Heat Treatment Qualification of Forged and Ring-Rolled Ti-6Al-4V components for Particle Accelerator Applications

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ABSTRACT

This paper presents the qualification of a heat treatment cycle for a Ti-6Al-4V (Titanium Alloy Grade F5) component manufactured by open-die forging and seamless ring rolling. The objective was to demonstrate compliance with the mechanical property and microstructural requirements specified by CERN for the beam dumps to be installed in the High Luminosity upgrade of the Large Hadron Collider. The qualification component was a seamless rolled ring with dimensions of approximately 720 mm outside diameter, 17 mm wall thickness, and 885 mm height, where material homogeneity, structural integrity, and reliable mechanical performance are essential.

A dedicated manufacturing and qualification program was developed to identify an optimum heat treatment cycle providing the required combination of strength, ductility and microstructural uniformity. Following forging and ring-rolling operations, the qualification ring was sectioned into multiple sectors and subjected to different heat treatment conditions. The investigated cycles included solution treatment at temperatures within the α+β phase field below the β-transus temperature, followed by water quenching and subsequent aging or annealing.

The effects of heat-treatment parameters were evaluated by tensile testing in longitudinal and transverse orientations and by metallographic examination at the outside diameter, mid-thickness, and inside diameter. Based on the results, a modified duplex annealing cycle consisting of solution treatment at 965 °C followed by annealing at 705 °C was selected as the optimum condition. This cycle provided compliant strength and ductility in both orientations together with a homogeneous, predominantly equiaxed α+β microstructure without a continuous α network at prior-β grain boundaries.

KEYWORDS: TI-6AL-4V - OPEN DIE FORGING - RING ROLLING - HEAT TREATMENT QUALIFICATION BETA-TRANSUS –TENSILE TESTING - MICROSTRUCTURE - PARTICLE ACCELERATOR

1. INTRODUCTION

Ti-6Al-4V is an α+β titanium alloy containing approximately **6% aluminium** and **4% vanadium** and is one of the most widely used titanium alloys because of its combination of low weight, specific strength, fracture toughness, and corrosion resistance. These characteristics make it suitable for demanding aerospace, defence, energy, scientific, and high-technology applications.

The component investigated in this study is a seamless ring manufactured by open-die forging followed by ring rolling for a particle accelerator beam system application. The finished seamless rings form the vessel of the beam dumps [17] of the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) [18] at CERN. The beam dumps are the only devices in the accelerator that are capable of safely and repeatedly absorbing the stored energy of the proton beams, which can reach up to 710 MJ in the HL-LHC era. The beam is absorbed by the 8.4 m-long dumps in only 86 µs. The seamless rings are circumferentially welded by electron beam to constitute the total length of the vessel. A series of carbon-based materials are shrink fitted inside the vessel to ensure a good thermal contact for cooling performance purposes.

The objective of this work was to qualify an industrially robust heat-treatment cycle capable of meeting the required mechanical and microstructural criteria prior to serial production.

2. COMPONENT AND RAW MATERIAL

The qualification component was manufactured from **Ti-6Al-4V, ASTM B381 Grade F-5,** using a **triple vacuum-arc-remelted (VAR) ingot** with a diameter of approximately 590 mm. The finished ring dimensions were approximately 722 mm OD × 688 mm ID × 885 mm height (Fig.1). The forged/ ring-rolled blank measured approximately **782 mm OD × 568 mm ID × 904 mm height**.

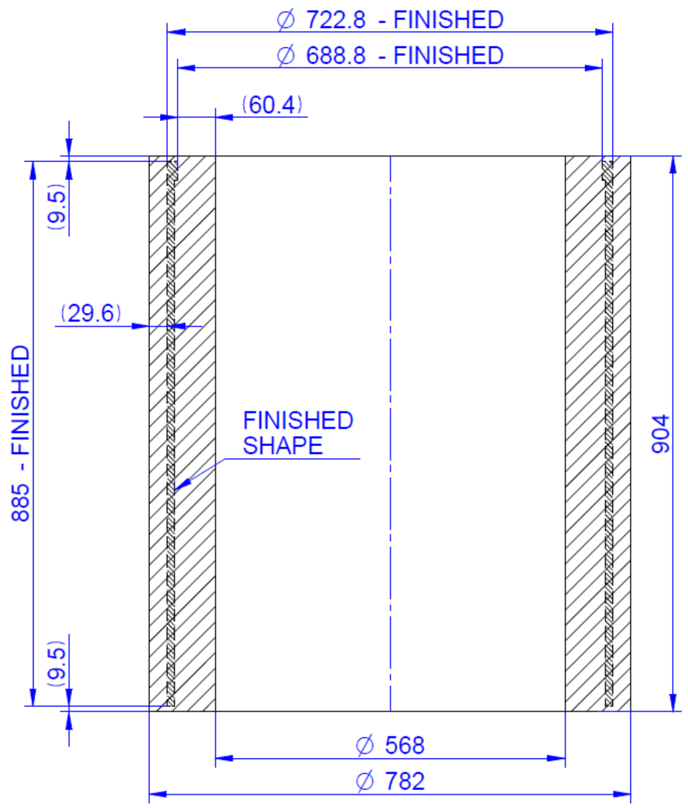


Fig.1 - Ti-6Al-4V qualification ring and principal dimensions.

