JOM, Vol. 70, No. 4, 2018
https://doi.org/10.1007/s11837-018-2747-x

TECHNICAL COMMUNICATION

Advances in Gammalloy Materials–Processes–Application Technology: Successes, Dilemmas, and Future

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For the last several years, gamma titanium aluminide (γ-TiAl)-based alloys, called "gammalloys," in specific alloy-microstructure forms began to be implemented in civil aero-engines as cast or wrought low-pressure turbine (LPT) blades and in select ground vehicle engines as cast turbocharger rotors and wrought exhaust valves. Their operation temperatures are approximately up to 750°C for LPT blades and around 1000°C for turbocharger rotors. This article critically assesses current engineering gammalloys and their limitations and introduces eight strengthening pathways that can be adopted immediately for the development of advanced, higher temperature gammalloys. Intelligent integration of the pathways into the emerging application-specific research and development processes is emphasized as the key to the advancement of the gammalloy technology to the next higher engineering performance levels.

INTRODUCTION

The finally realized implementations of current engineering gammalloy materials (cast 4822, cast 45XD and wrought TNM) as aero-engine low-pressure turbine blades (LPTB) for intermediate service temperatures (up to 750°C) began to establish the foundations of their respective materials–processes–manufacturing technologies.[1–6] The first commercial flights of gammalloy LPTBs took place in March, 2012 when Japan Airlines received purchased Boeing 787 Dreamliners powered by GEnx-1B engines equipped with alloy 4822 LPTBs on the last two LPT stages. That was 2 years after the first flight of B787 with GEnx engines, approximately 8 years after their successful implementation in GEnx engines, 17 years after the first certification for CFM CF6 engines [Guy Norris, Power House, Flight International, 13 June 2006], approximately 24 years after the development of alloy 4822 at GE and nearly 40 years after the first gammalloy exploration program initiated at AF Materials Laboratory and conducted by P&W.[7,8]

Cast gammalloys (Ti-46/47Al-3/6Nb base) began to be used for automotive engine turbocharger wheels first at 850°C (1999) and then at gradually increased gas temperatures up to 1000°C (2011):[9,10] This enhancement has been possible because of less stringent requirements in property balances, however with slow adoptions due to the reliability and cost issues. The first commercial application of gammalloy exhaust valves eventually took place with a near-alpha extruded and head-forged form of alloy 02B (Ti-44Al-6Nb-0.3W-0.1B)[11] in 2013 for race vehicle (F-1 and Moto GP) engines[12] where the operating temperatures are over 800°C.

Despite the exciting developments, their ongoing application expansion activities[13,14] and new applications[4,6] have shown that their respective temperature capabilities for aero-engine applications have remained unchanged ever since. The future of gammalloy technology will depend on whether or not or how we can develop or design gammalloy materials–processes–microstructure combinations yielding greater service temperature (750–900°C) capability for specific aero-engine applications and greater producibility–reliability for ground vehicle engine component applications.

This article first summarizes the exploration history of gamma TiAl alloys and reclassifies them by renaming them *gammalloys*, redefines their microstructures, assesses current engineering gammalloys and their limitations in service temperature, describes specific pathways to achieving greater temperature capabilities and then introduces the emerging "application-specific research

(Published online February 1, 2018)

and development (AsRD)" processes, with a recent realized example, for the development of higher temperature gammalloys.

GAMMALLOYS—CLASSIFICATION AND MICROSTRUCTURE EVOLUTION

The first major gammalloy development programs performed at PW investigated many alloy compositions, including Ti-45Al-5Nb, and in the end (1981) recommended Ti-48Al-based alloys, such as Ti-48Al-2W, Ti-48Al-2Nb-1W and Ti-48Al-1V-0.1C.[7,8] Based on the Ti-48Al-based compositions that undergo peritectic solidification, many conventional gammalloy (CG) compositions were explored and evaluated for over a decade starting in the late in 1980s. These alloys can be grouped in area CG of a quasi-ternary isothermal (900°C) phase field section (Ti-Al-Nb_{eq}) containing γ, α_2 and B2 (Fig. 1). The phase field was constructed by converting the electron probe microanalysis (EPMA) data of the equilibrium compositions of constituent phases to Nb_{eq} using the beta-forming equivalency (BFE) determined for the first time for gammalloys utilizing available ternary phase diagrams.[15] The BFE relation, Nb = Cr/3 = Mn/2 = V/2 = Mo/6 = W/8, was estimated based on Ti-44Al-X-based gammalloy compositions[15] and has been proven valid for a wide range of compositions.

