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available online www sciencedirect com sciencedirect material today proceeding 4 2017 8971 8982 www materialstoday com proceeding icaamm 2016 characteristic titanium alloy aircraft application paramjit singha harish pungotrab nirmal kalsib aresearch scholar k gujral punjab technical university kapurthala 144601 india bdepartment mechanical engineering beant college engineering technology gurdaspur 143521 india abstract complex aerodynamic design high mechanical thermal load extreme environmental service condition produce high magnitude dynamic stress various component airframe magnitude nature stress varies different phase flight governs need develop special material ability withstand variable stress high fuel cost scarcity raw material source need efficiency improvement growing demand new aircraft military civil raised environmental standard le co emission le noise pollution recyclability 2 material etc factor forced engineer make stronger light possible engine frame part aircraft factor open door stronger lighter metal like titanium alloy aerospace application segment titanium alloy offer unique set physical mechanical metallurgical composite compatibility characteristic help aerospace sector meet economy fuel efficiency global standard wide range temperature service condition starting first application 1950s till date wonder metal increase share presence becomes first choice aircraft fabricator paper present overview inherent mechanical metallurgical characteristic titanium alloy make ideal aircraft application brief summary induced stress aircraft critical component advantage titanium alloy manufacture component also discussed 2017 elsevier ltd right reserved selection peer review responsibility committee member international conference advancement aeromechanical material manufacturing icaamm 2016 keywords aircraft material attribute titanium alloy alloy composition characteristic aircraft application corresponding author tel 91 9855861155 fax 91 183 506 9535 e mail address er pannu266 gmail com 2214 7853 2017 elsevier ltd right reserved selection peer review responsibility committee member international conference advancement aeromechanical material manufacturing icaamm 2016 8972 paramjit singh material today proceeding 4 2017 8971 8982 1 aircraft material requirement limited availability resource raw material fuel continuous consumption forced design engineer design aviation transportation system giving optimum performance minimum level energy consumption 1 long term goal flightpath 2050 2 etc aviation research council like acar europe etc raised environmental standard 3 around globe demand improved aircraft design motto nomenclature α alpha β beta ω omega hcp hexagonal close packing bcc body cantered cubic twca teledyne wah chang albany acar advisory council aviation research cfrpc carbon fibre reinforced polymer composite sta solution treatment aging y yield strength ut ultimate tensile strength h hydrogen 2 mpa mega pascal rmi rmi titanium co timet titanium metal corporation pw pratt whitney co dac douglas aircraft co fly faster farter larger aircraft le fueling cost translated complex aerodynamics le overall weight aircraft improved design economy fuel energy strives make light possible aircraft addition light weight chemistry material must fulfill set property like high heat capacity toughness oxidation resistance thermal conductivity strength corrosion resistance density etc possibility reduce weight aircraft component 10 list 1 reduce component metal density 10 b increase component metal strength 35 c increase component metal stiffness 50 increase component metal damage tolerance 100 approach effective approach 1 1 general characteristic material aircraft application following aspect behind uncompromised selection criterion component material aircraft 4 initial cost purchasing new aircraft cost replace upgrade component material latest one meeting design requirement option complexity aeroengine frame pressure high fuel consumption cost level performance real condition operational parameter power requirement aeroengine maintenance type cost aircraft part operational life aircraft reliability safety demand plan dispose recycle dead aircraft meeting environmental issue standardsparamjit singh material today proceeding 4 2017 8971 8982 8973 figure 1 detail basic approach aircraft material selection approach selecting material first time aircraft part revolutionary material approach selecting already usable material manufacture new part aircraft material selection approach approach selecting improved evolutionary material stoa sta work hardened technique etc approach existing material fig 1 basic approach