set for this purpose.

[0032] The solidification speed cannot be exactly measured disadvantageously in this process, but it should preferably be less than 100 mm/s.

[0033] In these conditions, nucleation does not take place somewhere within the applied layer but advantageously directly at the substrate surface where it aligns itself with the predetermined orientation of the single crystal of the substrate. Epitaxial growth of the applied layer on the substrate is thus possible.

[0034] Preferably, the region of the substrate to be repaired is heated by means of a meandering movement of a plasma torch without powder feeding over the surface of the substrate.

[0035] In addition, the entire substrate is heated. The substrate can be heated in various ways: electrically, inductively or by electromagnetic radiation. Depending on the alloy, the entire substrate is advantageously heated to at least 700° C., advantageously to at least 800° C., preferably even to approximately 1100° C.

[0036] It is important that, although the substrate itself is heated during the application of the thermally sprayed layer, it is not heated up to temperatures at which the substrate would melt. During the repair process, the powder melted in the plasma thus theoretically impinges on a solid, polished substrate surface where it nucleates and can thus advantageously solidify in the same crystal orientation. In practice, however, a melting of the surface of the substrate locally by a few μm cannot be ruled out, depending on the implementation of the method.

[0037] This method step is clearly distinguishable from previously known repair methods, such as, for example, welding methods by means of a laser where the substrate itself is frequently also melted at least on the surface to be repaired.

[0038] In the composition of the plasma gas, it is important that it has hydrogen. Hydrogen causes reducing conditions which regularly suppress oxidation of the substrate material during the heating process. A suitable argon-containing plasma gas could thus have a minimum of 5 NLPM and a maximum of 25 NLMP hydrogen at 50 NLPM argon. NLPM means normal liter per minute and refers to a gas flow rate under standard conditions (T=273.15 K). This then corresponds to a concentration range of 10 vol % to 50 vol % of hydrogen in the plasma gas argon.

[0039] A vacuum plasma spraying system with a powder feed system and a device for heating a substrate (component) to temperatures of approximately 700° C. up to 1300° C. are preferably utilized to carry out the method. Preferably, the area on the component to be repaired should be polished.

[0040] The repair process of the damaged component generally starts by removing the bonding coat and topcoat of the thermal barrier layer with hydrofluoric acid (also referred to as stripping), provided that they are present on the substrate material.

[0041] In the next step, the critical damage is identified and regularly removed, ground and polished by a machining method.

[0042] Grinding can be carried out, for example, with 320, 640, 1200, or 4000 grit sandpaper.

[0043] The subsequent polishing can be carried out with a diamond suspension on a soft cloth, wherein, for example, first a suspension with diamond particles having an average particle size of approx. 3 μm and then a suspension with diamond particles having an average particle size of approx. 1 μm is used. A light microscope is suitable for checking the polished substrate surface. The treated substrate surface should be scratch-free.

[0044] The undamaged regions of the substrate are masked in a next step.

[0045] The stripped region can now be reconstructed using a method according to the disclosure. Layer thicknesses of approx. 10 μm up to several mm can be realized in this case. The layer thickness during single transition/spraying of the plasma torch can be adjusted individually and follows from the robot speed in conjunction with the powder delivery rate. The entire layer thickness is regularly realized by multiple transitions/spraying.

[0046] In the case of a single transition, for example, the layer thickness will be approximately 25 μm. The layer can have any thickness depending on the number of transitions. An excessive application rate during single transition should be avoided, however, as this could lead to increased pore formation which would be disadvantageous. Polishing between the individual transitions is not necessary.

[0047] The application of a plurality of layers is also possible provided that the respective surface is polished between application of the layers. This may be necessary, for example, where a further repair appears necessary after a first repair and examination of a region. Here, the repaired substrate can be polished again and used for another repair.

[0048] Since the applied layer is generally very low-stress due to the high application temperature, there is no physical limit to a maximum layer thickness that can be applied by a method according to the present disclosure. A layer thickness range of a few μm up to approximately 5 mm can be achieved by such a method.

[0049] This is followed by post-processing and, if applicable, by restoration of the original component dimensions and by heat treatment, for example in the form of solution annealing and precipitation annealing.

[0050] In the last step, a new thermal barrier layer can then be re-applied depending on the requirement, and cooling holes may be re-drilled.

[0051] Methods according to the disclosure can advantageously offer the possibility of bringing defective and discarded monocrystalline blades into a new state.

[0052] The ideal process parameters can be determined by a person skilled in the art making some preliminary experiments. Depending on the material, CET models and/or microstructure diagrams already existed for this, such as, for example, for CMSX-4® [5] (see FIG. **1**), which can be reverted to.