The phase field section in Fig. 1 redefines gammalloys as conventional gammalloys (CG) and beta solidified gammalloys (BSG) located across the arrowed dividing line near the gamma phase field. CG compositions exist within the range Ti-(48-45)Al-(0-8)Nb-(0-4)(Cr, Mn)-(0-1)(Mo, W)-(0-1)B-(0-0.8)(C, Si) and BSG compositions within Ti-(42-45)Al-(0-10)Nb-(0-4)(Cr, Mn)-(0-2)(Mo, W)-(0-0.2)B-(0-0.6)(C, Si).

The typical CG alloys include: 4822 (Ti-48Al-2Nb-2Cr),[1] XD alloys (Ti-45Al-2Nb-2Mn-0.8v/oTiB2),[3] K5 (Ti-46.2Al-3Nb-2Cr-xB-yC/Si)[16] and TNB (Ti-45Al-5/8Nb-0.2B-0.2C).[17] These gammalloys generate numerous microstructures that sensitively depend on alloy composition, solidification path, processing route, post-processing heat treatment cycle and aging/stabilization condition. The microstructures were first identified and classified into near-gamma, duplex, nearly lamellar (NL) and fully lamellar (FL),[18] and XD lamellar (XDL) is a complex form of FL. The first four are produced in cast as well as wrought forms,[15,18] while XDL is in cast forms,[3] and their microstructure–property relationships are too complex to quantify. However, the relationships could be described for well-controlled duplex and FL materials.[19]

BSG alloys are Ti-(42–44)Al based and contain significantly low (generally below 75%) amounts of gamma phase compared to those (> 85%) in CG alloys, as indicated by alloy 1 (Ti-42A-5Mn)[20] and alloy 2 (TNM: Ti-43Al-4Nb-1Mo-0.1B),[5,6] which are approximately located in Fig. 1. Unlike CG alloys, a small boron addition, (0.04–0.2) at.% B, helps the BSG compositions solidify to fine-grained (< 50 μm) lamellar structures, however with significant amounts of grain boundary gamma and/or β/B2[5,20–23] and varying randomness depending on the cooling rate.[24] Because of these and the apparent inability of producing coarser-grained isotropic FL microstructures and fair formability, efforts had been made to control characteristic wrought-processed nearly lamellar structures. This led to the development of TNM-WNL, a BSG alloy wrought material with a specific NL (WNL) structure, which has managed to make the last stage LPT application in geared turbofan engines.[6]

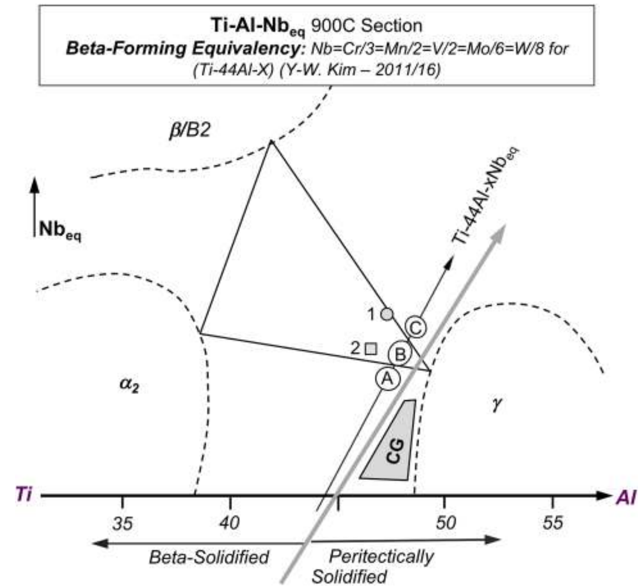

Fig. 1. A quasi-ternary isothermal (900°C) phase field section (Ti-Al-Nb_{eq}), consisting of γ, α_2 and β/B2 phases, shows two regions divided by an arrowed gray line that contain conventional gammalloy (CG) compositions and beta solidified gammalloy (BSG) compositions, respectively. CG alloys are characterized by peritectic solidification, and the BSG region includes special types of areas (A, B, C) that yield γ-rich (> 85%) alloys, called beta-gamma gammalloys (BG) (Gamteck DKI Base, Y-W. Kim, 15.0310).

