Recent Titanium Research and Development in Germany

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This paper gives an overview about recent research and development work performed at universities and major research facilities as well as at different areas of industry covering the production and application of Titanium alloys in Germany. Examples of research addressing the relationship of microstructure and mechanical properties on conventional Titanium alloys are presented; additionally, investigations on coatings protecting material from erosion will be highlighted. Furthermore, alloying concepts and latest alloy developments focusing on γ-Titanium-Aluminides are shown. On the production side, a review of new developments at Germany's major melting, forging and investment casting facilities is given. Finally, a brief survey is presented about recent development work on Titanium components used in a wide variety of different applications, covering aerospace, aero-engine and automotive industry.

Keywords: *Ti64, Ti6242, Ti6246, Ti5553, skull melting, Ti-Erosion coating, microstructure, fatigue, crack propagation, thermohydrogen processing*

1. Melting and Casting

ThyssenKrupp Titanium GmbH, Germany, and ThyssenKrupp Titanium S.p.A., Italy, have developed a skull melting route to serial production offering a broad range of possibilities especially with respect to shortage of raw materials. By skull melting the raw material as scrap, sponge and/or alloying elements are liquefied in a crucible and poured into a mould. The charge can be bulk weldables, sponge, master alloys, turnings, briquettes, feed stock as well as any randomly shaped pieces suitable to the configuration of the crucible for melting. By the skull melting process a high degree of metal homogeneity can be reached as the material is mixed well in the liquid state. The melting itself is similar to the vacuum arc remelting process. High interstitial defects (HID) and/or high density inclusions (HDI) as well as low density inclusions (LDI) are resolved or will remain in the skull and will become smaller and smaller during the run of the subsequent remelting phase. The described procedure uses the residual skull from the previous heat as the consumable electrode for the next one. Statistical evaluation of the analysis of the chemical composition of numerous single skull molten ingots in Ti-6Al-4V grade shows a high degree of homogeneity for both, metallic elements as well as gaseous components, which is at least equivalent to the standard VAR process regarding top as well as bottom location of the slab. The microstructure, internal integrity and mechanical properties of Ti-6Al-4V plates produced from skull melted slabs are suitable for aerospace application. Hot rolled plates out of the skull melting furnace fulfill the aerospace specification requirements of AMS 6945 to a high extent[1] (Figure 1).

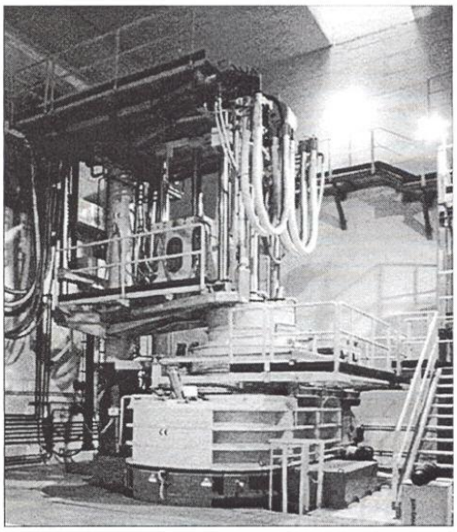

Figure 1: Skull melting furnace
(courtesy ThyssenKrupp Titanium)

Titan-Aluminium-Feinguss GmbH, Bestwig, Germany (Tital) has demonstrated the producibility of very thin walled structural titanium investment castings using their standard shelling technique and gravity titanium casting. The reference geometry used has a famous history: this part (Figure 2) was used in 1980 to show that aluminum investment castings are airworthy. Tests later on showed that the aluminum casting had 10 times the lifetime compared to an assembled design. The wall thickness of this casting is at a minimum 1.6 mm. In preparation for the titanium casting process, deliberately no pickling surplus was added to this pattern (in contrary to common practices in titanium investment casting). The reason was just to cast the 1.6 mm wall thickness and not to cast with additionally pickling surplus and subsequently etch down to the desired wall thickness. Using this technique the titanium cast parts have been manufactured fulfilling the desired targets. This successfully finished in-house program of Tital was the trigger for the decision to invest in a bigger VAR skull melting furnace. This investment will bring Titan-Alumium-Feinguss GmbH in a position to melt up to 500 kg of titanium and so to supply titanium investment castings up to a diameter of 1500 mm with a height of up to 800 mm.

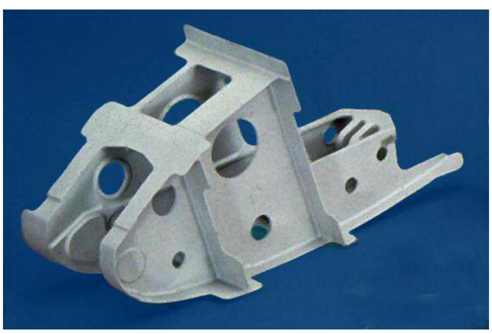

Figure 2: Structural Titanium Investment Cast Part
length: 510mm; width 180mm; height 260mm
minimum wall thickness: 1.6mm
(courtesy Titan-Aluminium-Feinguss GmbH)

2. Forging

The application of forgings made from high strength metastable beta titanium alloys has continuously increased because of their weight reduction potential for replacing titanium alloys like Ti- 6Al-4V or high strength steels. The alloy Ti-5Al-5V-5Mo-3Cr is a new candidate for the application of forged fuselage structures and forged landing gear of future aircraft. Besides attractive properties it offers a robust forging process and an air cooling after solution treatment resulting in a lower level of residual stresses and reduced distortion during machining.
Otto Fuchs KG, Meinerzhagen, one of Germany's major forging companies performed a project in collaboration with Airbus Deutschland GmbH, Hamburg and Bremen, and the Technical University Hamburg Harburg, covering a parameter study on hand forgings to optimize the combination of high fracture toughness at moderate strength on one hand and the combination of high strength and acceptable ductility and fracture toughness on the other hand [2]. From this parameter study it turned out that for achieving high fracture toughness a beta anneal process is the best compromise offering a better fracture toughness than an alpha/beta forged condition and more isotropic fracture toughness and ductility than a beta forged condition (Table 1).