[0053] In summary, it can be said that with methods according to the present disclosure it is important to first heat the entire substrate or the entire component externally to temperatures just below the melting temperature of the substrate. The temperature to be set is alloy-specific. The additional further heating by plasma jet is necessary to suppress oxidation of the surface. The hydrogen contained in the plasma jet creates reducing conditions. The desired temperatures should be as high as possible, so a temperature of 50 K below the melting temperature is desirable.

[0054] The temperature difference with the remaining substrate/component should be as low as possible because advantageously the region to be repaired should have as homogeneous a temperature distribution as possible. A high substrate temperature generally has an advantageous effect on the formation of residual stresses. Residual stresses can disadvantageously lead to flaking of the previously applied layer. The higher the substrate temperature, the lower the resulting residual stresses. Inhomogeneous temperature distribution of the component during spraying would therefore increase the susceptibility to residual stresses in the entire component.

[0055] The major difference with methods according to the present disclosure is the additional external heating of the substrate. Only with this is it possible to achieve the desired microstructure with the outstanding mechanical properties of the monocrystalline alloys and minimal residual stresses. In contrast, heating of the component only by the introduced energy of the plasma would not be sufficient.

[0056] The effects of the solidification speed and temperature gradient prevailing at that point on the resulting microstructure of the solidified material are shown in a CET (columnar to equiaxed transition) plot.

[0057] FIG. **2** schematically shows a solidification model for a method according to an embodiment. The molten powder particles impinge on the heated surface of the sample at velocity v_p. Three temperature zones arise close to the surface. The temperature near the substrate is below the melting temperature. There, the dendrites and the interdendritic region have already solidified. Above this is a transition region where the solidification front lies and where the dendrites form. The interdendritic region has not yet solidified. In the upper region of the image, the molten particles impinge on the substrate. Here, the temperature is above the melting temperature. Furthermore, the image in the substrate shows the large dendrite arm spacing $\lambda_{1\ substrate}$ that is formed by a very low solidification speed v and by a low temperature gradient G (see CET plot) during production of the monocrystalline substrates.

[0058] As a result of the high temperature of the molten powder particles, the temperature gradient G increases and the solidification speed v also increases due to the desired substrate temperature. This results in a reduced dendrite arm spacing of $\lambda_{1\ repair\ layer}$.

[0059] In the following, the directional solidification of CMSX-4® powder is shown by way of an example on an ERBO 1 substrate. These two alloys are very similar. The exact composition can be found in the table below. CMSX 4® is a registered trademark for a single crystal (SC) alloy by Cannon Muskegon, Mich. (USA). ERBO/1 is a second generation single crystal nickel-based superalloy by Doncasters Precision Casting, Bochum (Germany).

TABLE 1

Element [wt. %]	Al	Cr	Co	Hf	Mo	Re	Ti	Ta	W	Ni
CMSX-4 ® powder	6.0	6.4	9.5	0.1	0.6	2.9	0.9	8.5	8.1	Remainder
ERBO-1 ® substrate	5.7	6.5	9.6	0.1	0.6	2.9	1.0	6.5	6.4	Remainder

[0060] First, substrate samples measuring 32 mm×20 mm×2.5 mm and a hole with a diameter of 1.1 mm and a length of 10 mm are produced from ERBO 1 plates by means of spark eroding. FIG. **3** shows the sample geometry used here.

[0061] The substrate samples are ground and polished prior to coating. The surface was first treated successively with 320, 640, 1200 and finally with 4000 grit sandpaper.

[0062] The subsequent polishing was carried out by means of a soft cloth impregnated with a diamond suspension. First, a cloth with a suspension of diamond particles having an average particle size of approx. 3 μm was used and the surface was polished in a circular manner. A further cloth with a suspension of diamond particles having an average particle size of approx. 1 μm was then used and the surface was polished again.

[0063] The substrate surface thus treated and polished was examined with a light microscope. No scratches could be detected on the substrate surface.

[0064] Subsequently, the polished sample is incorporated into a heated sample holder. A technical drawing shows the exact configuration according to FIG. **4**.

[0065] An insulated SiN flat heater **2** having a power of 1000 W allows for heating sample **4** to up to 1100° C. in vacuo, preferably at 1 to 200 mbar. An SiC heating plate **3** is located on the heater **2** which ensures a constant temperature of the sample. The heater **2**, the thermally conductive plate (SiC) **3** and the sample **4** are surrounded by a fabricated insulation **1**, **5** which reduces convection. The sprayed layer or layers are applied via an opening in the panel **6**. The temperature is controlled by a controller and by the temperature measurement in the sample using a thermocouple. Both the cables of the thermocouple and the power cables of the heater are placed into the vacuum chamber separately by means of bushing.

[0066] The Sulzer Metco powder feeder twin 120 V is filled with CMSX-4® powder with spherical particles having an average geometric particle diameter of 25-60 μm. The average particle size was determined by means of laser diffraction using the Horiba LA-950V2 device by Retsch.