BSG alloys have not demonstrated the formation of fine-grained (40–150 μm), fully lamellar (FGFL) microstructures that are γ rich (> 85%) in any material forms. This dilemma was resolved by a special form of BSG alloys, called beta gammalloys (BG), that exist very close to the gamma phase field in three types, A, B and C, as mapped in Fig. 1.[15] Type B and A BG alloys lie within the γ-rich and β-lean phase distributions, (85–92)γ-(0–2.5)β/B2-(15–7)α_2 (vol.%). A type B BG alloy, 09C (Ti-43.8Al-4Nb-2Cr-xB-yC), has demonstrated FGFL (30–100 μm) microstructures in a wrought-processed material form that yields remarkable RT tensile properties (YS and ductility) and high-temperature strength retention.[15] Importantly, this alloy demonstrates similar characters in a cast/annealed material form.[23]

Table I. Gammalloys, types and related details (Gamteck DKI Base, Y-W. Kim, 17.0716)

Alloy type	Conventional gammalloys (CG)	Beta solidified gammalloys (BSG)
Typical composition range	Ti-(48–45)Al-(2–10)Nb-(0–4)(Cr, Mn)-(0–1)(Mo, W)-(0–1)B-(0–0.8)(C, Si)	Ti-(42–45)Al-(0–10)Nb-(0–5)(Cr, Mn)-(0–1)(Mo, W)-(0–0.2)B-(0–0.5)(C, Si)
Solidification type	Peritectic (or alpha) solidification	Beta solidification
Phase distribution (%) (< 1000°C)	γ (95–85) + α_2 (5–15) + B2 (< 0.5)	BSG: γ (< 75) + α_2 (0–26) + β/B2 (0–25) BG (A, B): γ (92–84) + α_2 (6–16) + β/B2 (0–2.5)
Example alloys	Current CG: Ti-4822, 45XD-High-order γ-rich CG (HCG): K5, K3	Ti-42Al-5Mn; current BSG: TNM High Nb BSG: Ti-(42–45)Al-(6–9)Nb-(0, 0.3)W-(0, 2)Mo-(0, 0.1)B BG alloys: 02B (type A) and 9C (type B)
As-cast microstructure type	Ti-4822: large-grained nearly FL 45XD: XD lamellar (XDL) HCG: large-grained FL	Fast cooling: elongated fine lamellar grains with GB B2 particles Slow cooling: equiaxed fine lamellar grains

High-Nb BSG alloys based on Ti-(44/45)Al have attracted significant attention, and typical examples include Ti-45Al-8.5Nb-0.2W-0.2B-0.0Y[25] and Ti-44/45Al-6/4Nb-2Mo-Y/B alloys.[26] These alloys contain more Al and Nb + Mo than TNM alloy, indicating greater environmental resistance and improved property balance, and enhanced operation temperatures if they exhibit the BG type phase distributions. Property measurements on a wide range of processing–microstructure combinations showed these potentials and the possibility of producing FGFL material (FGFL).[26,27] This was manifested by a type A BG alloy 02B (Ti-44Al-6Nb-0.3W-0.1B) for successful high-temperature racing valve applications.[11,12]

Table I lists and summarizes gammalloys, their types and composition ranges, phase and microstructure distributions, and related details, as discussed above.

ASSESSING CURRENT ENGINEERING GAMMALLOYS

Table II compares the current engineering gammalloys, Ti-4822, 45XD and TNM, and their processing-material details designed for their respective LPTB applications, and their pertinent engineering microstructures are shown in Fig. 2. The poor (or low) general plasticity is a continued concern that has often discouraged continued research or component development activities. This, however, has not deterred (rightly so) the application-specific component development activities at major aero-engine OEMs, as the current alloy materials in controlled microstructure forms demonstrate good resistance to fracture and fatigue as well as reasonable threshold intensities (ΔKth). Despite the low ductility (2–0.6%), therefore, their LPT blades have already been put in service extensively in advanced aero-turbine engines for more than 5 years.

The limiting factors for their low service temperatures (< 750°C) that can be drawn from Table II and Fig. 2 include: (1) none is FL with anisotropic lath structures; (2) casting Duplex/NL consists of degenerated lath structures (Ti-4822); (3) XDL with random lath bundles and boundaries and low anisotropy (45XD); (4) NL with low gamma volume (< 72%), grain boundary gamma and B2 particles and high α_2 volume (TNM). Collectively, significant increases in RT strength levels (4822 to XD to TNM) would not raise the operation temperature levels visibly, as the increases in RT strength lower the high temperature strength retention more rapidly.