Table 1. Mechanical properties of medium strength hand forgings

Medium Strength		α/β-route	β-annealed route	β-forged route
$R_{p0,2}$ [MPa]	L	1081	1088	1051
Goal ≥ 1000	ST	1121	1085	1047
R_m [MPa]	L	1147	1178	1148
Goal ≥ 1100	ST	1172	1147	1125
A_5 [%]	L	12,0	6,0	12,9
Goal ≥ 5	ST	10,1	8,5	11,2
K_{IC} [MPa√m]	L-T	56,6	66,8	74,3
Goal ≥ 70	S-L	37,6	61,3	66,0

Table 2. Mechanical properties of high strength hand forgings

High Strength		α/β-route	β-annealed route	β-forged route
$R_{p0,2}$ [MPa]	L	1350	1332	1288
Goal ≥ 1250	ST	1364	1328	1310
R_m [MPa]	L	1412	1373	1365
Goal ≥ 1300	ST	1402	1371	1389
A_5 [%]	L	4,6	2,1	6,1
Goal ≥ 5	ST	4,3	1,4	2,6
K_{IC} [MPa√m]	L-T	35,5	45,6	47,2
	S-L	28,8	43,3	33,1

For high strength requirements an alpha/beta forging route is preferable because it is the only route with acceptable ductility at a high strength level (Table 2).

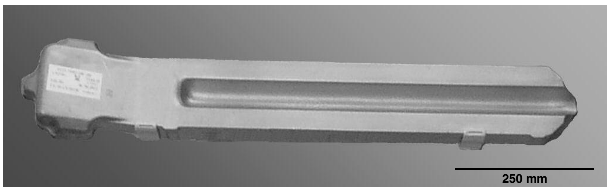

Figure 3: Airbus A320 flap track
(courtesy Otto Fuchs KG, Meinerzhagen)

The target properties for this component were: $R_{p0.2} \geq 1000$ MPa; $R_m \geq 1100$ MPa; $A_5 \geq 4\%$ and $K_{IC} \geq 60$ $MPam^{1/2}$. The results of the mechanical properties of the optimized beta annealed route are depicted in Table 3.

Table 3. Mechanical properties of the die forging

		average	range (from-to)
$R_{p0,2}$ [MPa] Goal ≥ 1000	12 L-values	1064	1036 – 1093
	6 LT-values	1069	1062 – 1077
	12 ST-values	1074	1047 – 1102
R_m [MPa] Goal ≥ 1100	12 L-values	1149	1120 – 1181
	6 LT-values	1148	1138 – 1159
	12 ST-values	1157	1135 – 1175
A_5 [%] Goal ≥ 4	12 L-values	8,6	6,5 – 11,3
	6 LT-values	7,4	6,0 – 9,7
	12 ST-values	8,4	6,0 – 10,0
K_{IC} [MPa√m]	5 L-T values	73,0	69,5 – 74,9
Goal ≥ 60	5 S-L values	73,9	66,1 – 79,9

As can be seen from Table 3 with the optimized beta annealed route aiming for medium strength and high fracture toughness, all required mechanical properties fulfill the targets.
Additionally, results from crack propagation tests in L-T- and T-L-direction from both, hand forgings and die forging, indicate excellent crack propagation behavior with curves for both directions at the lower crack growth limit of the β-Titanium alloys[2].

3. Application and New Products

Bugatti Engineering GmbH, a subsidiary of Volkswagen AG, Germany's biggest automobile company, has developed a highly sophisticated, high performance sports car named Bugatti Veyron. This extraordinary sports car currently represents the most powerful serial automobile with an engine performing 1001 horsepower. In order to limit the weight of this car and to fulfill specific requirements as for instance heat shielding many parts are made from different titanium alloys. The total amount of the built in parts is a little bit more than 40 kg, excluding the additional mass which is lost due to machining and forming. The Bugatti Veyron is depicted in Figure 4 with indication of used titanium parts:

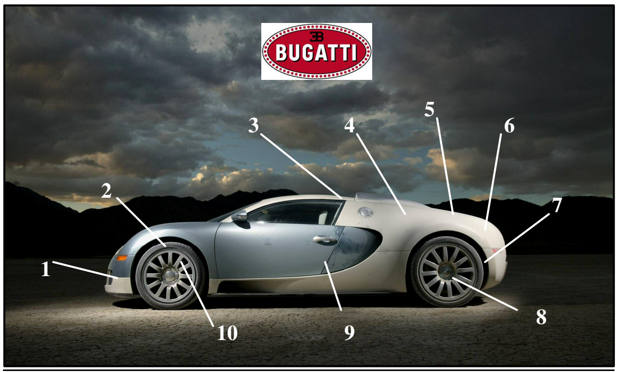

Figure 4: Application of Titanium in Bugatti Veyron (courtesy Bugatti Engineering GmbH)

