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Vacuum heat-treatment method for ultra-high-toughness, medium-strength, high-ductility TC32 titanium-alloy parts

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Abstract

The invention concerns scientific and technical processing of metallic materials, specifically a vacuum heat-treatment method for TC32 titanium-alloy parts with ultra-high toughness, medium strength and high ductility. Place the parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa. Heat with the furnace at 0.3 °C/s to Tβ + 10 °C and soak for 45-90 min. Then cool with the furnace at 80-180 °C/s to Tβ - 10 °C and soak for 25-35 min. Subsequently cool at 0.001-0.1 °C/s to 500-550 °C and soak for 300-380 min, then remove and air cool. Rapid cooling across the phase-transformation region followed by slow cooling in the two-phase region precisely controls the microstructure. The disclosed method significantly improves the overall properties of TC32, attaining fracture toughness of at least 140 MPa·m^1/2, ductility of at least 15%, and strength of at least 850 MPa.

Claims

1. A vacuum heat-treatment method for ultra-high-toughness, medium-strength, high-ductility TC32 titanium-alloy parts, comprising: (1) place cleaned TC32 parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa; (2) heat the parts uniformly with the furnace to Tβ + 10 °C and soak for 45-90 min, where Tβ is the phase-transformation temperature of TC32; (3) cool uniformly with the furnace to Tβ - 10 °C and soak for 25-35 min; (4) cool uniformly with the furnace to 500-550 °C, soak for 300-380 min, and remove for cooling. The process applies to the alpha-beta two-phase titanium alloy designated TC32. Its principal chemical-element contents by mass are Al 4.5-5.5%, Mo 2.5-3.5%, Cr 2.5-3.5%, Zr 0.5-1.5%, Si 0.1-0.2%, Fe ≤0.3%, C ≤0.08%, N ≤0.05%, H ≤0.0125%, O ≤0.2%, and Ti balance.

2. The method of claim 1, wherein the vacuum heat-treatment furnace in step 1 is a vacuum furnace with a controllable cooling rate.

3. The method of claim 1, wherein step 2 heats the TC32 titanium-alloy parts with the furnace at 0.3 °C/s.

4. The method of claim 1, wherein Tβ in step 2 is the TC32 phase-transformation temperature determined metallographically.

5. The method of claim 1, wherein step 3 uses a furnace cooling rate of 80-180 °C/s after the holding period.

6. The method of claim 1, wherein step 4 uses a furnace cooling rate of 0.001-0.1 °C/s after the holding period.

7. The method of claim 1, wherein the cooling after removal from the furnace in step 4 is air cooling to room temperature.

8. The method of claim 1, wherein the TC32 parts in step 1 may be cleaned with organic solvents such as industrial ethanol or acetone.

Description

Original paragraph identifiers are retained for comparison. Tables are re-typeset in English; original values and reported inconsistencies are preserved.

[0001] Technical field. The invention belongs to scientific and technical processing of metallic materials and concerns a vacuum heat-treatment method for TC32 titanium-alloy parts with ultra-high toughness, medium strength and high ductility.

[0002] Background. As aviation technology has developed, aircraft structural design has progressed through static strength, dynamic strength and fatigue strength to fracture strength. Titanium alloys with high fracture toughness have therefore received attention, promoting their application technology. Increasing overall performance requirements for a new generation of Chinese aircraft require the design allowable fracture-toughness value of the titanium alloy in certain critical structural parts to reach the ultra-high-toughness class of 140 MPa·m^1/2, together with medium strength and high ductility. The high-fracture-toughness alloys currently used in Chinese aviation are mainly TC4-DT and TC21. After quasi-beta heat treatment (granted patent ZL200410090864.3), the maximum measured mean fracture toughness of TC4-DT can reach the 110 MPa·m^1/2 class. After quasi-beta forging (granted patent ZL01131237.8), the maximum measured mean for TC21 can reach the 100 MPa·m^1/2 class. Neither meets these use requirements.

[0003] TC32 is a new titanium alloy with low cost and high overall performance, developed successfully by the Beijing Institute of Aeronautical Materials using low-cost alloying and combined strengthening and toughening technologies (the source cites granted patent ZL201218001211.9). Its principal composition is Ti-5Al-3Mo-3Cr-1Zr. Research found that its favourable chemical composition provides a wide hot-working window and particularly good strength-toughness matching: strength does not fall markedly as fracture toughness increases significantly. Conventional treatment in resistance or fuel-fired furnaces, such as beta or quasi-beta heat treatment, currently produces a maximum measured mean fracture toughness in the 125 MPa·m^1/2 class but ductility of only about 11%, still insufficient. One reason is the inability to control cooling rates precisely at different stages, which prevents adequate suppression of brittle grain-boundary alpha precipitation. Another is the tendency of the part matrix to absorb hydrogen and oxygen during high-temperature holding. These effects limit further gains in toughness and ductility. Finer microstructural control and a new treatment method are therefore needed to reach the 140 MPa·m^1/2 toughness class, achieve high ductility and retain sufficient strength.

