DEFECT HEALING OF DEPOSITED TITANIUM ALLOYS

BACKGROUND OF THE INVENTION

[0001] The invention relates to deposition of Ti-based materials. More particularly, the invention relates to addressing deposition defects.

[0002] A growing art exists regarding the deposition of Ti-based materials. For example, electron beam physical vapor deposition (EBPVD) may be used to build a coating or structural condensate of a Ti alloy atop a substrate of like or dissimilar nominal composition. Such techniques may be used in the aerospace industry for the repair or remanufacture of damaged or worn parts such as gas turbine engine components (e.g., blades, vanes, seals, and the like).

[0003] Deposition defects, however, potentially compromise the condensate integrity. One group of such defects arises when a droplet of material is spattered onto the substrate or the accumulating condensate. The melt pool may contain additives not intended to vaporize and accumulate in the condensate. For example, U.S. Patent No. 5,474,809 discloses use of refractory elements in the melt pool. Once the droplet lands on the surface (of the substrate or the accumulating condensate) further deposition builds atop the droplet and the adjacent surface. Along the sides of the droplet, there may be microstructural discontinuities in the accumulating material due to the relative orientation of the sides of the droplet. As further material accumulates, these discontinuities may continue to build all the way to the final condensate surface.

SUMMARY OF THE INVENTION

[0004] One aspect of the invention involves a method for treating a deposited titanium-base material from an initial condition to a treated condition. The material is heated from

a first temperature to a second temperature. The first temperature is below an equilibrium β transus. The second temperature is above the equilibrium β transus. The heating includes a portion at a rate in excess of 5°C/s. The material is cooled from the second temperature to a third temperature below the equilibrium β transus.

[0005] In various implementations, the heating may be to a peak at least 10°C above a non-equilibrium β transus. The material may be above the equilibrium β transus for a brief period (e.g., no more than 2.0 seconds). The heating and cooling may have sufficient rates to maintain a characteristic grain size of at least a matrix of the material below 100μm. In the initial condition, the material may include a number of defects having trunks with microstructures distinct from a microstructure of a matrix of the material. In the treated condition, the trunks' microstructures may be essentially integrated with the matrix microstructure.

[0006] In one group of implementations, the heating may be to a peak 10-50°C above a non-equilibrium β transus. The material may be above the equilibrium β transus for a very brief period (e.g., no more than 1.0 seconds). In another group of potentially overlapping implementations, the heating may be to 1-30°C above the equilibrium β transus for a somewhat longer period (e.g., 1.0-5.0 seconds). The cooling may be sufficiently rapid to limit β growth to a characteristic size smaller than 100μm. One group of materials consist in largest weight parts of titanium, aluminum, and vanadium. An exemplary material thickness may be at least 2.0mm (e.g., for relatively thick structural and repair material, contrasted with thinner coatings).

[0007] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description

below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 is an optical micrograph of a Ti-6Al-4V condensate atop a like substrate and showing defects.

[0009] FIG. 2 is a view of a healed condensate.

[0010] FIG. 3 is a temperature-time diagram showing healing processes.

[0011] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0012] FIG. 1 shows a condensate 20 accumulated atop a surface 22 of a substrate 24. Exemplary condensate thickness may be from less than 0.2mm (e.g., for thin coatings) to in excess of 2mm (at least locally - e.g., for structural condensates such as certain repairs). The condensate has a first defect 26 triggered by a spattered molybdenum droplet 28 that landed atop the surface 22. Exemplary droplet sizes are 30-500μm (measured as a characteristic (mean/median/mode) transverse dimension). The defect comprises a trunk 30 extending from the droplet 28 toward the condensate surface (not shown). A second defect 32 is shown and may have been triggered by a droplet below the cut surface of the view.

[0013] The exemplary deposition is of nominal Ti-6Al-4V condensate atop a like substrate. Alternate depositions may include Ti-6Al-2Sn-4Zr-2Mo and Ti-8Al-1Mo-1V. The deposition may be from a melted ingot at least partially through a pool containing one or more refractory or other elements which may be essentially non-consumed during deposition (e.g., a pool formed from a 30%Mo-70%Zr mixture). Accordingly, the droplets may tend to have composition similar to the surface layers of the pool. In the absence of the non-consumed pool additive, the droplet 28 might have a similar composition to the ingot yet still produce similar defects. Many droplets in systems using an Mo-containing pool would have Mo concentrations of at least 10% by weight; others at least 20%. This may be somewhat less than the Mo percentage of the non-expending pool material to reflect possible dilution by deposition material elements in the pool.