1) meshed metal baffle, Titanium grade 2
2) bolts of suspension, Ti-6Al-4V with PVD-MoS coating
3) bolts and inserts within the carbon fiber reinforced monocoque, Ti-6Al-4V (bi-modal microstructure)
4) engine: connecting rods, Ti-6Al-4V (bi-modal microstructure)
5) heat shielding sheets, Titanium grade 2
6) exhausting system, Titanium grade 1 (outer surface), Titanium grade 1 plated with Aluminum (inside)
7) heat shielding sheets for brake, Ti-6Al-4V, superplastically formed
8) brake bells, Ti-6Al-4V (bi-modal microstructure)
9) crash clamps, Ti-6Al-4V (bi-modal microstructure)
10) suspension springs, Beta-Titanium alloy LCB

It is worth mentioning that the exhausting system with aluminum plating of the inside surface as it was presented for the first time during the last World Conference on Titanium four years ago in Hamburg[3] has found its way into serial production. The inner surface of this exhausting system is modified by an adequate heat treatment of the aluminum plating forming a stable aluminum/titanium oxide which can prevent the system to suffer from heavy surface oxidation and degradation when operating at temperatures up to 800°C.

MTU Aero Engines, Germany's major aero-engine company has developed a new category of erosion-inhibiting coatings to protect compressor blades from premature loss of material (Figure 5). The compressors of gas turbine aero-engines are particularly prone to performance losses due to erosion of the compressor blades when being operated in regions with dusty and sandy atmosphere and when sand, fly ash, salt and ice crystals or volcanic ashes are ingested. These new coatings are now offered under the label of ERCoat^{nt} for protection of new blades and for overhaul applications without the need of redesign.
At the present state of the art thin vapor-deposited TiN coatings provide best possible protection against erosive attack on compressor blades. ERCoat^{nt} coatings, applied by physical vapor deposition (PVD), are characterized by a multi-layer structure and a special chemical composition (several patent pending), the structure being achieved by alternating deposition of hard-material layers and soft intermediate layers.

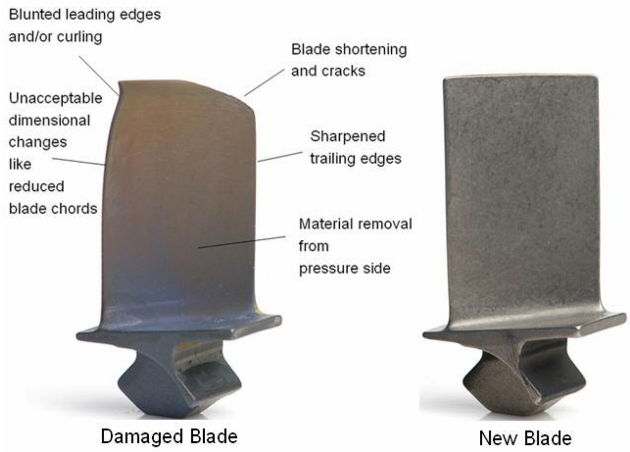

Figure 5: Comparison of eroded compressor blade and new blade (courtesy MTU Aero Engines)

Thanks to the modest thickness of 5 µm to 50µm and the moderate surface roughness of ERCoat^{nt} negative effects on aerodynamics can be ruled out also when the coating is deposited subsequently during shop visits of the engine. Figure 6 shows a metallographic microsection of the coating with an overall thickness of about 25µm which is built up by layers of alternating ceramic and metallic material of approximately 3 µm thickness.

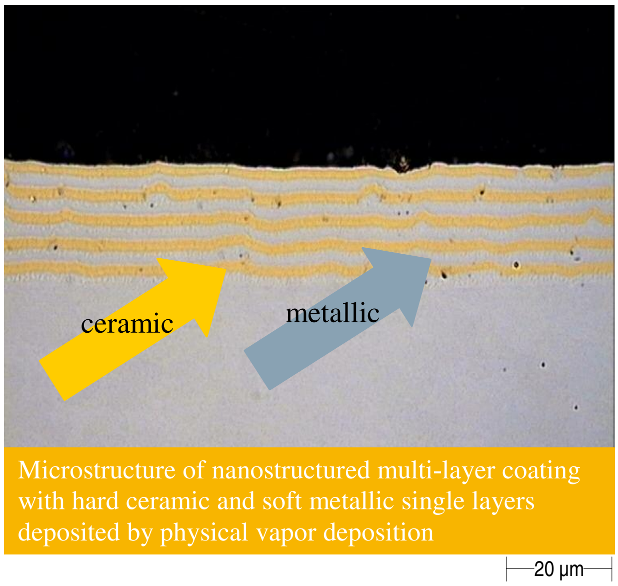

Figure 6: Multi-layer structure of an ERCoat^{nt} coating (courtesy MTU Aero Engines)

Erosion tests on MTU's own erosion test rig have been performed, using silica sand as an erodent with particle sizes between 75 µm and 200 µm which were accelerated with compressed air to a speed of between 200m/s and 350m/s and hit the surface of specimens under a test angle of 20°. Figure 7 compares the weight loss curves of a version 1 and a version 2 of ERCoat^{nt} coated coupons with an uncoated coupon (base material: Ti-6Al-4V). The weight loss measured for the base material Ti-coupon occurs in direct proportion to time.