[0004] Disclosure of the invention. The objective is to remedy deficiencies in existing technology by providing this vacuum heat-treatment method, meeting the requirements of critical structural parts in a new generation of advanced Chinese aircraft.

[0005] Heat-treatment experiments on TC32 found that a lamellar microstructure provides the highest fracture toughness; the treatment temperature should therefore be above the phase-transformation temperature. However, increasing temperature and holding time markedly enlarges prior-beta grains

and reduces ductility. Grain-growth kinetics research shows that prolonged holding at Tβ + 10 °C does not cause pronounced grain growth in TC32, allowing toughness to improve without significantly reducing ductility.

[0006] The relatively low ductility of lamellar structures produced by existing methods is due not only to some grain growth but also to straight grain-boundary alpha, particularly at triple junctions, where early microcracks more readily initiate. Grain-boundary alpha also reduces toughness. Research on its precipitation in TC32 shows that rapid cooling from above the transformation point can suppress it. Verification found substantial suppression above 80 °C/s, but rates above 180 °C/s cause excessive quench-induced internal stress, leading to microcracks or distortion. A rate of 80-180 °C/s across the transformation region is therefore appropriate to suppress grain-boundary alpha to some extent.

[0007] Alpha-colony size is a microstructural parameter that significantly affects fracture toughness. Larger colonies markedly improve TC32 fracture toughness. Their precipitation and development are principally controlled by elemental diffusion. Excessively rapid cooling causes intragranular alpha to precipitate in a basketweave arrangement, producing colonies that are too small for favourable toughness. Slower cooling during colony formation and growth is therefore beneficial. Experiments confirmed that rates below 0.1 °C/s favour full precipitation and development, but the minimum should not be below 0.001 °C/s when treatment time and cost are considered. During prolonged slow cooling, hydrogen and oxygen absorption by the matrix must also be rigorously avoided to protect toughness and ductility.

[0008] Research on alpha-colony precipitation in TC32 also shows that colonies first precipitate at grain-boundary alpha and rapidly grow into the grains. Because rapid cooling across the transformation region partly suppresses grain-boundary alpha precipitation, choosing the rate-change temperature within the two-phase region becomes especially important. Experiments compared rate-change temperatures of Tβ - 50 °C, Tβ - 30 °C, Tβ - 20 °C, Tβ - 15 °C and Tβ - 10 °C. Lower changeover temperatures extend the rapid-cooling interval; along with grain-boundary alpha, they suppress alpha-colony precipitation and development. The resulting structures are mostly high-aspect-ratio, non-uniform basketweave structures and do not favour higher toughness. When the rate-change temperature in the two-phase region is above Tβ - 10 °C, alpha precipitation can be suppressed to some extent without preventing full alpha-colony precipitation and development.

[0009] Finally, prolonged holding at 500-550 °C enables dispersed alpha to precipitate fully from residual beta. Dispersion strengthening maintains TC32 at a medium-to-high strength level above 850 MPa.

[0010] This analysis shows that precisely controlling the structure of TC32 parts to obtain ultra-high toughness (≥140 MPa·m^1/2), high ductility (≥15%) and adequate strength (≥850 MPa) cannot be fully achieved with resistance or fuel-fired furnace treatment that cannot precisely regulate cooling rates in different temperature ranges.

[0011] The technical solution adopted by the invention is as follows.

[0012] Step 1: place cleaned TC32 titanium-alloy parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa.

[0013] Step 2: heat the parts with the furnace at 0.3 °C/s to Tβ + 10 °C and soak for 45-90 min; Tβ is the TC32 phase-transformation temperature.

[0014] Step 3: after the hold, cool with the furnace at 80-180 °C/s to Tβ - 10 °C and soak for 25-35 min.

[0015] Step 4: after the hold, cool with the furnace at 0.001-0.1 °C/s to 500-550 °C and soak for 300-380 min; remove and air cool.

[0016] The furnace in step 1 is a vacuum furnace with a controllable cooling rate.

[0017] Compared with existing technology, the invention has the following advantages.

[0018] Using a vacuum furnace with controllable cooling, the invention rapidly cools TC32 parts across the phase-transformation region and slowly cools them through the two-phase region, achieving fine microstructural control. The method substantially suppresses grain-boundary alpha precipitation in the lamellar structure while ensuring full alpha-colony precipitation and development. It also eliminates the risk, described in the invention, of oxygen and hydrogen interstitial uptake during slow cooling. The reported overall mechanical properties are significantly improved: fracture toughness is at least 140 MPa·m^1/2, ductility at least 15%, and strength at least 850 MPa.