material selection aircraft application characteristic required aerospace material closely governed structure made design type loading service environmental condition structure worked figure 2 author summarizes basic factor property select material fir aircraft design factor property aircraft material selection manufacturing structural environment economic issue basic specialist durability property impact issue castibility property service fatigue strength life emission material environment fabricability thermal impact damage greenhouse availability dimensional aspect expansion moisture tolerance transportation tolerance conductivity absorption rigidity modulus processing raw material surface quality thermal resistance elastic modulus hazardous waste cost number part electrical value rate hardness density sustainability maintenance required testing shock thermal oxidation rate strength rupture flammability cost method resistance corrosion stress life carcinogen regulatory procedure quality stealth rate creep rate hazard issue assurance fig 2 basic factor property material aircraft application general total take weight aircraft composed 5 7 weight engine 7 12 weight fuselage 8 14 weight wing 4 due consideration needed selecting weight efficient material manufacture engine structural component aircraft author summarize general property material aircraft application table 1 selecting material listed property maintain whole life component aircraft always difficult job aerospace engineer pick suitable material 120000 competitive material 65000 metal 10000 ceramic 15000 plastic wood composite etc 4 manufacture part however 0 05 total 120000 material suitable respect needed property aerospace component 4 2 titanium alloy 4 51 g cm 3 density titanium ranked ninth abundant element earth crest 7 light metal also honor fourth plentiful structural material available aluminum iron magnesium 8 ti alloy class chemically similar physically different material exhibit hcp bcc structure 8974 paramjit singh material today proceeding 4 2017 8971 8982 table 1 material property necessity aircraft component property necessity aircraft component high strength stiffness intense static dynamic landing load component landing gear take requirement ability carry standing situation aerodynamic dead structural shell type structure wing empennage fuselage generally subjected compressive load buckling stress landing compound loading body load surface load aircraft structure produce severe torsion shear bending stress take tailplane load coupled wing box load fuselage result severe bending stress fuselage flight crown bottom part fuselage subjected tensile compressive stress respectively rolling turning aircraft produce high magnitude shear twisting stress respectively along fuselage much stiff material always obliged aircraft wing facing reversal tensile compressive stress resting flight moment pressurization flight cause severe bending fuselage component wing angle dihedral produce high compression fuselage high stiffness need corrugated sheet wing face regular compression tension cap shaped spar stern bending wing stern compressive force nacelle due high engine wieight good fracture toughness heavy landing static load good fatigue endurance strength superior fatigue resistance titanium replaces aluminium fighter aircraft frame bulkhead resist variability loading moment wind gusting unavoidable turbulence etc military aircraft face numerous manoeuvrings war practice session high fatigue occurs fuselage skin material due cyclic depressurization pressurization five ten failure gas turbine engine component due fatigue failure 5 6 high thermal strength withstand 1500 c temperature jet engine good corrosion resistance flight hot freezing temperature condition working corrosive fluid body paint stripper jet fuel lubricant good impact strength damage movement bird strike aircraft damage resistance key property tolerance property take moment fluttering debris may strike leading edge aircraft intense landing load component landing gear take resting moment good durability entire design life aircraft typically 8000 4000 30000 60000 journey hour military aircraft commercial airliner respectively light weight usually airframe major share upto 40 total weight aircraft light weight material definitely reduce burden good fabricability welding riveting airframe cost initial cost purchasing new aircraft maintenance cost lead time le lead time easy machining raw material finished component allotropy hcp bcc structure widen range mechanical property hence scope ti alloy aircraft industry 1155 k allotropic adaptation α hcp low temperature β bcc high temperature provides base titanium alloy offer wide range variety property