The method to raise the service temperature is to improve both the strength and its high temperature strength retention capability together, which is directly related to the above shortcomings. However, the (obvious) shortcomings have not been assessed or even noticed, largely because of our tendency to take the existing situation for granted. This lack of the integral physical-mechanistic understanding has

Table II. Current engineering gammalloys and application material details (Gamteck DKI Base, Y-W. Kim, 17.0712)

Alloy	Ti-4822[28]	45XD[3,4,29]	TNM[6]
Alloy class	Conv. or peritectic-solidified	XDL	Beta solidified
Composition	Ti-47.2Al-2Nb-2Cr (targeted)	Ti-48Al-2Nb-2Mn-1B (N)	Ti-43Al-4Nb-1Mo-0.1B (N)
Processing	Cast- HT1-HIP-HT2	Cast- HIP- HT	Cast-forge-HT
Microstructure	Casting duplex/NL	XDL (low anisotropy)	Wrought NL
Phase distribution (v/o)[23]	γ (88–95) + α^2 (Bal) + B2(< 0.5)	83γ + 16α^2 + 1TiB_2	68γ + 26α^2 + 6B2
Ductility (%)	~ 2	1.5	~ 0.6
Property description	Low strength with high HT retention, but most balanced	Strong at RT but low HT strength retention	Very strong at RT but very low HT strength retention
LPTB application (year)	GEnX (2012) & LEAP	RR engines (~ 2018)	GTF engines (2016)
Approximate limit of operation T (°C)	< 700	< 700	< 750

Ti-4822: The phase distribution range of Ti-4822 (spec) was estimated based on the value (95.5γ + 4α_2 + 0.5B2) measured on the Ti4822 (actual) casting duplex.[23] 45XD: The phase distribution was estimated based on the composition and the BSE imaging in Fig. 2b.[23] TNM: The phase distribution was estimated[23] based on the experimental value,[6] 72γ + 23α_2 + 5B2, measured on a composition of Ti-43.9Al-4Nb-1Mo-0.1B.

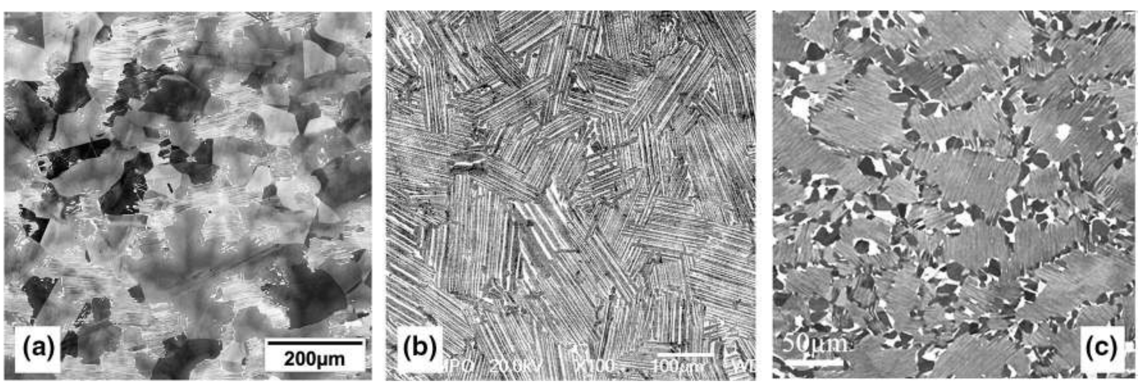

Fig. 2. Current engineering gammalloys showing their application-specific microstructures: (a) Ti-4822 with casting duplex/NL; (b) 45XD with cast + heat treated XDL;[29] (c) TNM with wrought + heat treated NL[6].

often led us to vague R&D directions or targets, thereby guiding the materials community to delve into added investigation of the known data, knowledge and information (DKI) or unnecessary or redundant details. Most of the additionally generated research and development outcome over the last decade therefore has not helped resolve the shortcomings.

PATHWAYS TO ADVANCED GAMMALLOYS

The above shortcomings of the current gammalloys can be alleviated or removed by realizing the pathways to achieving greater high-temperature (HT) capability that will increase both the RT strength level and/or HT strength retention. The needed steps and abilities required for this process include: (1) hands-on experience in fundamental as well as applied RD, (2) mechanistic as well as physical understanding of the existing DKI, (3) valuation and selection of DKI for specific targets, (4) processing experience and knowledge, (5) knowledge of industrial infrastructure, and (6) manufacturing and application information.