[0019] Brief description of the drawing. The invention is described in further detail below with reference to the drawing and examples.

[0020] Figure 1 is the heat-treatment flow diagram of the technical solution.

[0021] Detailed embodiments. The Chinese-designated TC32 alpha-beta two-phase titanium alloy complies in composition with GB/T 3620.1-2016, Designation and composition of titanium and titanium alloys. Its principal element contents by mass are: Al 4.5-5.5%, Mo 2.5-3.5%, Cr 2.5-3.5%, Zr 0.5-1.5%, Si 0.1-0.2%, Fe ≤0.3%, C ≤0.08%, N ≤0.05%, H ≤0.0125%, O ≤0.2%, Ti balance.

[0022] Example 1: heat treatment of a critical structural part for an aircraft type. The phase-transformation temperature of this heat of TC32 is 912 °C.

[0023] Step 1: place the cleaned TC32 parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa.

[0024] Step 2: heat with the furnace at 0.3 °C/s to 922 °C and soak for 55 min.

[0025] Step 3: cool with the furnace at 120 °C/s to 902 °C and soak for 30 min.

[0026] Step 4: cool with the furnace at 0.01 °C/s to 520 °C and soak for 360 min; remove and air cool.

[0027] Table 1 gives the mechanical-test results from a sectioned TC32 critical structural aircraft part.

[0028] Table 1. Mechanical properties of sectioned TC32 critical structural aircraft parts.

[0029]

Direction	Tensile strength / MPa	Yield strength / MPa	Elongation / %	Area reduction / %
L	866	788	17.2	34.6
L	856	780	16.8	33.7
L	863	781	17.4	35.0
T	853	783	16.9	33.2
T	855	785	16.8	34.6
T	868	795	17.1	34.3

Fracture toughness: T-L orientation: 148.87 and 149.42 MPa·m^1/2.

[0030] Example 2: heat treatment of a critical structural part for an aircraft type. The phase-transformation temperature of this heat of TC32 is 915 °C.

[0031] Step 1: place the cleaned TC32 parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa.

[0032] Step 2: heat with the furnace at 0.3 °C/s to 925 °C and soak for 70 min.

[0033] Step 3: cool with the furnace at 150 °C/s to 905 °C and soak for 30 min.

[0034] Step 4: cool with the furnace at 0.05 °C/s to 540 °C and soak for 360 min; remove and air cool.

[0035] Table 2 gives the mechanical-test results from a sectioned TC32 critical structural aircraft part.

[0036] Table 2. Mechanical properties of sectioned TC32 critical structural aircraft parts.

[0037]

Direction	Tensile strength / MPa	Yield strength / MPa	Elongation / %	Area reduction / %
L	876	800	16.3	30.7
L	873	792	15.8	32.6
L	882	802	16.4	33.3
T	871	799	16.7	30.9
T	864	789	16.5	34.0
T	878	800	15.6	32.8

Fracture toughness: T-L orientation: 146.44 and 147.36 MPa·m^1/2.

[0038] Example 3: heat treatment of a critical structural part for an aircraft type. The phase-transformation temperature of this heat of TC32 is 910 °C.

[0039] Step 1: place the cleaned TC32 parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa.

[0040] Step 2: heat with the furnace at 0.3 °C/s to 920 °C and soak for 60 min.

[0041] Step 3: cool with the furnace at 80 °C/s to 900 °C and soak for 30 min.

[0042] Step 4: cool with the furnace at 0.001 °C/s to 500 °C and soak for 360 min; remove and air cool.

[0043] Table 3 gives the mechanical-test results from a sectioned TC32 critical structural aircraft part.

[0044] Table 3. Mechanical properties of sectioned TC32 critical structural aircraft parts.

[0045-0046]

Direction	Tensile strength / MPa	Yield strength / MPa	Elongation / %	Area reduction / %
L	890	821	15.4	30.4
L	894	823	15.5	31.5
L	899	824	16.3	32.4
T	889	825	15.7	30.5
T	895	829	14.8	29.8
T	893	826	14.7	28.8

Fracture toughness: T-L orientation: 142.35 and 141.48 MPa·m^1/2. Source values of 14.8% and 14.7% elongation are retained as printed.

[0047] Example 4: heat treatment of a critical structural part for an aircraft type. The phase-transformation temperature of this heat of TC32 is 913 °C.

[0048] Step 1: place the cleaned TC32 parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa.

[0049] Step 2: heat with the furnace at 0.3 °C/s to 923 °C and soak for 80 min.