grouping type content alloying element b effect physical behavior possible phase c effect mechanical behavior possible phase stability phase four base reason manipulation property addition b c reason processing route treatment method welcome metallurgy particularly ofparamjit singh material today proceeding 4 2017 8971 8982 8975 β alloy develop composition superior property enough satisfy need aeroengines airframe attachment component 9 2 1 titanium candidate aircraft application good specific strength except composite variation wide range alloy possible chemical composition broaden utilization wing box undercarriage component fuselage part airframe attachment etc table 2 titanium property rational aircraft component application property rationale description strength weight ratio 40 lesser density steel extraordinary flexibility titanium weighs 56 weight steel 50 lesser modulus steel replacing steel spring manufacturing aircraft application working temperature nearly 600 c temperature nozzle plug engine component 10 embrittlement material due contamination engine temperature 2 cryogenic temperature rocket engine impeller 270 f aluminum loos strength titanium space constraint 737 757 fitting landing gear beam possible titanium good ballistic resistance 15 35 le weight armor titanium equally strong due good ballistic resistance counterpart made steel high galvanic compatibility carbon titanium electrochemically compatible prevents galvanic corrosion galvanic ti composite among competitor aerospace metal titanium offer highest compatibility cfrpcs compatibility 11 thermal expansion coefficient stiffness titanium matched cfrpcs high thermal conductivity enormous heat production aeroengine demand quick release titanium suitable post low expansion coefficient property make possibility titanium combine glass ceramic composite aerospace application corrosion resistance titanium ability make oxide film natural prevents environmental oxidizing mineral acid chemical water inorganic salt solution etc attack oxide film also prevents cavitations abrasion due dense air flow flight landing gear made titanium need le maintenance due excellent corrosion resistance therefore cost reduction negligible pitting almost service condition part made titanium advantageous compared competitor metal cost titanium per kg cost competitor metal due extraction melting complexity titanium ingot costly almost six time pricey produce compare aluminum ingot 12 cost reliability density corrected life cycle cost taken economics titanium proved economic option aerospace sector 13 good weldability joining ti alloy easily joined diffusion bonding welding 4 thereby diffusion bonding reduces number mechanical fastener screw bolt rivet comparison assembly made aluminium alloy weldment ti maintains strength giving almost 100 weld joint efficiency negligible lose durability fracture toughness 14 titanium resists exfoliation stress corrosion corrosion form far better aluminium alloy steel etc titanium resists attack corrosion agent forming maintaining oxide surface layer application environment whereas one hand ability titanium retain strength enormous hot8976 paramjit singh material today proceeding 4 2017 8971 8982 condition replaces polymer fiber composite hand property light weight replaces counterpart material nickel alloy steel high temperature load application candidature ti alloy aerospace application based following aspect table 2 early 1950s use manufacture part pw j57 aeroengine b52 bomber titanium quickest noticed material aerospace industry next 1952 firewall nacelle dc 7 aircraft product dac second application titanium aerospace industry since unique attribute cold war metal appreciably increase demand aircraft industry thermal stability ti alloy extends use airframe subjected frequent aero kinetic heating 2 2 α titanium alloy quantity wt α stabilizer alloying element α ti alloy divide two class e super α alloy near α alloy inherent property α ti alloy like ductility resistance creep hotter environment always welcomed aeroengine part super α alloy containing 5 wt alloying element composed α ti grain ti 5al 2 5sn alloy belongs class near α alloy contain β stabilizer 2 wt dispersed among large volume α ti grain solid solution hardening work hardening rolling extrusion plastic forming process grain size refinement etc strongly affect strength α ti alloy plastic forming process even double tensile strength alloy presence aluminium upto 9 valence shell ti stabilizes α phase thereby rapidly increase tensile strength adding aluminium 9 adverse effect ductility fracture toughness important reason use α ti alloy aeroengine part ability retain strength heat treatment process thermal stability thermal aging