The chemical composition of the qualification component is indicated in the below table 1 with titanium as the balance.

Tab. 1 - Chemical Composition

Element	Al	V	Fe	O	H	N	C
wt.%	6.34	4.25	0.174	0.162	0.0006	0.006	0.011

A key characteristic of Ti-6Al-4V is its **β-transus temperature**, above which the microstructure consists entirely of the β phase, while below this temperature α and β phases coexist. Since the heat treatment cycles investigated in this study were performed below the β-transus, this temperature represents an important reference for controlling the resulting microstructure and mechanical properties. For Ti-6Al-4V, the β-transus is typically in the range of **995-1000°C**.

3. FORGING PROCESS

The triple-VAR ingot was heated to 950 °C and forged within the range **950–820 °C.** Intermediate reheating was performed when the forging temperature approached 820 °C. The open die forging route comprised drawing, upsetting and re-drawing operations, followed by upsetting in a die and piercing with a Ø250 mm mandrel to produce a ring preform. The preform was subsequently radial-axial ring rolled from approximately 570 mm OD × 250 mm ID to 782 mm OD × 568 mm ID. **The reported total hot-working reduction ratio was approximately 6.7**. After ring rolling, the component was air cooled to room temperature.

4. HEAT TREATMENT QUALIFICATION OBJECTIVES

The qualification programme was designed to identify a heat-treatment cycle satisfying both mechanical-property and microstructural acceptance criteria.

The minimum target properties derived from ASTM B381 and supplemented by CERN specification are summarized in Tab.2.

Tab. 2 - Target Mechanical Properties

Property	Requirement
Tensile strength, Rm	≥ 895 MPa
0.2% yield strength, Rp0.2	≥ 828 MPa
Elongation, A5 (L and T)	≥ 10%
Reduction of area (L and T)	≥ 25%
Legends: *L - Longitudinal (along the grain flow direction i.e. Tangential/ Circumferential orientation for Rolled Ring).* *T - Transverse (across the grain flow direction i.e. Axial orientation representing Long-Transverse direction for Rolled Ring)*	

The required microstructure comprised equiaxed or equiaxed-and-elongated primary α in a transformed β matrix, or an essentially complete field of equiaxed and/or elongated α with or without intergranular β. In all cases, a continuous α network at prior-β grain boundaries was unacceptable.

Following heat treatment and machining, the component was also required to meet the specified surface and volumetric NDE requirements. Surface NDE include 100% Dye Penetrant Testing according to EN 10228-2, Quality Class 3 using Colour or Fluorescent penetrants. Volumetric NDE include 100% Ultrasonic Flaw Detection as per AMS-STD-2154 Class AA.

5. CUT PLAN OF THE QUALIFICATION RING

Following the forging and ring-rolling operations, the qualification ring was cut into three sections: **A**, **B** & **C** as shown in Fig. 2, measuring approximately **782 mm OD × 568 mm ID × 160 mm H**. Each section of the ring was rough machined to **772 mm OD × 652 mm ID × 150 mm H** as shown in Fig. 3 before heat treatment.

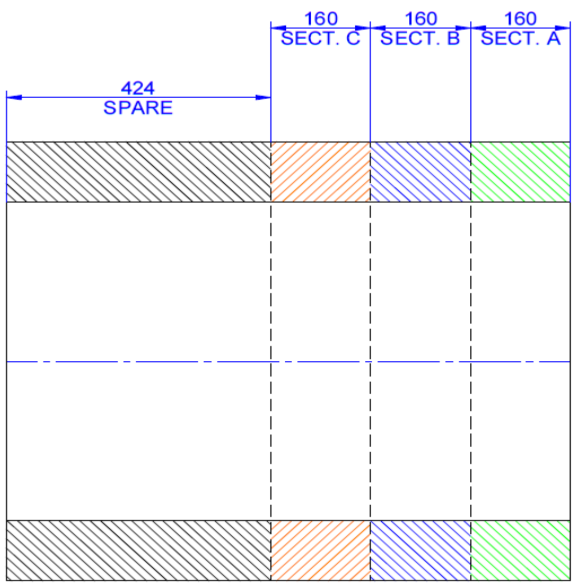


Fig.2 - Schematic representation of the qualification ring cut into different sections

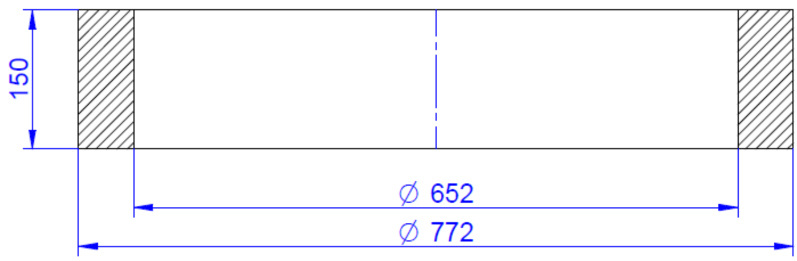


Fig.3 - Rough machined section

6. QUALIFICATION MATRIX

The qualification matrix was established in accordance with the requirements and processing windows defined by **SAE AMS-H-81200** and the applicable Ti-6Al-4V material specifications, including **AMS4928**, **AMS4950**, **AMS 4965**, **AMS4967, AMS 6930 and AMS 6931**. These standards were used to define the permissible heat treatment temperatures and to ensure that all evaluated cycles remained within established industrial practice for Ti-6Al-4V forgings and rings.