[0014] In the exemplary implementation, the substrate 28 has an α-β microstructure of medium to coarse grains (e.g., 10-40μm characteristic grain size (e.g., mean) or about ASTM 10.5-6.5). An exemplary 10-20% by weight of the substrate is β

phase with the remainder essentially α phase. The condensate matrix (away from the defects) also has an α-β microstructure but of very fine grains (e.g., acicular α grains of 5-10μm in length and 2-5μm in thickness, lengthwise oriented along the condensate growth/deposition direction). The trunk size will depend, in substantial part, upon the droplet size. Exemplary trunk diameters are from about 20μm to about 50μm. However, much larger trunks are possible. The trunks have a columnar α-β microstructure. This microstructure may have a characteristic grain size several times greater than that in the matrix and the grains may be elongated in the direction of accumulation (i.e., away from the substrate). Particularly in the case of very large diameter trunks (e.g., in excess of 100μm in diameter), there may be porosity around the trunk. The grain discontinuity at the trunk-matrix interface and the particular alignment of trunk grains may cause structural weaknesses affecting, *inter alia*, ductility, fracture toughness, fatigue resistance, fretting fatigue resistance, corrosion resistance, wear resistance, crack nucleation resistance, and the like.

[0015] We have, accordingly, developed heat treatment regimes for healing workpieces having such defects. FIG. 2 shows a condensate 50 after healing. In this view, the substrate is not shown. The condensate surface 52 is, however, shown. A defect within the condensate had been caused by a droplet 54. The resultant trunk had propagated all the way to the surface forming a bulge 56. The healed condensate, however, shows essentially no remaining artifacts of the defect other than the original droplet 54 and bulge 56. The trunk has been microstructurally integrated with the condensate matrix as a fine β equiaxed microstructure (e.g., grain size of 10-100μm (~ASTM 10.5-3.5)). Additionally, laminar variations in chemistry or microstructure may be diminished or eliminated, thereby increasing the isotropy of the condensate mechanical

properties. The bulge 56 may be removed (e.g., during a subsequent surface machining). The healing permits the workpiece (e.g., a blade, vane, seal, or the like) to be operated at ambient temperature (e.g., 0-40°C) and/or at elevated temperatures (e.g., above 250°C, such as in the range of 300-500°C) essentially without increased chances of failure.

Example 1

[0016] In a first exemplary healing method, the workpiece is initially at room temperature (condition/location 100) on the temperature against time plot of FIG. 3. FIG. 3 further shows a line 102 representing the equilibrium β transus (T^{e}_{β}) as well as curves 104 and 106 of non-equilibrium β transus temperatures for the condensate and substrate, respectively (specific to the microstructural and thermal history of this Example 1). The equilibrium β transus temperature is a function of chemistry only. Because the exemplary condensate and substrate have the same chemistry, they share the same equilibrium β transus temperature (e.g., 960-1010°C for Ti-6Al-4V). The non-equilibrium β transus temperature is a function of composition, grain size/morphology, and heating rate. The smaller the grains, the lower the transus temperature. The more rapid the heating rate, the higher the transus temperature. At very slow heating rates, the equilibrium transus temperature equals the non-equilibrium transus temperature. Given very fine condensate grains, medium to coarse substrate grains, and a heating rate of approximately 100°C/sec, it is estimated that the difference between the non-equilibrium β transus of the two structures is about 100°C.

[0017] In a first stage, the workpiece is heated 109 moderately above the condensate non-equilibrium β transus

(condition/location 110). This heating may be under vacuum or in an inert atmosphere. This heating is advantageously rapid (e.g., occurring at a rate of 5-100°C/s or greater) so as to prevent excessive grain growth. Excessive grain growth (e.g., above 150μm (~ASTM 2.5) or even 100μm (~ASTM 3.5), depending upon the application) is disadvantageous because it excessively reduces structural properties including one or more of ductility, fracture toughness, fatigue resistance, fretting fatigue resistance, corrosion resistance, wear resistance, crack nucleation resistance, and the like. The heating reaches a peak of ΔT_1 above the condensate non-equilibrium β transus of approximately 10-50°C. The heating substantially converts the condensate microstructure to β. The upper limit on ΔT_1 will reflect the microstructural/thermal history and is advantageously sufficiently low to avoid excessive β grain growth (in view of time considerations discussed below). The lower limit is advantageously high enough to provide essentially complete transition to the β phase (α+β to β). The substrate may be essentially unaffected.