resistance α ti alloy allow appreciable change mechanical property working hotter condition long duration following section inherent characteristic aircraft application α ti alloy discussed 2 2 1 cp ti addition low specific strength moderate yield strength normally 170 480 mpa cp ti restricts use aero structural engine part 4 presence small trace atomic fe 2 impurity cp ti advantageous disadvantageous effect one hand impurity improves ultimate tensile strength cp ti 0 01 content 250 mpa 0 2 0 4 content 2 2 300 450 mpa hand impurity reduces creep resistance thermal stability ductility material property like good toughness strength cryogenic temperature 220 c favor use cp ti making fuel tank store h liquid form space vehicle 2 2 2 2 ti 3al 2 5v developed 1950 ductile alloy good toughness exhibit y ut equal 483 mpa 620 mpa respectively y ut cold workable alloy enhanced upto 830 mpa 910 mpa respectively sta treatment however sta reduces elongation 15 normal temperature 11 sta high pressure ducting tube aircraft made ti 3al 2 5v save 40 weight compared tube made 21 6 9 steel cold workable characteristic ti 3al 2 5v alloy made feasible replace cp ti fabrication aircraft honeycomb core acceptable corrosion resistance good weldability ability fabricate seamless tube favor use aircraft hydraulic tubing paramjit singh material today proceeding 4 2017 8971 8982 8977 2 2 3 ti 5al 2 5sn good stability ti 5al 2 5sn welded joint offer oxidation resistance upto 1000 f temperature make ti 5al 2 5sn suitable fabrication blade jet steam turbine 15 ti 5al 2 5sn difficult forge forged ti 5al 2 5sn exhibit y ut typically equal 758 mpa 792 mpa respectively without notable effect elongation value annealing ti 5al 2 5sn plate increase y ut upto 779mpa 827mpa respectively inherent capability ti 5al 2 5sn alloy retain ductility fracture toughness upto cryogenic temperature make possible use alloy store h liquid form turbo pump space 2 vehicle 2 2 4 ti 8al 1mo 1v 1960s metallurgist succeed develop ti 8 1 1 alloy aluminium content offer young modulus α β alloy american supersonic airplane first use ti 8al 1mo 1v structure heat resistance capability upto 400 c made unique material manufacture compressor blade normal temperature ti 8 1 1 elongates upto 10 yield 930 mpa 16 however le corrosion resistance restricts extensive use 2 2 5 ti 6 2 4 2 ti 5 5a1 3 5sn 3zr 1nb 0 25mo 0 3si 540 c temperature gas turbine engine requires much stronger creep resistant tougher material manufacture part component ti 6 2 4 2 forged bar ut equal 999 mpa y equal 930 mpa posse retains characteristic upto 540 c jet engine part e rotor disc blade manufactured ti 6 2 4 2 alloy 960 mpa yield strength ti 5 5a1 3 5sn 3zr 1nb 0 25mo 0 3si almost double counterpart al alloy rb211 535 e4 engine boeing 757 aircraft utilizes ti 5 5a1 3 5sn 3zr 1nb 0 25mo 0 3si alloy manufacture spacers blade compressor disc alloy enhanced strength β sta treatment 17 withstands 540 c temperature aircraft engine 2 3 α β titanium alloy adding α stabilizer 2 6 β stabilizer 6 10 formation grain α ti β ti normal temperature form favorable class titanium alloy α β ti aircraft component manufacturer fracture toughness excellent creep strength ductility α β titanium alloy superior α ti alloy tensile strength fatigue resistance alloy superior β ti alloy grain boundary strengthening solid solution hardening work hardening β ti grain precipitation hardening improves strength α β ti alloy thermal aging transforms ti β phase ω precipitate ti α phase thereby improves strength class ti alloy thermal aging 480 650 c double proof strength compared simple annealed alloy following section inherent characteristic aircraft application α β ti alloy discussed 2 3 1 ti 6al 4v 80 90 volume total titanium used airframe part skin panel stiffener wing box spare etc made ti 6al 4v alloy alloy also major share volume jet engine part 60 total titanium consumed airframe 80 90 total titanium consumed cooler part fan compressor blisk f 35 lightening ii fighter part working 300 c made ti 6al 4v impact strength needed withstand bird striking cockpit window often provided forged ti 6al 4v helicopter bk117 bk105 forged ti 6al 4v extensively used rotor head 8978 paramjit singh material today proceeding 4 2017 8971 8982 2 3 2 ti 6al 2sn 2zr 2mo 2cr si rmi 1970s developed ti 6al 2sn 2zr 2mo 2cr si alloy alloy known superplastic formability thermal stability oxidation resistance presence 0 15 si improves creep resistance deep hardenability ut y equal 1069 mpa 1034 mpa respectively annealed condition make useful make aft fudelage engine mount wing structure bay bulkhead f 22 raptor fighter aircraft recently alloy restructured lockheed f 22 raptor 2 3 3 ti 6 2 4 6 ti 5ai 2sn 2zr 4mo 4cr