Sections **A** and **B** were solution treated at **954°C** and **920°C** respectively. The **954°C** solution treatment temperature was selected towards the upper limit of the recommended α+β solution treatment range to maximize the strengthening effect while remaining below the β-transus temperature. The **920°C** solution treatment temperature was chosen as a lower-temperature condition within the allowable specification range to evaluate its influence on microstructure, strength, ductility, and property isotropy.

Each section was subsequently divided into four equal sectors and subjected to different Aging treatments, as defined in the qualification matrix (Tab. 3). The aging temperatures of **538°C, 593°C, and 620°C** were selected to represent the range of aging treatments permitted by aerospace material specifications for solution-treated and aged Ti-6Al-4V products. These conditions were investigated to assess the effect of precipitation strengthening on the strength-ductility balance.

Section **C** was divided into four sectors to evaluate annealing and solution treatment plus annealing cycles (Duplex annealing), as defined in the qualification matrix (Tab. 2). The annealing temperatures of **705°C and 730°C** were selected based on the recommendations of **SAE AMS-H-81200**, **AMS4928**, **AMS4967**, and **AMS6931** for annealed Ti-6Al-4V products. These temperatures were chosen to evaluate their ability to promote a stable and homogeneous equiaxed α+β microstructure while maintaining adequate strength and ductility. For Duplex annealing cycles (i.e. solution treatment plus annealing heat treatment), the solution treatment temperature of **965°C** was chosen in accordance with **SAE AMS-H-81200** with subsequent annealing to the aforementioned temperatures without the intermediate stabilization ageing.

Tab. 3 - Heat Treatment Qualification Matrix

Section	Sector	Heat treatment Condition
A	**A1**	Solution treat 954°C/1.5 h, water quench, no aging
	A2	Solution treat 954°C/1.5 h, water quench + Aging 593°C/ 4 h, air cool
	A3	Solution treat 954°C/1.5 h, water quench + Aging 538°C/ 4 h, air cool
	A4	Solution treat 954°C/1.5 h, water quench + Aging 620°C/ 4 h, air cool
B	**B1**	Solution treat 920°C/1.5 h, water quench, no aging
	B2	Solution treat 920°C/1.5 h, water quench + Aging 593°C/ 4 h, air cool
	B3	Solution treat 920°C/1.5 h, water quench + Aging 538°C/ 4 h, air cool
	B4	Solution treat 920°C/1.5 h, water quench + Aging 620°C/ 4 h, air cool
C	**C1**	Anneal 705°C/ 4 h, air cool
	C2	Anneal 730°C/ 4 h, air cool
	C3	Solution treat 965°C/1.5 h, water quench + Anneal 705°C/ 4 h, air cool
	C4	Solution treat 965°C/1.5 h, water quench + Anneal 730°C/ 4 h, air cool

This experimental matrix enabled the evaluation of the effects of solution treatment temperature and aging/ annealing on the mechanical properties and microstructural evolution of the forged Ti-6Al-4V ring.

7. HEAT TREATMENT PROCEDURE

For solution treatment at 954 °C, heating from 250 °C to 940 °C was performed at 80 °C/h, followed by heating from 941 °C to 954 °C at 30 °C/h. The soak time was 1.5 h after the set temperature was reached on the contact thermocouple. The component was then immersion quenched in water. For the 920 °C condition, the corresponding intermediate temperature was 905 °C, followed by heating to 920 °C at 30 °C/h. The water temperature was maintained below 40 °C and the reported quench delay was within 60 s.

Ageing treatments for Sections A and B were performed at 538 °C, 593 °C and 620 °C for 4 h, followed by still-air cooling. The heating rate for all ageing treatments was performed at 80 °C/h from 200°C till 30 °C below the set temperature and then at 30 °C/h to the set temperature by the contact thermocouple.

For Section C, annealing was performed at 705 °C and 730 °C for 4 h followed by air cooling. The solution-treated-and-annealed conditions used 965 °C / 1.5 h, water quench followed by annealing at 705 °C / 4 h. No stabilization ageing between 565-595°C/ 8 h as per SAE AMS-H-81200 was carried out prior to annealing, to optimize the processing cost. The heating rate for all annealing cycles was performed at 80 °C/h from 250°C till 30 °C below the set temperature and then at 30 °C/h to the set temperature by the contact thermocouple.

8. MATERIAL SAMPLING AND TEST PLAN (MSTP)

After completion of the heat-treatment cycles, two tensile specimens and three metallographic specimens were extracted from each sector, as shown in Fig.4. Tensile specimens were taken in longitudinal (tangential) and transverse (axial) orientations at mid-thickness location (½T). Metallographic examination was performed at the OD, mid-thickness (½T), and ID locations. Tensile testing followed ASTM E8/E8M and the applicable CERN test specification (EDMS No. 3316137 Annex 1, §2.5) by using a strain rate of 0.005 mm/mm/min ± 0.002 mm/mm/min through the 0.2% offset yield strain. Metallographic examination followed AMS 2380 and the applicable CERN specification (EDMS No. 3316137 Annex 1, §2.4) on the cross section of the longitudinal (tangential) direction.