[0018] In a second stage, the workpiece is rapidly cooled 111 back to room temperature (condition/location 112). This heating may be under the same vacuum or atmosphere as the first stage. During this cooling, metastable martensite may accumulate in the condensate and the substrate. The cooling is advantageously sufficiently rapid to further limit β grain growth. The rapid heating and cooling maintain the condensate above its equilibrium β transus for a time interval sufficiently brief to avoid the excessive β grain growth noted above while providing the β phase transition. An exemplary time interval above the equilibrium β transus is 1.0 seconds or less. Once below the β transus, the β will transform to α+β in a β-transformed (also known as transformed β) microstructure. This microstructure is characterized by

preservation of the boundaries of the prior β grains with α (e.g., in needle- or platelet-like form) in a β matrix within such boundaries. The rapid heating and cooling may provide a sufficiently short time at elevated temperature (in view of the magnitude of such temperature) to greatly limit oxidation even if the procedure is performed in an ambient atmosphere rather than under vacuum or an inert atmosphere. Thus, especially for workpieces to be exposed to relatively low thermal and mechanical stresses (e.g., some non-rotating turbine engine parts), there may be greater environmental flexibility during the heating and/or cooling.

[0019] An optional third stage (not shown in FIG. 3) involves annealing/aging by heating the workpiece to an annealing temperature (e.g., in the vicinity of 500-600°C for the exemplary Ti alloy). The exemplary annealing/aging is for a period of 1-24 hours and is effective to eliminate the martensite but without producing β grain growth. This may leave the condensate as essentially fine grain β (e.g., broadly smaller than 150μm, more narrowly smaller than 100μm, and preferably smaller than 50μm (~ASTM 2.5, 3.5, and 5.5, respectively)) plus the droplets and leaves the substrate as essentially medium to coarse grain α-β. However, the cooling of the second stage may be sufficiently slow to avoid martensite formation, in which case it is particularly appropriate to omit the aging/annealing.

Example 2

[0020] In a second exemplary healing method, the initial heating stage 119 is similarly rapid but to a temperature above the equilibrium β transus but below the condensate non-equilibrium β transus. The resulting condition/location 120 may be at a temperature of ΔT_2 above the equilibrium β transus (e.g., by 10-30°C). The upper limit on this range is

advantageously effective to avoid excessive β grain growth. The lower limit on this range is advantageously high enough to provide essentially complete transition to the β phase (α+β to β). The substrate may be essentially unaffected.

[0021] Rather than being immediately followed by rapid cooling, the workpiece is maintained 121 at such a temperature for a moderate time interval (e.g., of about two seconds, more broadly 1.5-4.0 seconds or 1.0-5.0 seconds) to achieve a condition/location 122. It is during this time interval that the condensate microstructure changes to fine β as in condition/location 110. Thereafter, a rapid cooling 123 may transition the workpiece to a condition/location 124 similar to 112 and may, in turn, be followed by a similar annealing/aging if appropriate or desired.

[0022] The heating and cooling may be performed by a variety of techniques. One family of rapid heating techniques provides highly local heating (exemplary such techniques include induction heating, laser heating, electron beam heating, and the like). Such heating facilitates heating of the condensate with less substantial heating of the substrate, thereby minimizing any structural effects on the substrate. The desired heating depth may be controlled in view of the coating thickness by means including frequency control of induction heating, beam intensity of laser or electron beam heating, and the like. With some implementations of such heating, the heating may progress across the condensate (e.g., by moving or reorienting the workpiece relative to the heating source). Direct electrical resistance heating may be used to more generally heat the workpiece. The exemplary rapid cooling may be performed by forced cooling with an inert gas (especially when the heating is performed under vacuum), forced air cooling, liquid quench (e.g., in oil or water), and the like.

[0023] One or more embodiments of the present invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, details of the chemical composition of the particular substrate and condensate and of the physical configuration of the substrate and thickness of the condensate may influence details of any particular implementation. Accordingly, other embodiments are within the scope of the following claims.

CLAIMS

What is claimed is:

1. A method for treating a deposited titanium-base material from an initial condition to a treated condition comprising:

heating from a first temperature to a second temperature, the first temperature being below an equilibrium β transus, the second temperature being above the equilibrium β transus, and the heating including a portion at a rate in excess of 5°C/s; and

cooling from the second temperature to a third temperature below the equilibrium β transus.