The most important requirement, DKI, has been documented over the last 30 years in a number of publications since 1989.[19,30–41] The critical areas include: (1) composition-processing-microstructure-property relations, involving phase distribution, microstructure evolution and control, inverse relations, solid solution and compositions of gamma phase, precipitation hardening, deformation-fracture, creep and fatigue; (2) processing details such as ingot-casting, investment casting, forging, extrusion, rolling, directional processing and heat treatment cycles; (3) alloying and phase distribution effects on oxidation, surface protection,[41] joining, machining, wear and erosion.

Since alloy materials having higher temperature capability tend to lower the ductility, the best way to compensate for the degradation is minimizing it and/or toughening the newly strengthened matrix.

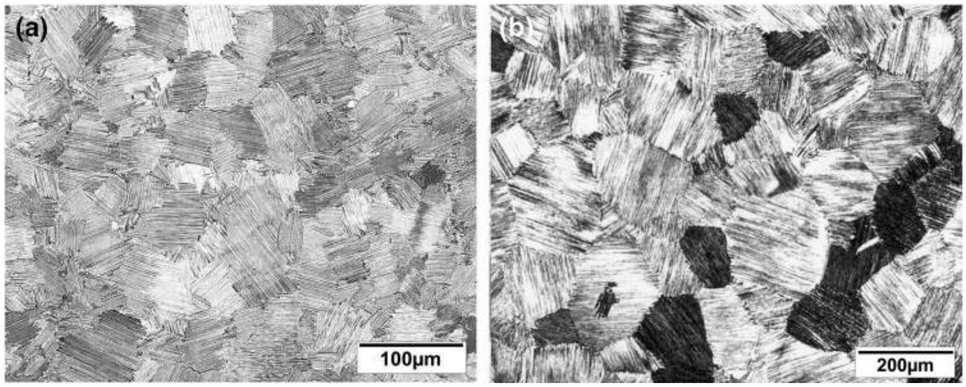

Fig. 3. Fully lamellar BSE microstructures of: (a) beta gammalloy (BG) 9CN wrought FG-FL (55 μm) and (b) conventional (peritectic) gammalloy (CG) K3 wrought-processed RFL ($\sim$ 220 μm).

This can be accomplished by generating a microstructure and material form based on fine lamellar grains consisting of the highest possible anisotropic laths with a desired γ-rich (> 85%) phase distribution, which will help retain the plasticity and enhance the resistance to crack initiation/growth and creep deformation. The fullest high temperature performance in balance will be reached when the alloy material is produced into uniform FGFL[15] or refined FL (RFL)[15,16] forms with the highest deformation anisotropy in the lamellar grains and optimized grain boundary morphologies. Further improved temperature capabilities can be most effectively achieved in lamellar structures when small additions of C or C + Si are segregated from decomposing α_2 laths in the forms of stable incoherent precipitates (Ti_2AlC, Ti_5Si_3) along the lath interfaces.[33] The used-to-be coherent and easy slip planes are disturbed with incoherent precipitates, residual alpha-2, small amounts of B2 particles and some openings, effectively pinning and blocking dislocation movements.

Another or additional improvement in RT as well as high temperature performance can be made when the material is processed directionally into an aligned lamellar grain structure employing controlled alpha-field hot working, such as extrusion,[12,15] forging[15] or rolling. Recent advances in the directional solidification (DS) processes for small ingots have shown some possibilities for producing highly textured DS[42–44] or single-crystalline like PST[45] material forms. Producing such forms with highly anisotropic creep-resistant laths is a daunting task even for simple shapes, not to mention complex shapes.

Based on the above discussions, eight (8) specific pathways to achieving greater temperature capabilities are identified as listed below:

P1—Microstructure optimization (4822-NL formed upon cooling, 45-Refined XDL, TNM-NFL).
P2—Higher order (than 4822), gamma-rich conventional gammalloys (HCG) in NL forms.
P3—NFL microstructure generation in conventional gammalloys in cast or wrought material forms.[18]
P4—FGFL microstructure generation in BG alloys in cast as well as wrought material forms.[15]
P5—RFL microstructure generation in HCG alloy wrought processed material forms.[15]
P6—Incoherent particle strengthening of the HCG alloy cast as well as wrought FL (NFL, FGFL, RFL) material forms.[33]
P7—Directional processing—alpha forging,[15] alpha extrusion[11,12] and possibly alpha rolling.
P8—Directional solidification[42–45]—possible realization requires long-term efforts.