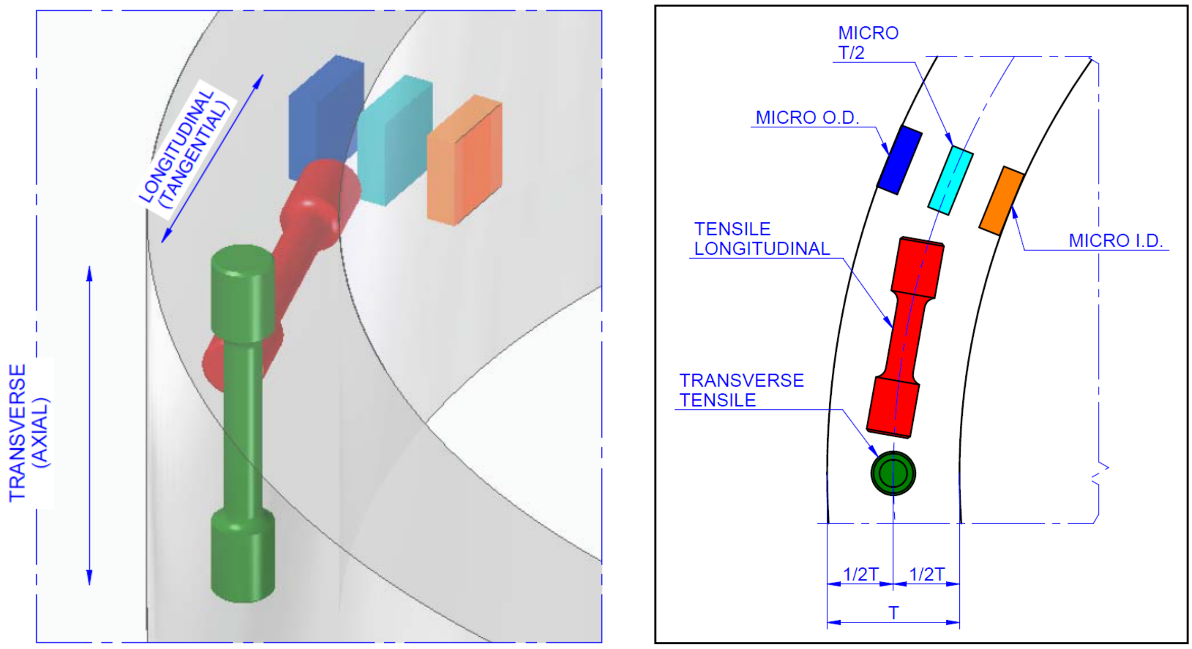


Fig.4 - Definition of sampling locations and orientations for tensile testing and microstructural examination.

9. TENSILE TEST RESULTS

The tensile test results obtained for the investigated heat treatment conditions are summarized in Tab. 4.

Tab. 4 - Tensile test results for the investigated heat treatment conditions

Sample	Direction	Heat treatment cycle	Sy [MPa]	Ut [MPa]	El. [%]	RA [%]
		Specification →	***≥ 828***	***≥ 895***	***≥ 10***	***≥ 25***
A1	L	ST 954°C	836	998	8.5	18.0
A1	T	ST 954°C	829	957	7.5	22.0
A2	L	ST 954°C + Age 593°C	917	1041	9.0	24.0
A2	T	ST 954°C + Age 593°C	885	967	8.5	28.0
A3	L	ST 954°C + Age 538°C	956	1067	11.0	22.0
A3	T	ST 954°C + Age 538°C	883	990	9.0	26.0
A4	L	ST 954°C + Age 620°C	895	985	13.5	24.0
A4	T	ST 954°C + Age 620°C	865	955	10.5	23.5
B1	L	ST 920°C	901	1038	10.0	25.0
B1	T	ST 920°C	858	982	11.5	22.0
B2	L	ST 920°C + Age 593°C	928	1023	9.5	21.0
B2	T	ST 920°C + Age 593°C	911	993	7.0	24.0
B3	L	ST 920°C + Age 538°C	935	1036	10.0	27.0
B3	T	ST 920°C + Age 538°C	896	982	6.5	23.0
B4	L	ST 920°C + Age 620°C	886	976	11.5	23.5
B4	T	ST 920°C + Age 620°C	862	958	10.5	22.5
C1	L	Anneal 705°C	898	984	14.5	31.5
C1	T	Anneal 705°C	881	968	13.5	28.5
C2	L	Anneal 730°C	895	971	14.0	30.0
C2	T	Anneal 730°C	886	961	13.0	28.5
C3	L	ST 965°C + Anneal 705°C	922	1012	17.5	31.5
C3	T	ST 965°C + Anneal 705°C	908	995	15.0	28.0
C4	L	ST 965°C + Anneal 730°C	908	998	17.0	31.0
C4	T	ST 965°C + Anneal 730°C	892	984	15.5	28.5

(Legends; L- Longitudinal (Tangential); T-Transverse (Axial) Note: The values shown in green are compliant with ASTM B381 and CERN Specification, whereas the values shown in red are outside the acceptance limits)

All investigated conditions met the minimum yield- and tensile-strength requirements. However, the decisive differentiator was ductility. Conditions in Sections A and B frequently failed the elongation and/or reduction-of-area requirements, particularly in the transverse direction. In contrast, all Section C conditions met the specified tensile, yield, elongation and reduction-of-area requirements in both orientations.