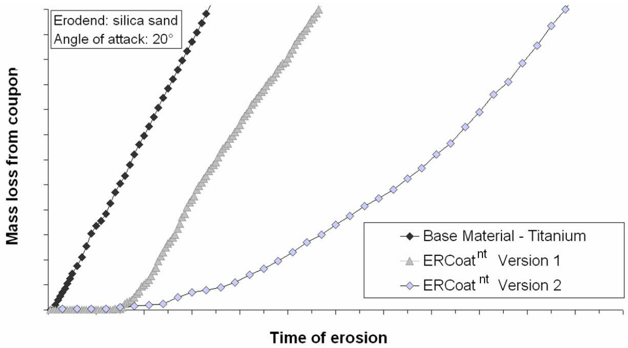

Figure 7: Result from erosion tests on coated and uncoated Ti-6Al-4V specimens (courtesy MTU Aero Engines).

The ERCoat^{nt} coated coupons can sustain the erosion loading for certain duration without suffering any measurable weight loss. In this phase, called the initiation phase, protection against erosion is 100%. As the erosive load continues the erosion-inhibiting coating is gradually attacked and finally completely worn off. During this phase, called the transition phase, the erosion rate (mass loss over time) increases. During the last phase, removal of base material starts which can be concluded from the identical erosion rate as for unprotected base material.
These tests demonstrated that ERCoat^{nt} coatings can appreciable slow down (if not fully suppress) erosive attack on compressor blades. As can be seen in Figure 8, MTU Aero Engines has developed the technique not only to coat single blades but also integrated bladed disks (blisks).

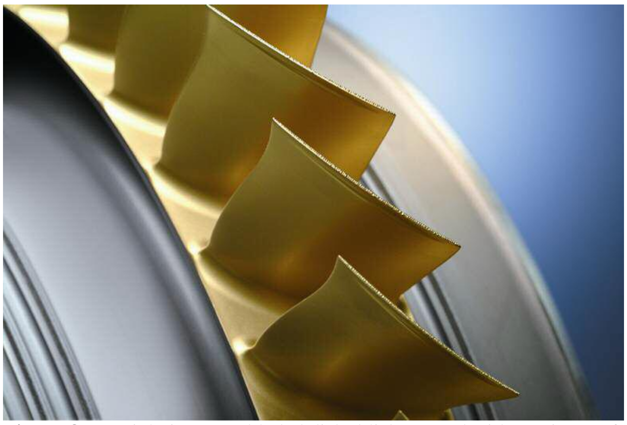

Figure 8: Partial view on a bladed disk (blisk) coated with version 1 of ERCoat^{nt}

Beside the erosion protection technology MTU Aero Engines has enlarged the knowledge about the production of bladed disks via the linear friction welding process in comparison to the already published features[3]. Within a joint program funded by the European Community the partners SNECMA (France), Böhler Schmiedetechnik (Austria), CNRS-ENSMA (France) and UPC-University of Barcelona (Spain), under the leadership of MTU developed and validated the required technology for the production of a new "Dual Material Titanium Alloy Linear Friction Welded Blisk" (acronym: DUTIFRISK). The aim was to identify optimized linear friction welding parameters for the production of linear friction welded blisks made from a wide variety of different alloys and/or microstructures for the disk and blade, respectively. Additionally, the microstructure and mechanical properties of the resulting welds were investigated and the production of two demonstrator blisks with bores made from Ti-6Al-2Sn-4Zr-6Mo and Ti 17, respectively, and blades made from the alloys Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo, and Ti-6Al-2Sn-4Zr-6Mo with two different microstructures (bi-modal and lamellar) were validated.

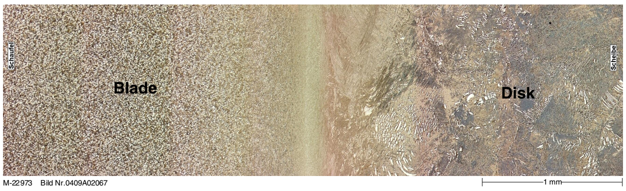

Figure 9: Microstructure of a linear friction weld;
blade: Ti6246 (α/β-forged) – disk: Ti 6246 (β-forged)
(courtesy MTU Aero Engines)

Figure 9 shows a linear friction weld made from Ti-6Al-2Sn-4Zr-6Mo with different microstructures of the disk (lamellar due to β-forging) and the blade (bi-modal due to α/β-forging). The characterization of all welded material combinations showed results as follows: tensile properties are similar to base material properties. Failure occurs in one of the base materials well away of the weld and heat affected zone. High cycle and low cycle fatigue properties are characterized by failure in one of the base materials outside the weld and heat affected zone, therefore the fatigue properties of the corresponding weakest weld partner are relevant for a design of a dual alloy/dual microstructure blisk. So the best combination of material properties relevant for disk and blade requirements can be chosen for a future intelligent design.