[0050] Step 3: cool with the furnace at 180 °C/s to 900 °C and soak for 30 min. [Translator note: 900 °C is the value printed in this example and is retained without correction.]

[0051] Step 4: cool with the furnace at 0.1 °C/s to 550 °C and soak for 360 min; remove and air cool.

[0052] Table 4 gives the mechanical-test results from a sectioned TC32 critical structural aircraft part.

[0053] Table 4. Mechanical properties of sectioned TC32 critical structural aircraft parts.

[0054]

Direction	Tensile strength / MPa	Yield strength / MPa	Elongation / %	Area reduction / %
L	864	789	17.6	34.8
L	863	785	16.9	34.1
L	866	785	17.8	35.2
T	856	779	16.5	33.7
T	867	782	16.4	33.5
T	860	789	17.3	34.1

Fracture toughness: T-L orientation: 150.36 and 154.52 MPa·m^1/2.

[0055] Example 5: heat treatment of a critical structural part for an aircraft type. The phase-transformation temperature of this heat of TC32 is 916 °C.

[0056] Step 1: place the cleaned TC32 parts in a vacuum heat-treatment furnace at a pressure no greater than 6.7 × 10^-2 Pa.

[0057] Step 2: heat with the furnace at 0.3 °C/s to 926 °C and soak for 75 min.

[0058] Step 3: cool with the furnace at 100 °C/s to 906 °C and soak for 30 min.

[0059] Step 4: cool with the furnace at 0.08 °C/s to 550 °C and soak for 360 min; remove and air cool.

[0060] Table 5 gives the mechanical-test results from a sectioned TC32 critical structural aircraft part.

[0061] Table 5. Mechanical properties of sectioned TC32 critical structural aircraft parts.

[0062]

Direction	Tensile strength / MPa	Yield strength / MPa	Elongation / %	Area reduction / %
L	869	787	17.3	34.4
L	865	784	16.8	34.3
L	867	787	17.5	34.5
T	858	778	15.5	32.7
T	865	783	15.9	32.8
T	869	786	16.2	33.3

Fracture toughness: T-L orientation: 149.52 and 147.38 MPa·m^1/2.

Drawings

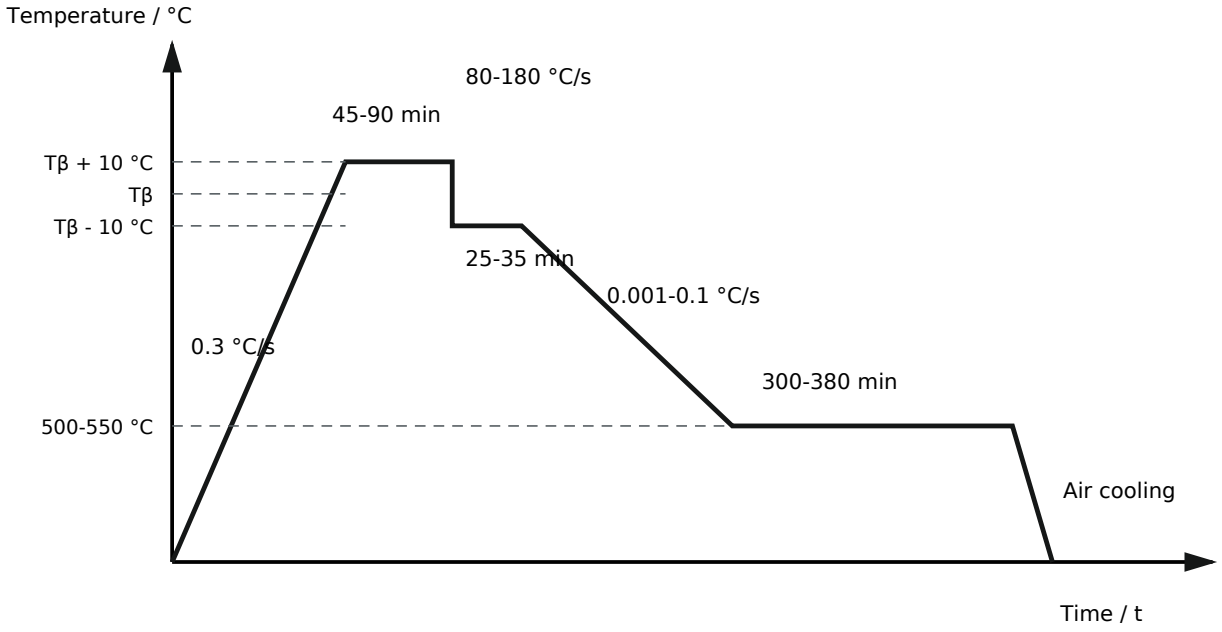


Figure 1. Heat-treatment sequence (schematic; original labels translated into English).