Condition C3 gave the strongest overall combination of properties: longitudinal YS/UTS of 922/1012 MPa and transverse YS/UTS of 908/995 MPa, with elongation of 17.5% and 15.0% and reduction of area of 31.5% and 28.0%, respectively. Condition C4 was also compliant but showed slightly lower strength. Therefore, C3 was selected as the preferred production condition.

Fig.5.1 -Yield Strength (0.2% Rp0.2) by Heat treatment condition and orientation

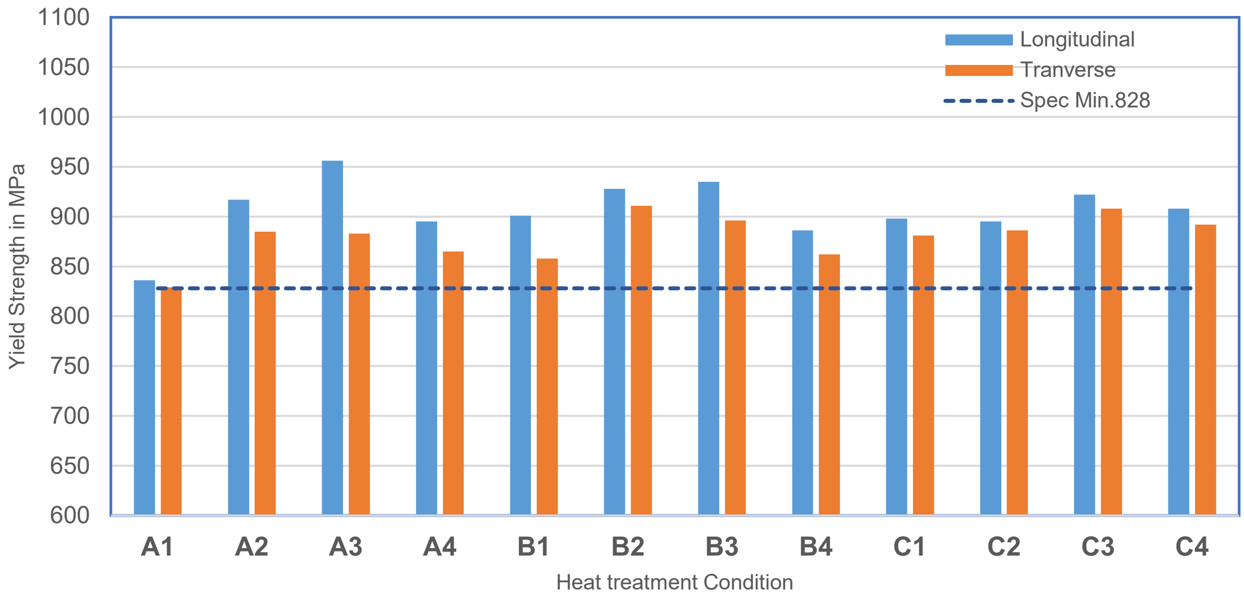
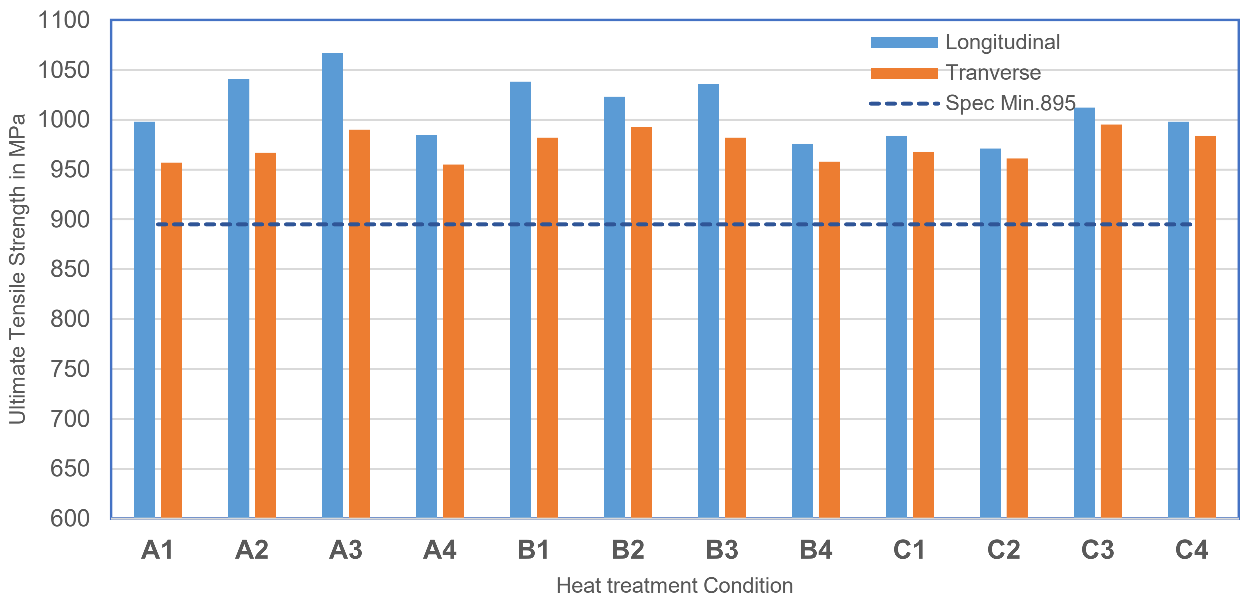
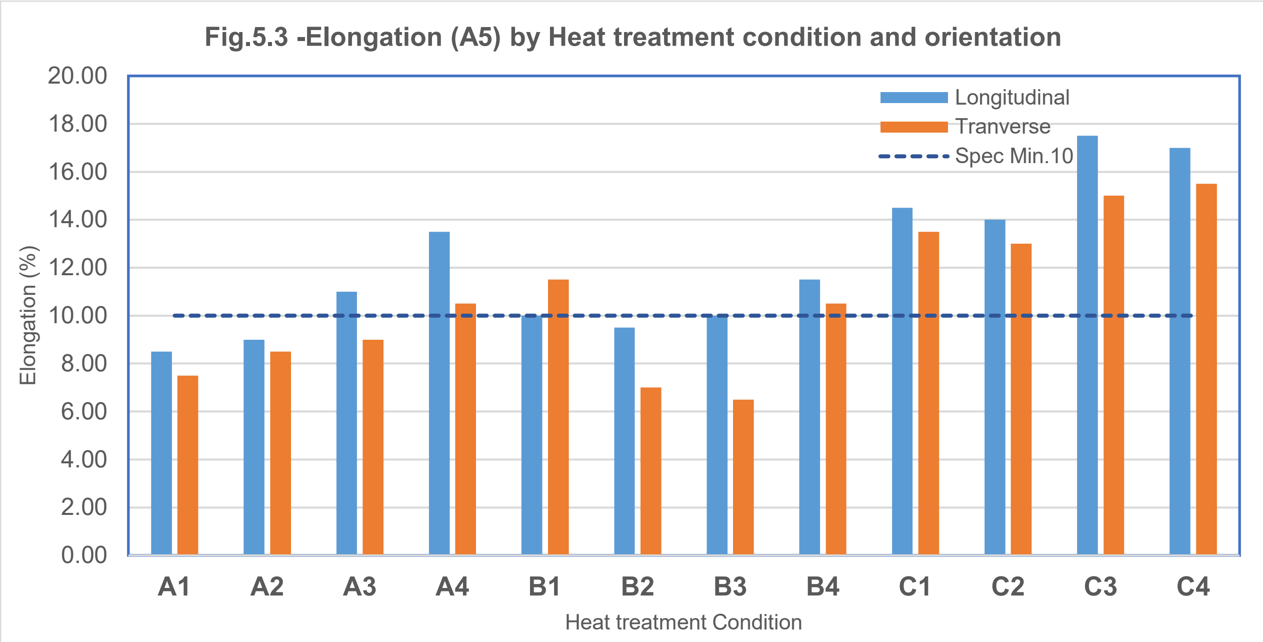
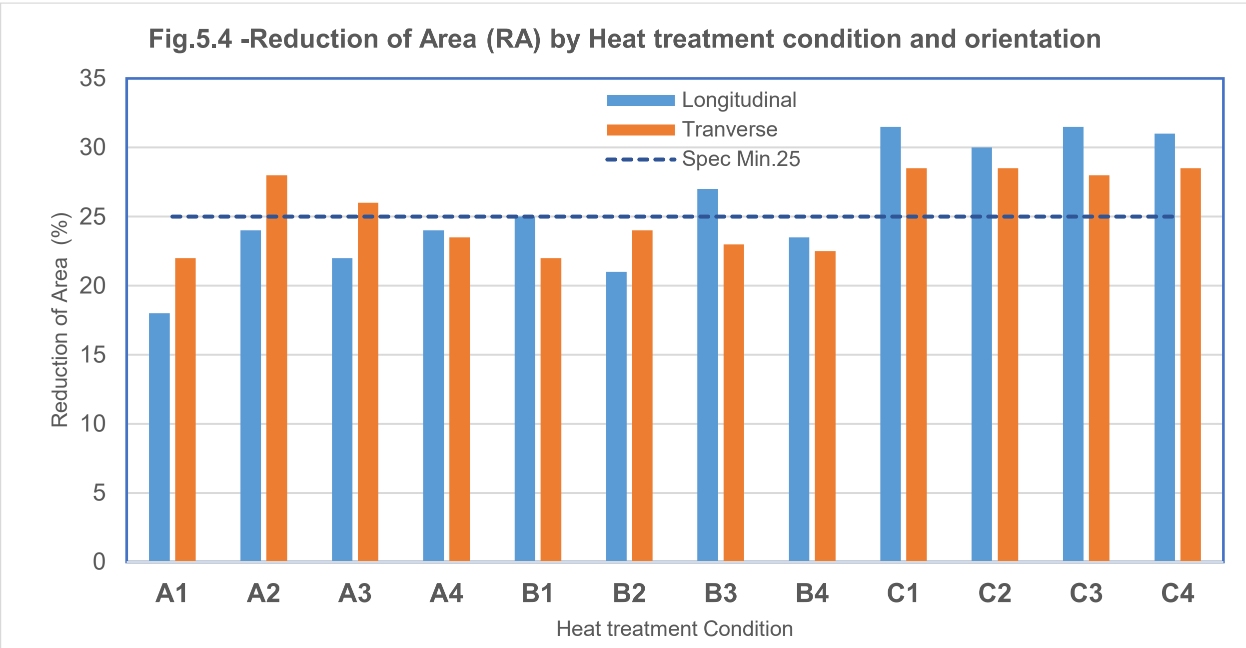