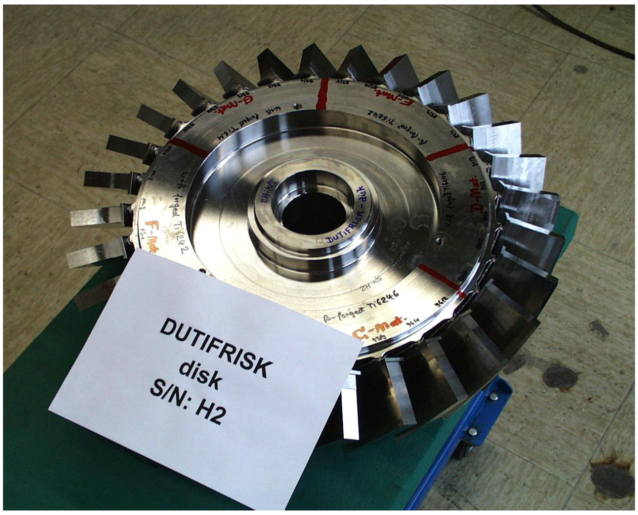

Figure 10: Blisk demonstrator from DUTIFRSK program
disk made from β-forged Ti6246 with attached blades made from Ti 64 (α/β-forged), Ti6242 (α/β-forged), and Ti6246 (α/β-forged and β-forged, respectively)
(courtesy MTU Aero Engines)

4. Research

A wide variety of different research work on conventional titanium alloys and new γ-Titanium-Aluminides covering the relationship of microstructure and mechanical properties, surface treatment and processes to influence microstructural features have been performed at different research institutes and universities in Germany within the last four years.

The role of hydrogen in titanium alloys is one of the research fields with particular emphasis at the Institute of Materials Technology of the University of Siegen.

In order to predict the applicability range of β-titanium alloys in hydrogen containing environments or to provide a basis for using hydrogen as a temporary alloying element, the hydrogen diffusion coefficient D_H needs to be known quantitatively. The use of titanium alloys in hydrogen containing environments might be limited due to intrinsic hydrogen effects which can be detrimental with respect to mechanical properties. In order to achieve a more fundamental understanding of how β-stability and microstructure affect hydrogen diffusion, research work was performed to gain results in binary titanium alloys to obtain information, how a change in concentration of just one alloying element influences the hydrogen diffusion coefficient. By focusing on cast alloys of the systems Ti-Mo and Ti-V the most important β-stabilizing alloying element were selected and effects due to forging, e.g. residual stresses or dislocation densities, which are assumed to influence hydrogen diffusion, were reduced. This study results in following major conclusions[4]:

- For binary Ti-Mo and Ti-V alloys, Ti-21.45 Mo and Ti-19.66V are sufficiently β-stabilized to retain the β-structure at room temperature.
- Hydrogen concentration profiles established by electro-chemical charging and subsequent diffusion annealing show that hydrogen concentrations below 1500 ppm lead to D_H-values considered to be independent of hydrogen concentration for all titanium alloys studied.
- The temperature dependence of the hydrogen diffusion coefficient obeys the Arrhenius-type behavior.
- An increase of β-stability of the alloy apparently leads to higher hydrogen diffusion coefficients.
- Hydrogen diffusion in the (hex) α-phase is much slower than in the (bcc) β-phase at corresponding temperature.
- Hydrogen diffusion coefficients in commercial multi-element β-titanium alloys are similar to those found in binary Ti-Mo and Ti-V alloys.

Based on the gained knowledge of hydrogen diffusion coefficients in titanium alloys another program was started in Siegen with the target to improve fatigue properties in terms of fatigue limit and fatigue crack growth threshold of a metastable β-titanium alloy (Ti-10-2-3) by the strategic use of hydrogen as a temporary element. The idea was to take advantage of the β-stabilizing effect of hydrogen, thereby creating modified microstructures in terms of fine β-grains or optimized α-precipitation conditions. Former results[5] on the influence of hydrogen on mechanical properties of various β-titanium alloys were the initial point to develop a Thermohydrogen Process (THP) which should lead to an increase of strength (UTS and fatigue) at a sufficient ductility. The idea of THP is depicted in Figure 11 schematically.

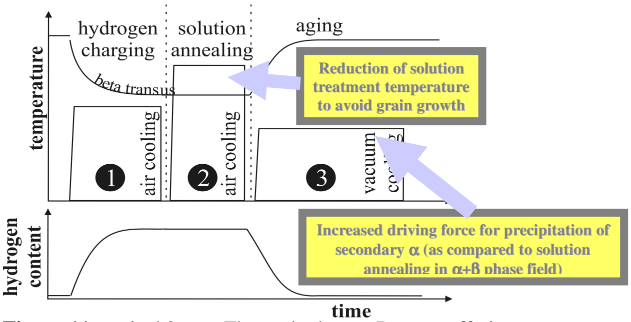

Figure 11: typical 3-step Thermohydrogen Process offering:
- fine grain hardening in second step
- precipitation hardening in third step

(courtesy Institute for Materials Technology/University Siegen)

In the first step a homogeneous hydrogen distribution is facilitated by hydrogenating the titanium samples in hydrogen containing gas atmospheres usually below final β-transus to avoid grain coarsening. In a second step solution annealing can be done above the reduced β-transus without extensive grain growth offering a contribution for fine grain hardening. In the third step during aging a complete or partial dissolution of α_p-phase occurs maximizing the driving force for formation of α_s-phase, so enhancing the contribution of precipitation hardening.

Based on this idea a modified strategy was developed to use hydrogen as a temporary alloying element within the heat treatment of Ti-10-2-3 combining a short THP cycle and a subsequent technical heat treatment. This 4-step cycle differs from the originally strategy with respect to dehydrogenation which was performed together with the solution annealing in a combined single process step at higher temperature (Figure 12).