2. The method of claim 1 wherein:

the heating is to a peak at least 10°C above a non-equilibrium β transus; and

the material is above the equilibrium β transus for a period of no more than 2.0 seconds.

3. The method of claim 1 wherein:

the heating and cooling have sufficient rates to maintain a characteristic grain size of at least a matrix of the material smaller than 100μm.

4. The method of claim 1 wherein:

in the initial condition, the material includes a plurality of defects having trunks with a microstructure distinct from a microstructure of a matrix of the material; and

in the treated condition, the trunks' microstructure have been essentially integrated with the matrix microstructure.

5. The method of claim 1 wherein:

the heating is to a peak 10-50°C above a non-equilibrium β transus; and

the material is above the equilibrium β transus for a period of no more than 1.0 seconds.

6. The method of claim 1 wherein:

the heating is 1-30°C above the equilibrium β transus for a period of 1.0-5.0 seconds; and

the cooling is sufficiently rapid to limit β growth to a characteristic size smaller than 100μm.

7. The method of claim 1 wherein:

the material consists in largest weight parts of titanium, aluminum, and vanadium; and

the material has a maximum thickness of at least 2.0mm.

8. The method of claim 1 wherein:

the material is on a titanium-base substrate; and

the heating leaves essentially unaffected a microstructure of a major portion of the substrate.

9. The method of claim 1 wherein:

the heating is selected from the group consisting of direct resistance heating, induction heating, electron beam heating, and combinations thereof.

10. The method of claim 1 further comprising:

depositing the material on a titanium-base substrate.

11. The method of claim 10 wherein:

the depositing comprises electron beam physical vapor deposition.

12. The method of claim 10 wherein:

the material and the substrate consist essentially of an alloy of 5-7 weight percent aluminum, 3-5 weight percent vanadium, balance titanium, with less than 3 weight percent other components.

13. The method of claim 1 further comprising:
maintaining the material at a temperature of 500-660°C.

14. The method of claim 1 further comprising:
an annealing and aging step.

15. The method of claim 1 used to repair a gas turbine engine component having a titanium-base substrate.

16. The method of claim 15 further comprising:
operating the repaired component at a temperature in excess of 250°C.

17. The method of claim 1 wherein in the treated condition a laminar variation in at least a first alloy component is less than in the initial condition.

18. A method for treating a deposited titanium-base material, the material initially having:
a matrix having first nominal chemistry and a first characteristic grain size and first characteristic grain structure;
a plurality of spits within the matrix and having:
a droplet having a higher level of refractory impurities than the matrix; and
a trunk extending from the droplet and having essentially the same chemistry as the matrix, but a larger second characteristic grain size and less equiaxed second grain structure,

the method comprising:

heating the material; and

cooling the material, the heating and cooling being sufficiently rapid to convert an α-β microstructure of the material to an essentially β-transformed microstructure, optionally including metastable martensite, and having a characteristic grain size smaller than 100μm.

19. The method of claim 18 wherein:

the first nominal chemistry is essentially Ti-6Al-4V;

the second nominal chemistry is essentially Ti-6Al-4V; and

the material is atop an essentially Ti-6Al-4V substrate.

20. The method of claim 18 wherein:

at least some of the spits are further characterized by porosity adjacent their trunks; and

at least some of the porosity is healed.

21. The method of claim 18 wherein:

the droplets comprise at least 10% of one or a combination of refractory metals, by weight.

22. The method of claim 18 further comprising:

an annealing/aging step effective to essentially eliminate the martensite.

23. The method of claim 18 wherein:

the material is a repair material on a turbine engine component.

24. A component having:

a Ti-based metallic substrate; and

a Ti-based condensate atop the substrate and having:

a surface;

a plurality of embedded droplets below the surface;

regions directly between the droplets and the surface characterized by

an essentially β-transformed microstructure of a characteristic grain size below 100μm.

25. The component of claim 24 wherein:

at least some of said droplets are at least 200μm below the surface.

26. The component of claim 24 wherein:

at least some of said droplets are at least 20μm in characteristic transverse dimension.

27. The component of claim 24 wherein:

at least some of said droplets comprise at least 20% Mo, by weight.

28. The component of claim 24 wherein:

the substrate and the condensate each consist essentially of Ti-6Al-4V.

29. The component of claim 24 being one of a gas turbine engine compressor blade, fan blade, disk, drum rotor, bearing housing, vane, and seal element.