Fig.5.2 -Ultimate Tensile Strength by Heat treatment condition and orientation







10. MICROSTRUCTURAL EVALUATION

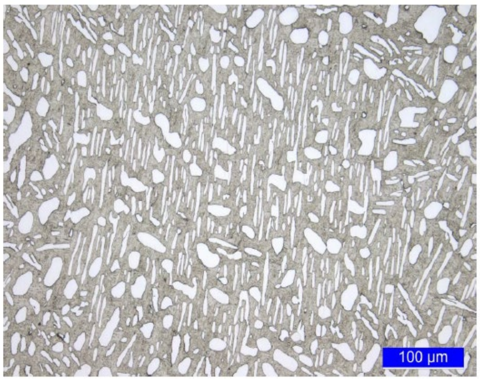
Metallographic evaluation focused on primary-α morphology, transformed β, and the absence of a continuous α network at prior-β grain boundaries. The 954 °C + 538 °C aged condition (A3) showed a high fraction of transformed β and a less uniform primary-α morphology. The 920 °C + 538 °C condition (B3) showed an α+β structure with predominantly elongated primary α.

The annealed condition C1 showed a predominantly equiaxed α+β microstructure, although localized elongated α regions remained. Condition C3 (965 °C solution treatment followed by 705 °C annealing for 4 h) produced the most favorable result: a homogeneous, predominantly equiaxed α+β microstructure without evidence of a continuous α network at prior-β grain boundaries. This observation was consistent with its superior combination of strength and ductility.

Representative microstructures for the most significant heat treatment conditions are shown in **Fig**. 6

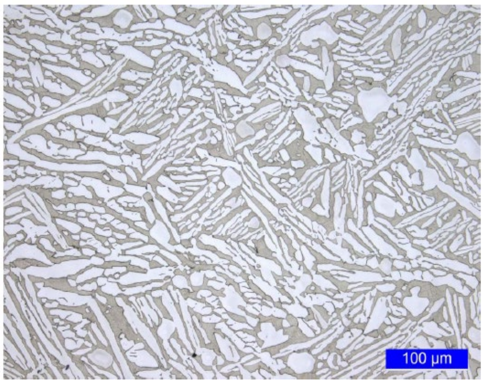
(a) **A3**

Solution treated 954°C + Aged 538°C



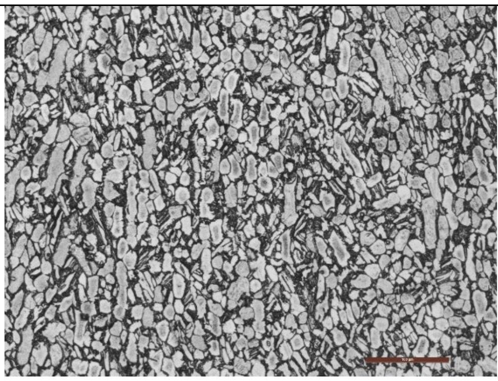
(b) **B3**

Solution treated 920°C + Aged 538°C



(c) **C1**

Annealed 705°C



(d) **C3**

Solution treated 965°C + Annealed 705°C

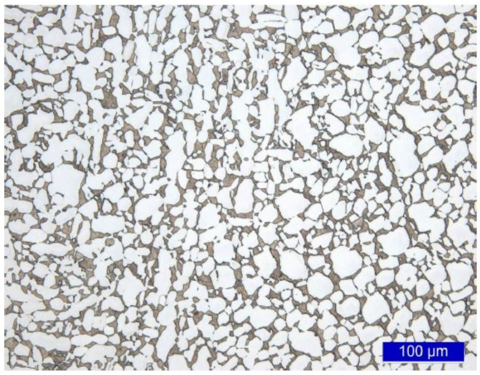


Fig. 6 Representative microstructures of the most significant heat treatment conditions evaluated during the qualification program. (a) **A3** showing a high fraction of transformed β and non-uniform primary α morphology; (b) **B3** exhibiting an elongated α+β structure; (c) **C1** presenting a predominantly equiaxed α+β microstructure after annealing; and (d) **C3** showing a homogeneous equiaxed α+β microstructure free from continuous grain-boundary α, which was selected as the production heat treatment condition.