[0067] For the powder having an average particle diameter of 38.53 mm, for example, the D_{10} value was 27.70 μm, the D_{50} value was 39.77 μm and the D_{90} value was 55.27 μm.

[0068] The powder was stored beforehand at 150° C. over a period of 2 hours. This step serves to remove water in the powder.

[0069] This was followed by a coating process according to an embodiment. The injection parameters set for this purpose can be gathered from the following Table 2.

TABLE 2

Experiment No: v-17-061-f4	User:
Project: WDS, internally	Description: 20 × 30 × 2.5 mm
Injection part no.: RX samples	
Powder (line 1): CMSX 4/V2	Injection site (line 1): bottom (90°)
Powder (line 2): —	Injection site (line 2): —
Powder (line 3): —	Injection site (line 3): —
Scraper (line 1): NI	Powder gutter (line 1): 16 × 1.2
Scraper (line 2): —	Powder gutter (line 2): 11 × 0.5
Scraper (line 3): —	Powder gutter (line 3): 11 × 0.5
Process pressure (mbar): 60	Sputtering current (A):
Spray distance (mm): 275	Turntable (1/min):
Robot speed (mm/s): 440	Robot PRG: MHOR4 Y440 X120
Coating cycles/time: 8	0_2 addition (SLPM): 0
Substrate: CMSX-4	Surface treatment: blasted, polished
Coating temp. (° C.): 900	Layer thickness (μm): 320
Remarks: heated sample holder X +– 135 R10 = 3	Layer weight (g): 0
Diagnosis:	Report File: heated with meander program and powder fed directly

[0070] When the heating process is initiated, the sample heater is first activated. Starting from a temperature of approximately 300° C., the plasma flame of the F4-VB by Oerlinkon Metco supports the heating of the substrate surface until the coating temperature of approx. 900° C. is reached.

[0071] The hydrogen contained in the plasma gas containing argon (plasma gas: 50 NLPM argon and 9 NLPM hydrogen) provides for reducing conditions. This way, the oxygen contained in the argon can be selectively oxidized without reacting with the substrate surface and disadvantageously forming an oxide layer.

[0072] The parameters selected for the coating can be found in Table 3.

TABLE 3

Argon [NLPM]	50.0 ± 6.1
Hydrogen [NLPM]	9.0 ± 0.6
Sample temperature [° C.]	900 ± 10
Spray distance [mm]:	275 ± 0.1
Robot speed [mm/s]:	440 ± 5
Process pressure [mbar]:	60 ± 1
Powder feed rate in % based on the maximum feed rate	15 ± 0.5
(Absolute) powder feed rate	47.7 g/min.

[0073] After coating, a heat treatment is regularly advantageous.

[0074] Solution heat treatment (SHT) may be beneficial, for example, to reduce any inhomogeneities present in the structure of the coating.

[0075] Advantageously, the above-mentioned heat treatment can be carried out in a pressure-assisted manner with a hot isostatic press (HIP). The pressure-assisted heat treatment will regularly reduce pores in the structure.

[0076] The regular arrangement of the γ' precipitates within the γ matrix is regularly carried out by precipitation annealing. The γ' precipitates are mainly responsible for the very good mechanical properties in the high-temperature range.

[0077] The precise temperature profiles of the heat treatments made for this exemplary embodiment are listed below:

[0078] Annealing treatments: 1300-1315° C. in a protective atmosphere for 6 hours with subsequent cooling of 150-400° C./min to approx. 800° C.

[0079] Precipitation annealing: 1140±10° C. for 4 hours, then 870±10° C. for 16 hours in protective atmosphere.

[0080] FIGS. **5***a* and **5***b* show scanning electron micrographs of transverse grinds of the samples thus treated which show the directional solidification on the monocrystalline substrate. FIG. **5***a* shows the monocrystalline substrate onto which the repair layer was sprayed. The stalk-like structure of the grains in the polycrystalline layer is an indication of directional solidification. At the transition between substrate and layer, a region with a similar gray coloration as the substrate can be observed. Due to the crystal orientation contrast in the backscatter electron image of the scanning electron microscope, this means the same crystal orientation for substrate and layer in this same colored region. FIG. **5***b* shows a higher magnification of this region. There is no oxide in the transition from the substrate to the layer. This is very important for nucleation of the molten powder on the substrate. The dark γ' precipitates in the γ matrix can be seen in the substrate.

[0081] FIGS. **6***a* and **6***b* show scanning electron micrographs of transverse grinds of the same sample which, after coating with the above-mentioned parameters, was first solution annealed and then precipitation annealed.