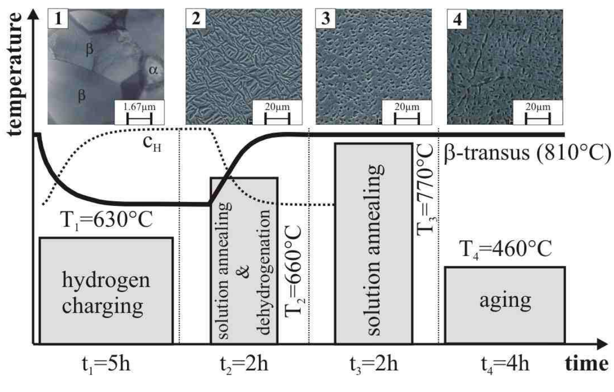

Figure 12: Designed 4-step-short THP for Ti-10-2-3
(courtesy Institute for Materials Technology/University Siegen)

This 4-step-THP could increase the ultimate tensile strength of Ti-10-2-3 by about 200 MPa with a reduced but sufficient ductility. Unfortunately, the fatigue limit was reduced by about 100 MPa due to microstructure inhomogeneities in form of coarse α-lamellae, resulting from the dehydrogenation process (second step). More details and results can be found elsewhere[5].

At the Institute for Physical Metallurgy and Materials Technology of the Technical University Hamburg-Harburg intensive research work was performed to investigate the influence of microstructure on the effect of periodically applied tensile overloads on the fatigue crack propagation behavior in Ti-6Al-4V[6]. Fatigue tests on C(T)-specimens with two different microstructures (lamellar and bi-modal, Figure 13) were carried out at room temperature in air.

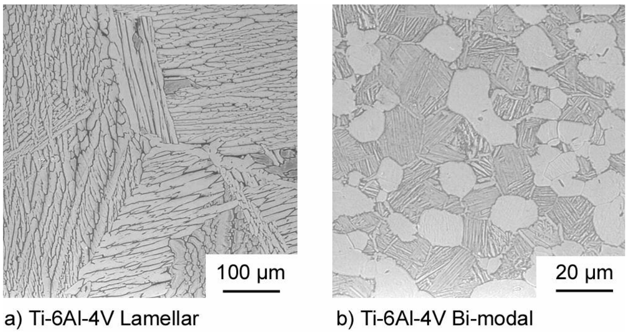

Figure 13: Microstructure of tested material (light microscopy) (courtesy Technical University Hamburg-Harburg, Physical Metallurgy and Materials Technology)

Tests with constant stress amplitude were compared to tests with periodically applied overloads. The load spectrum used in the experiments with periodically applied overloads is shown schematically in Figure 14.

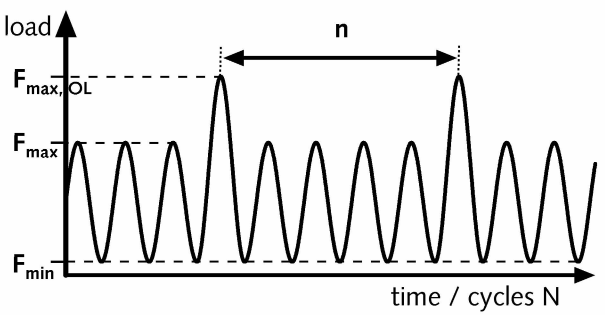

Figure 14: Load spectrum for overload tests (courtesy Technical University Hamburg-Harburg, Physical Metallurgy and Materials Technology)

The ratio of overload maximum stress to the maximum stress of the baseline cycles amplitude was 1.5. The single tensile overloads were applied with constant interval n of 5000 baseline cycles. Crack closure was monitored within all experiments using a back face strain gage.

For both loading conditions the coarse lamellar micro-structure showed a higher fatigue crack propagation resistance compared to the bi-modal condition, which is due to the drastically rougher crack front profile of the lamellar microstructure. For both microstructures the crack propagation rate was reduced in the presence of overloads (Figure 15). This retardation is more pro-nounced for the bi-modal microstructure compared to the lamellar condition. For both microstructures the retardation cannot be explained by a change in the crack front geometry due to overloads, equally crack closure showed no significant difference between constant amplitude loading and periodic overload cycling. Detailed investigations of the fracture surfaces revealed the presence of steps parallel to the fatigue crack propagation direction emanating from the overload markers. The presence of these steps is the major difference between constant and variable amplitude loading.

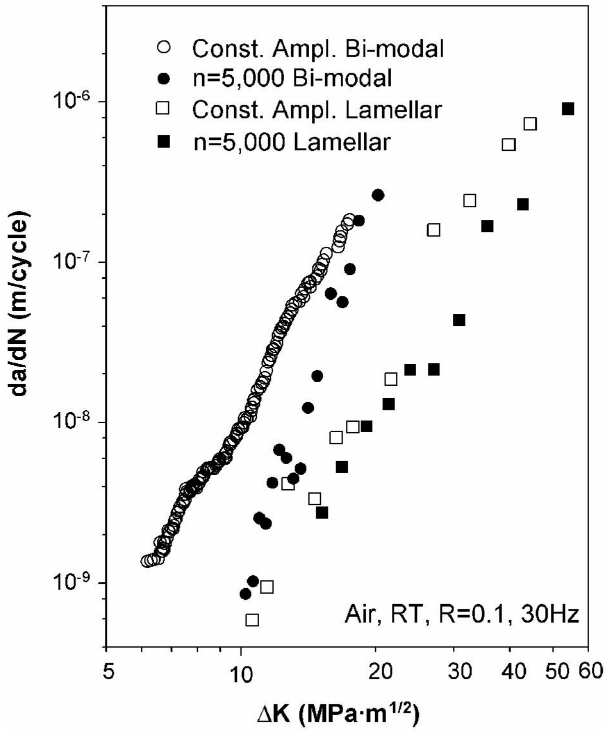

Figure 15: Crack propagation curves (courtesy Technical University Hamburg-Harburg, Physical Metallurgy and Materials Technology)

The steps are generated at the intersection of the overload marker with interfaces like grain boundaries or colony boundaries (Figure 16). These steps act as strong obstacles to crack propagation. A quantitative analysis of the geometry of the steps showed that the number of steps along the overload markers is the major variable in determining the amount of retardation, explaining the difference between the lamellar and the bi-modal microstructure. More details can be found elsewhere[6].