Most of the pathways have proven to be valid experimentally or using DKI-based concepts,[23] and each can be validated/realized with minimum validation experiments, except for **P8**, on a few pathway-specific-alloy-processing combinations. All alloys for **P2** through **P7** are required to have phase distributions within the γ-predominant (85–92)γ-(0–2.5)β/B2-(16–7)α_2 (%), which are rich in γ and deficient in beta.

Two examples are a BG alloy 9C (Ti-43.7Al-4Nb-2Cr-0.2B-0.2C) for **P4**[15] and an HCG alloy K3 (Ti-45.5Al-2Cr-2.5Nb-0.3W-X) for **P5**.[15] The 9C composition was used to yield FGFL material forms through wrought processing (alloy 9C) and also casting (alloy CN). Their average FL grain sizes in these alloy forms were approximately 55 μm and 60 μm, respectively. Alloy K3 was controlled to have two different wrought RFL grain sizes, K3FL1 (110 μm), K3FL2 (220 μm) and K3FL3 (700 μm). Figure 3 compares 9C (a) and K3FL2 (b) microstructures in BSE imaging conditions.

Figure 4 shows tensile yield strengths (a) and specific YS values (b) as a function of temperature for three current gammalloy materials (4822-CDP/NP, 45XDL, TNM-WNL) and two advanced gammalloy materials (9C-FGFL, CN-FGFL, K3FL1 and K3FL2). For TNM, the data from a cast + heat treated material[46] were used for convenience. For comparison, the yield strength variation of a high-Nb BSG gammalloy with modulated microstructures[47] is also plotted along

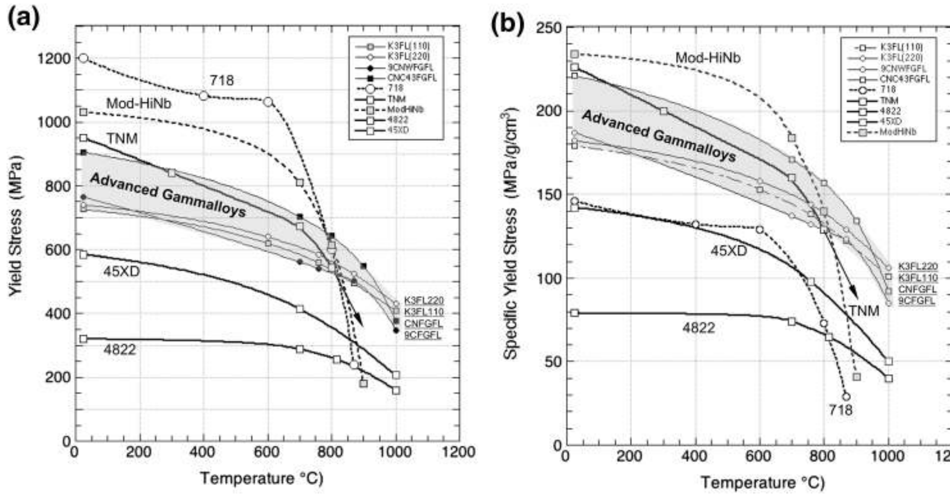

Fig. 4. Yield stress versus temperature (a) and specific YS versus temperature (b) of two advanced alloys (CG alloy K3 and BG alloy 9C) in their specific processing-FL microstructure combinations are compared with those of current engineering gammalloy materials, 4822-CDP,[3,28] 45XDL[3] and cast TNM,[46] and a modulated high-Nb alloy material,[47] along with wrought superalloy 718 (Gamteck DKI Base, Y-W. Kim, 17.0910).