[0082] FIG. **6***a* shows the transition region from the monocrystalline substrate to the repair layer. The dashed white line indicates the former interface. As a result of this heat treatment, the grains nucleated on the monocrystalline substrate grow into the polycrystalline layer at the expense of the small grains. A single-crystal structure with the same crystal orientation as the substrate is formed at least at the interface. The repair layer has only a slightly increased pore density which would disappear after pressure-assisted heat treatment by means of HIP. The smaller black dots mark Al_2O_3 inclusions which have formed as a result of slight oxidation of the injection material.

[0083] FIG. **6***b* shows an enlarged section. At the former interface, an Al_2O_3 porous zone towards the latter. Precipitation annealing leads to a reduction in the size of the γ' precipitates in the γ matrix and they are arranged in cubic fashion. This arrangement provides for the best possible mechanical properties of the alloy. In addition to the same crystal orientation contrast, the orientation of the precipitates shows that the monocrystallinity of the substrate was continued into the repair layer.

[0084] In addition to the examinations with a scanning probe microscope, recordings of electron backscatter diffraction (EBSD) analysis were also made for these samples (not shown here). The coating applied can be seen based on its red color, wherein the red color signals the (001) crystal plane in which the substrate material is also oriented. This serves to prove that with the application according to an embodiment, the applied, sprayed layer solidifies at least in wide areas in the same orientation as the monocrystalline substrate material.

[0085] During the development of the repair methods described herein, it was found that the porosity in the sprayed layer is determined by the rate of application resulting from the powder feed rate and the robot speed. Porosity of the layer is reduced as the application rate decreases. Furthermore, it was found that the size of the solidified grains depends on the powder size used. The size of the directionally solidified grains increases as particle diameters become larger.

[0086] If an oxide layer forms between the substrate and the repair layer which prevents nucleation, the quality of the argon should be improved with regard to oxygen content. Another reason for the formation of an oxide layer could be an unfavorable robot movement during spraying. Preferably, it should be adapted such that the sample does not leave the region of influence of the plasma torch. If no nucleation takes place on the polished surface of the region to be repaired although there is no oxide layer, the temperature of the workpiece to be repaired must be increased.

[0087] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive. It will be understood that changes and modifications may be made by those of ordinary skill within the scope of the following claims. In particular, the present invention covers further embodiments with any combination of features from different embodiments described above and below.

[0088] The terms used in the claims should be construed to have the broadest reasonable interpretation consistent with the foregoing description. For example, the use of the article “a” or “the” in introducing an element should not be interpreted as being exclusive of a plurality of elements. Likewise, the recitation of “or” should be interpreted as being inclusive, such that the recitation of “A or B” is not exclusive of “A and B,” unless it is clear from the context or the foregoing description that only one of A and B is intended. Further, the recitation of “at least one of A, B and C” should be interpreted as one or more of a group of elements consisting of A, B and C, and should not be interpreted as requiring at least one of each of the listed elements A, B and C, regardless of whether A, B and C are related as categories or otherwise. Moreover, the recitation of "A, B and/or C" or "at least one of A, B or C" should be interpreted as including any singular entity from the listed elements, e.g., A, any subset from the listed elements, e.g., A and B, or the entire list of elements A, B and C.

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1. A method for coating, with a coating material, a monocrystalline substrate surface of a component comprising a monocrystalline alloy, the method comprising:

polishing the monocrystalline substrate surface;

transferring the substrate to a vacuum chamber;

heating the entire substrate to a temperature of at least half a melting temperature of the substrate but less than a melting temperature of the substrate;

applying the coating material in powder form onto the polished monocrystalline substrate surface by vacuum plasma spraying, wherein the powder has a mean particle size in a range of 10 to 200 μm, wherein a pressure in a range of 1 to 200 mbar is set for the vacuum plasma spraying, and wherein an argon atmosphere having a hydrogen content in a range of 10 to 50 vol. % is used as a working gas for the vacuum plasma spraying; and

thereby generating at least one region directly at an interface of the coating material and the polished monocrystalline substrate surface having a same single-crystalline orientation as the substrate.

2. The method according to claim **1**, wherein the coating material is identical to a substrate material.

3. The method according to claim **2**, wherein the coating material and the substrate material are a monocrystalline nickel-based alloy or a cobalt-based alloy.

4. The method according to claim **1**, wherein the entire substrate is heated to at least 700° C.

5. The method according to claim **1**, wherein the entire substrate is heated electrically, inductively, or by electromagnetic radiation.

6. The method according to claim **1**, wherein the substrate surface is heated by a plasma torch without powder feed.

7. The method according to claim **1**, wherein the coated substrate is subsequently subjected to solution annealing, precipitation annealing, and/or pressure-assisted heat treatment for coating.

8. The method according to claim **1**, wherein the substrate has at least one cooling hole.

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