11. QUALIFICATION OUTCOME

Tab. 5 - Summary of Heat Treatment Qualification Results

Cond.	Heat Treatment	Strength Compliance	Ductility Compliance	Microstructure Assessment	Overall Assessment
A1	ST 954°C	✓	✗	--	Rejected
A2	ST 954°C + Age 593°C	✓	✗	--	Rejected
A3	ST 954°C + Age 538°C	✓	✗	Predominantly transformed β, non-uniform α	Rejected
A4	ST 954°C + Age 620°C	✓	Partial	--	Rejected
B1	ST 920°C	✓	Partial	--	Rejected
B2	ST 920°C + Age 593°C	✓	✗	--	Rejected
B3	ST 920°C + Age 538°C	✓	✗	Elongated α+β structure	Rejected
B4	ST 920°C + Age 620°C	✓	Partial	--	Rejected
C1	Anneal 705°C	✓	✓	Predominantly equiaxed α+β	Acceptable
C2	Anneal 730°C	✓	✓	--	Acceptable

C3	ST 965°C + Anneal 705°C	✓	✓	Homogeneous equiaxed α+β	✅ **SELECTED**
C4	ST 965°C + Anneal 730°C	✓	✓	Comparable to C3	Alternate

Legend: ST = Solution Treatment; ✓ = Meets requirements; ❌ = Does not meet requirements.

12. CONCLUSIONS

- A heat-treatment qualification program was completed for a forged and ring-rolled Ti-6Al-4V (ASTM B381 Grade F-5) ring intended for a particle-accelerator beam-system application.
- Solution treatment at 920 °C and 954 °C, with or without ageing, generally provided adequate strength but did not consistently satisfy the required ductility criteria.
- Annealing-based conditions in Section C provided the most favorable balance of strength and ductility, with compliant results in both longitudinal and transverse orientations.
- Condition C3-965 °C solution treatment for 1.5 h, water quenching, followed by 705 °C annealing for 4 h and air cooling ("modified" duplex annealing)-provided the highest overall mechanical performance among the investigated conditions.
- The C3 microstructure was homogeneous and predominantly equiaxed α+β, with no continuous α network at prior-β grain boundaries.
- C3 was therefore selected as the production heat-treatment cycle for the CERN beam-dump ring-rolled forgings.
- The qualified heat treatment cycle on the production parts complies with all the requirements of the applicable CERN technical specification for Ti-6Al-4V forged ring products, including tensile properties, microstructure, non-destructive examinations and dimensional controls.

13. REFERENCES

[1] ASTM B381 - 21 - Standard Specification for Titanium and Titanium Alloy Forgings
[2] ASTM B348/B348M - 25 - Standard Specification for Titanium and Titanium Alloy Bars and Billets
[3] ASTM E8/E8M - 24 - Standard Test Methods for Tension Testing of Metallic Materials
[4] SAE AMS2380 REV.H - Approval and Control of Premium-Quality Titanium Alloys
[5] SAE AMS4920 REV.H - Titanium Alloy, Forgings 6Al - 4V Alpha-Beta or Beta Processed, Annealed
[6] SAE AMS4928 REV.X - Titanium Alloy Bars, Wire, Forgings, Flash-Welded Rings, and Drawn Shapes, 6Al - 4V Annealed
[7] SAE AMS4950 REV.F - Titanium Alloy, Bars, Wire, Forgings, and Rings 6.0Al - 4.0V Solution Heat Treated and Aged Modified Strength
[8] SAE AMS4965 REV.N - Titanium Alloy, Bars, Wire, Forgings, and Rings 6.0Al - 4.0V Solution Heat Treated and Aged
[9] SAE AMS4967 REV.N - Titanium Alloy, Bars, Wire, Forgings, and Rings 6.0Al - 4.0V Annealed, Heat Treatable
[10] SAE AMS6930 REV.G - Titanium Alloy Bars, Forgings and Forging Stock, 6.0Al - 4.0V, Solution Heat Treated and Aged
[11] SAE AMS6931 REV.D - Titanium Alloy Bars, Forgings and Forging Stock 6.0Al - 4.0V Annealed
[12] SAE AMS2801 REV.D - Heat Treatment of Titanium Alloy Parts
[13] SAE AMS-H-81200 REV.D - Heat Treatment of Titanium and Titanium Alloys
[14] EDMS No 3316137 August 2025 Technical Specification - Supply of Titanium Grade F-5 (Ti 6Al-4V) - Ring Rolled Forged Blanks for HL-LHC Beam Dumps
[15] EDMS No 3316137 Annex 1 Material Specification - Supply of Titanium Grade F-5 (Ti 6Al-4V) - Ring Rolled Forged blanks for HL-LHC Beam Dumps Titanium alloy - Grade F-5 - Ti (6Al-4V) UNS R56400
[16] EDMS No 2912302 11.07.2023 - Titanium alloy forged blanks/hollow shapes for general applications Titanium alloy - Grade F-5 - Ti (6Al-4V) UNS R56400
[17] The High Luminosity Large Hadron Collider-HL-LHC by O.Bruning and L.Rossi, CERN
[18] Towards the detailed Design of HL-LHC beam dumps by A.Lund, N.Solieri, IPAC 2026, France