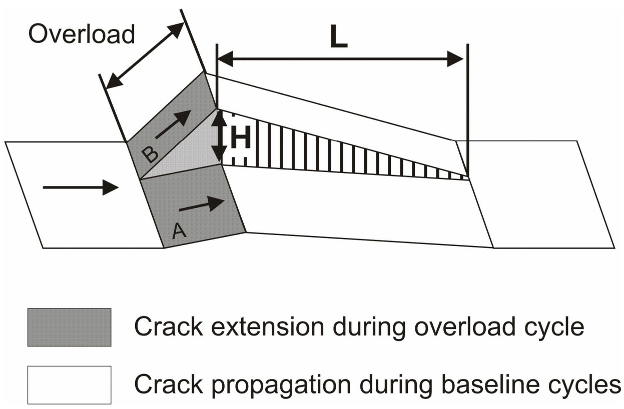

Figure 16: Formation of overload steps (schematically, out of scale) (courtesy Technical University Hamburg-Harburg, Physical Metallurgy and Materials Technology)

Additional research activities in Hamburg-Harburg dealt with investigations on the effect of yield stress level on mechanical properties of the alloy Ti 6246. Three different microstructures were produced by β-annealing (lamellar, equiaxed β-grains), β-processing (lamellar, pancake type β-grains), and α/β-processing (bi-modal). The yield stress level of each microstructure was varied between 1050 MPa and 1600 MPa. The results of mechanical tests demonstrated that at high yield stress values (>1300 MPa) the bi-modal microstructure exhibits a higher tensile ductility, a higher HCF strength, and even a higher fracture toughness as compared to the β-annealed and β-processed microstructures. For more detailed information refer to the paper of T. Krull et.al.[7].

Main emphasis on research on titanium alloys is also put at the Institute of Materials Science and Engineering at the Clausthal University of Technology.

One major point of interest deals with the influence of microstructure and mean stress effects on the fatigue performance of various titanium alloys with smooth, electrolytically polished reference surface condition and shot peened surface condition, respectively. Results from fatigue tests on shot peened Ti-6Al-4V specimens with fully equiaxed and duplex (or bi-modal) microstructures indicate that, depending on the cooling rate from the annealing temperatures, the HCF strengths of these microstructures could be enhanced by shot peening, not changed or even decreased relative to an electropolished reference[8]. These results can be explained by peening induced residual tensile stresses which necessarily are located below the work-hardened surface layer to balance the outer compressive stress field (Figure 17).

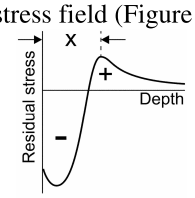

Figure 17: Residual stress depth profile (schematic) indicating a tensile peak stress below the compressive stress field (courtesy Institute of Materials Science and Technology/ Clausthal University of Technology)

Only material showing a normal mean stress sensitivity (Figure 18a) can respond to shot peening with enhanced fatigue performance (Figure 19b). This is observed on duplex microstructure material with fast cooling rate after annealing (D/WQ). In case of an anomalous tensile mean stress sensitivity of the material (Figure 18b), these residual tensile stresses lead to subsurface crack nucleation at low stress amplitudes. This was observed for the equiaxed microstructure (EQ) and the duplex microstructure (D/AC) with low cooling rate after annealing (Figure 19a and 19c). Further investigations on other titanium alloys show that α-titanium alloys such as Ti-2.5Cu respond very well to a shot peening treatment because the fatigue strength in vacuum (crack initiation in the interior of the material, subsurface) is much higher than in air and because the material exhibits a normal mean stress sensitivity. An anomalous mean stress sensitivity as observed in (α+β) titanium alloys as well as an insensitivity to the air environment as found in meta-stable β-alloys such as Timetal LCB can contribute to a poor response to shot peening[9, 10].