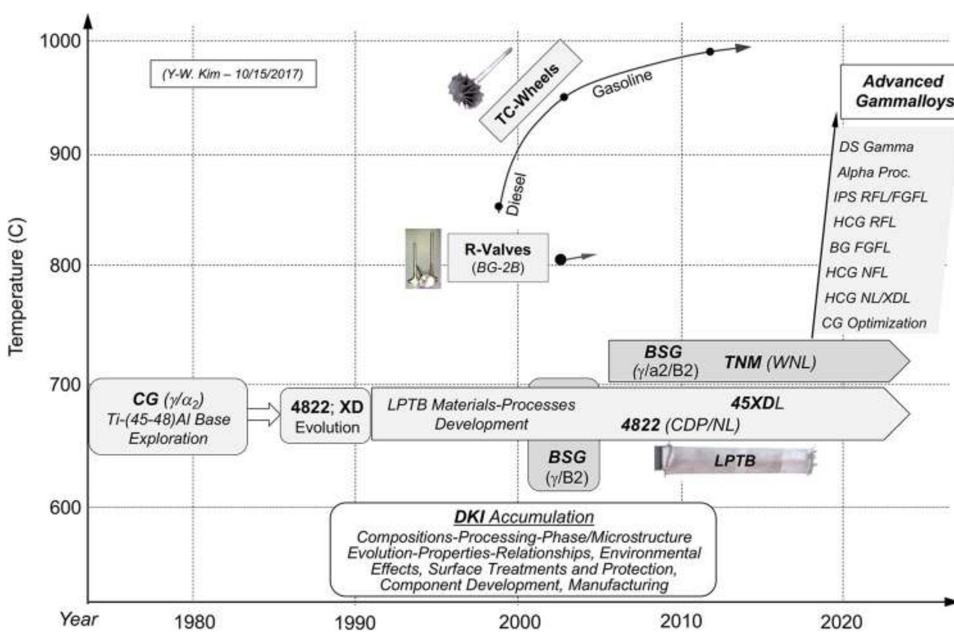

Fig. 5. Advances in service temperature capabilities of: (1) current gammalloys (4822, XD and TNM) realized for aero-engine LPT blades; (2) Ti-46/47Al-3/6Nb base alloys for automotive engine turbocharger wheels; (3) advanced gammalloys having potential for future aero-engine higher temperature rotational components. The initial BSG development effort leading to low temperature ($<$ 650°C) two-phase alloys[20,48] is depicted. An advanced alloy BG-2B (Ti-44Al-6Nb-0.3 W-X) has been used for race vehicle exhaust valves. LPTB (low-pressure turbine blades); CG (conventional gammalloys); CDP/NL (casting duplex/nearly lamellar); XDL (XD lamellar); BSG (beta-solidified gammalloys); WNL (wrought-processed NL); HCG (high-order γ-rich CG); BG (beta gammalloys); FGFL (fine-grained FL); IPS (incoherent-precipitates strengthened); R-valves (race vehicles wrought exhaust valves); TC-wheels (automotive turbocharger cast wheels); DKI (data, knowledge and information) (Gamteck DKI Base, Y-W. Kim, 17.1108).

with Ni-base alloy 718. The YS levels of current gammalloys vary significantly, however, to reach similar low values around or below 200 MPa at 1000°C. For example, TNM shows a very low retention from 950 MPa at RT to a value below 200 MPa at 1000°C. Even this low retention[46] is better than those of the stronger mod Hi-Nb alloy material[47] and the forged + heat treated 718. Remarkable HT strength retentions are achieved in advanced gammalloys, especially an HCG alloy K3 in RFL forms (110 μm and 220 μm) that exhibit a high YS = 730 MPa at RT and 420 MPa at 1000°C, showing a 58% retention. This high HT strength retention is expected to yield accordingly enhanced creep resistance at high temperatures.

Table III. Properties of current engineering gammalloys (CG and BSG) and advanced gammalloys (BG and ACG) for aero-engine applications versus superalloys (Gamteck DKI base, Y-W. Kim, 17.0907)

Property	CG alloys	BSG alloys	BG alloys	ACG alloys	Superalloys[a]
PD (%)	$\gamma + \alpha_2$	$70\gamma + 25\alpha_2 + 5$B2	$\gamma + \alpha_2 + (0–2.5)$B2	$\gamma + \alpha_2 + (0–0.5)$B2	$\gamma + \gamma'$
Density (g/cm^3)	3.9–4.1	4.0–4.2	4.0–4.3	3.9–4.2	7.9–8.9
RT YS (MPa)	300–550	700–900	650–850	400–800	800–1200
1000°C YS (MPa)	150–200	180–220	350–400	240–500	–
RT ductility (%)	1–2.5	0.5–1.5	1–2	0.5–2	3–25
RT K1c (MPa√m)	14–18	13–17	13–17	14–20	30–80
RT ΔK_{th} (MPa√m)	5–7	5–7	6–8	5–9	–
BDTT (°C)	~ 700	~ 750	750–800	760–830	–
L-Creep (°C)	650–750	700–750	750–850	750–930	650–800
L-Oxidation (°C)	750–800	700–800	750–850	800–900	800–1000

[a]Property ranges in wrought superalloys, PD (phase distribution); CG (conventional, peritectic solidified gammalloys): 4822 and XD; BSG (beta solidified gammalloys): BG (beta gammalloys); TNM; ACG (BG and advanced CG gammalloys); YS (yield strength); TS (tensile strength); K1c (crack initiation toughness); ΔKth (stress intensity for fatigue crack initiation); BDTT (brittle-ductile transition temperature); L-Creep (long-term creep resistance); L-Oxidation (long-term oxidation resistance).