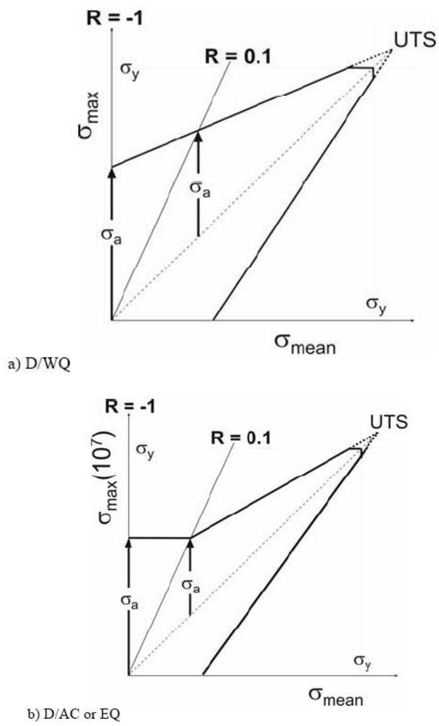

Figure 18: Smith diagrams for various microstructures

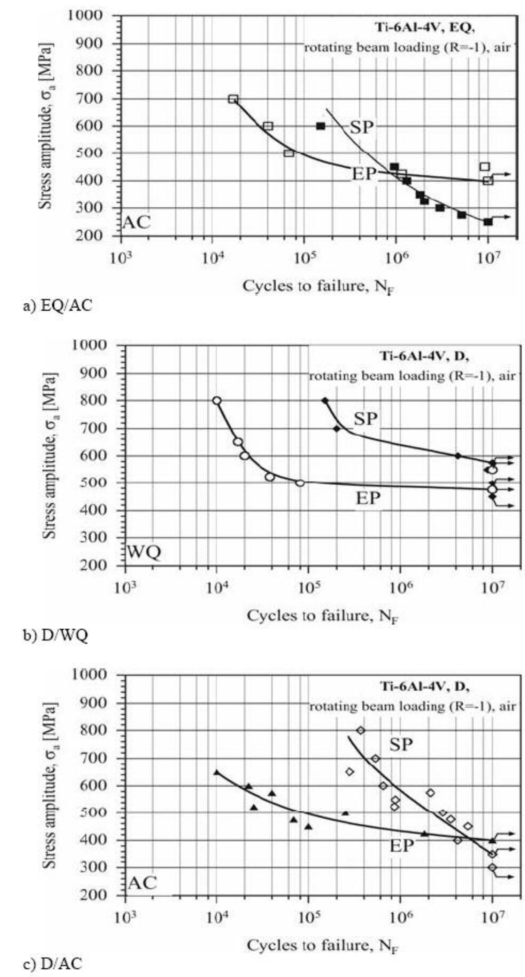

Figure 19: S/N-curves of reference condition (EP) and shot peened condition (SP) for various microstructures (courtesy Institute of Materials Science and Technology/ Clausthal University of Technology

In a joint effort scientists from Germany (Materials Physics and Technology, Technical University Hamburg-Harburg; Institute for Materials Science, GKSS-Research Center, Geesthacht) and Austria (Department for Materials and Materials Testing, Montan-University Leoben) as well as technologists of titanium producing and forging companies from both countries (GFE mbH, Nuremberg; Boehler Forging Company, Kapfenberg) have developed a new γ-TiAl based alloy which is characterized by β-solidification[11].

Conventional high Nb bearing γ-TiAl based alloys exhibit a relatively strong tendency to segregations because of their peritectic solidification path. This leads to local inhomogeneities of the microstructure which come along with non-reproducible mechanical properties. The β-solidified Ti-43Al-4Nb-1Mo-0.1B alloy (composition in atomic percent) exhibits a more homogeneous and fine microstructure due to solidification via the cubic β-phase. Heat treatment experiments and additional extrusion trials demonstrated that the microstructure could be adjusted and a reduction of the mean grain size was achieved. In tensile tests at room temperature, 700°C and 800°C the alloy Ti-43Al-4Nb-1Mo-0.1B shows higher strength and elongations than conventional high Nb containing γ-titanium aluminides. Figure 20 shows a microsection of the alloy perpendicular to the extrusion direction.

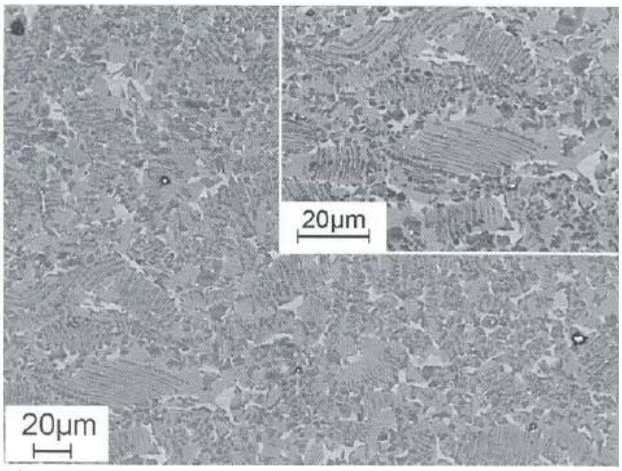

Figure 20: Microsection (SEM) of an extruded specimen, Perpendicular to the extrusion direction[11]

Table 4: Tensile properties of Ti-43Al-4Nb-1Mo-0.1B

condition	Temp. [°C]	E [GPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	$A_{5.65}$ [%]
reference 2 x VAR + extruded (7:1)	RT	147	1248	1319	0.5
Reference + stress relieved 954°C/4h/FC	RT	170	905	953	2.5
Reference + stress relieved 954°C/4h/FC	700	147	978	1159	10.4
Reference + stress relieved 954°C/4h/FC	800	111	455	573	75.0

As can be see from Table 4 as-extruded specimens exhibit a very high yield strength at the expense of low ductility. Stress relieve at 954°C for 4 hours with subsequent furnace cooling improves the ductility significantly while yield and tensile strength is lowered to a level even a little bit higher than conventional TNB-alloys. Up to 700°C this behavior remains unchanged or even slightly improved as compared to room temperature. Testing at 800°C reduces the tensile properties to roughly 50% with significantly enlarged elongation.

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