ADVANCES IN GAMMALLOY TECHNOLOGY AND APPLICATION-SPECIFIC RD PROCESS

Figure 5 graphically summarizes the previously discussed advances in the gammalloy materials–processes–application technology in terms of operation temperature capability. The lateral expansion of current aero-engine LPTB gammalloys is shown to be steady but remains in the same temperature range (< 750°C). A short-lived development effort for beta solidified alloys with two-phase ($\gamma + \beta$) distributions[20,48] is added in the schematic. Automotive engine turbocharger wheels began to be used in diesel engines at 850°C and later on in gasoline engines at much higher temperatures up to 1000°C or higher. At these high temperatures, most gammalloy materials need to be properly coated.[41]

Higher temperature (> 740°C) service capabilities for future or higher-performance aero-engine rotational applications require advanced gammalloys in specific processing-phase-microstructure combination forms that can be developed and produced through specific development pathways integrated with value-added DKI, as discussed already. The enhanced service temperatures are expected to range from 740°C to over 900°C depending on the selected pathway. The pathways can be selected and executed independently or in parallel, or two or three may be combined into an integrated form.

The application-specific research and development (AsRD) process that has been proposed and exercised[11,12,15] is target-oriented and starts with the knowledge of applications requiring specific properties. The next step is to identify a relevant microstructure type and form that can generate such properties, which leads to the selection or prediction of the most suitable pathway consisting of the alloy and processing route. This top-to-bottom step needs detailed valuation of DKI and its integration into the process. Accelerated validation experiments and tests are to be followed to determine and optimize the alloy-processing-microstructure-property combination that can be used to produce the material suitable for the application.

Example The wrought gammalloy exhaust valves produced for select race vehicles by Dell West Engineering are the first gammalloy component developed employing the AsRD process.[11,12] The required properties were high tensile and high-cycle-fatigue (HCF) strengths and their high retention and oxidation resistance at HT. Pathway **P7**, alpha-extrusion,[15] was selected for producing textured FL microstructures suitable for the valve forms, and an innovative multi-rods extrusion method was formulated and employed for the cost effectiveness.[12] The alloy that would potentially satisfy the specific property requirements through the specified extrusion-forging process was determined and selected to be an Hi-Nb BG alloy 2B (Ti-44Al-6Nb-0.3W-X) that had been developed earlier for improved processibility and HT uses.[11] Accelerated validation experiments were conducted following the formulated alloy material-processing-heat treatment path that would generate desired microstructures and properties.[12] The experiments included ingot size optimization, acceptable composition range determination, material and component evaluation, engine tests and scaling-up, while a component-specific isothermal head forging process was developed and refined in parallel. The whole process, including the establishment of a manufacturing vendor chain, took 2 years until the thus-produced valves were accepted and implemented in race vehicle (Formula 1 and Moto Grand Prix) engines.[12]

Table III lists important properties of current engineering gammalloys (CG and BSG) and advanced gammalloys, BG and advanced CG

(ACG), and typical superalloys. Some values for advanced gammalloys were estimated based on a few data points. Nonetheless, they are useful as future references as advanced gammalloy development processes proceed.

SUMMARY

Finally, we have three gammalloys implemented in aero-engine turbines. They are one (4822) among many conventional (peritectic) alloy compositions that have been explored over the last 3 decades, one XDL alloy (45XD) and one beta solidified alloy TNM. Their operation temperature limitation (750°C) has remained unchanged for nearly 3 decades to many years. This slow progress is largely due to our tendency to neglect the vast DKI pileup and instead chase the new ones, which are often vaguely targeted, redundant or subjective. As demonstrated in the specified pathways, exciting opportunities exist for moving the gammalloy materials-processes forward to achieving greater temperature capabilities. This opportunity can be realized through the application-specific R&D process, which is a powerful, accelerated methodology to select and utilize the application- or component-specific pathways to targeted advanced alloy materials and processes technology development.

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