exceptional creep resistance capacity resist heat upto 450 c temperature made ti 6 2 4 6 unique choice aeroengine component sta component ti 6 2 4 6 elongated upto 10 yield strength 1105 mpa 1970s usa metallurgist succeed develop ti 5ai 2sn 2zr 4mo 4cr alloy tensile strength yield strength 1250 mpa 1150 mpa respectively excellent fracture toughness superior crack propagation resistance capacity resist heat upto 350 c recommends alloy damage tolerance design shaft fan single unit aircraft 2 4 β titanium alloy r jaffee 18 first categorized β ti alloy distinct class ti alloy initial research effort direction developed ti 13v 11cr 3al alloy offered high strength 1276 mpa inconsistent response heat treatment adding isomorphous β stabilizer hf v ta cr nb mo etc cooling ti metal purpose resist martensitical decomposition β phase shift β α β transformation boundary towards room temperature inherent property β ti alloy like extraordinary fatigue resistance high tensile strength always welcomed heavily loaded structural part microstructural alteration β ti alloy heat treatment regime offer verity mechanical property 19 20 suit airframe component subjected sta ti β alloy except ti 3al 8v 6cr 4mo 4zr lead develop dispersed secondary α precipitate improves tensile strength aircraft industry ti 15v 3al 3sn 3cr ti 10v 2fe 3al ti 5al 5v 5mo 3cr 0 5fe ti 15mo 3al 3nb 0 2si ti 3al 8v 6cr 4mo 4zr six ti β alloy continuing use till date 21 22 23 since inception written table 3 following section inherent characteristic aircraft application β ti alloy discussed 2 4 1 ti 10v 2fe 3al alloy timet 1974 filed patent chemical composition newly developed titanium alloy ti 10v 2fe 3al exceptionally high fracture toughness ductility tensile strength 28 29 initial performance alloy checked making landing gear boeing 777 forging application 21 except outer inner cylinder component landing gear made ti 10v 2fe 3al alloy 30 without compromising desired strength component total reduction 270 kg weight achieved aircraft 31 later 1980 exceptional property ut 1240 mpa kic 44 mpa etc forced design engineer recommend application boeing 757 airframe well future aircraft design 32 table 3 show dominating share v 9 0 11 0 wt fe 1 6 2 2 wt make constituent prominent β stabilizer presence fe make possible manage microsegregation promotes hardenability alloy al 2 6 3 4 wt catalysis hardening reaction providing necessary α phase whereas oxygen 0 13 wt maintains fracture toughness optimum strength level needed aerospace application 28 33 paramjit singh material today proceeding 4 2017 8971 8982 8979 2 4 2 ti 15v 3cr 3al 3sn alloy 1970 air force supported project develop titanium alloy coldworking application manage repair work 34 lockheed timet experimentation lower chromium level minimum develop cold rolled coil sheet ti 15v 3cr 3al 3sn alloy first application hundred part non structural structural rockwell b1b bomber fabricated tested successfully excellent formability alloy result net saving fabrication cost compared competitor alloy 35 1990s ti 15v 3cr 3al 3sn alloy replaced cpti material ducting tube boeing 777 result net saving 63 5 kg weight boeing airframe 21 36 ti 15v 3cr 3al 3sn spring le weight upto 70 le volume upto 50 corrosion resistant steel spring 2 4 3 ti 3al 8v 6cr 4mo 4zr alloy 1960s rmi titanium production company took assignment develop ti 3al 8v 6cr 4mo 4zr alloy substitute ti 13v 11cr 3al alloy airplane frame component without compromising hot cold workability physical mechanical property etc rmi reduced chromium content minimize segregation tendency ti 3al 8v 6cr 4mo 4zr alloy 37 excellent deep hardenability 150 mm section size good corrosion resistance light weight superior strength offered alloy break barrier limiting production 1 total ti production due high initial cost special attention involved melting fabrication traditionally melted plasma arc melting 38 processed hot working process extrusion rolling gorging etc 795 c ti 3al 8v 6cr 4mo 4zr alloy posse good forgability deep hardenability solution treatment ti 3al 8v 6cr 4mo 4zr alloy 790 925 c one hour followed suitable method cooling normal air forced air water quenching etc increase strength alloy 39 suitable aging treatment 470 620 c 4 12 hour solution treatment affect mechanical property ti 3al 8v 6cr 4mo 4zr exhibit many metastable phase α phase β phase β■ phase ω phase ti zr si ticr etc 37 put application fastener fitting landing gear coiled actuation 5 3 2 spring aircraft ti 3al 8v 6cr 4mo 4zr offer improved corrosion resistance 70 weight reduction compared component manufactured conventional 17 4ph steel 31 2 4 4 ti 15mo 3al 3nb 0 2si alloy timet 1988 developed ti 15mo 3al 3nb 0 2si alloy unique property like foil producability extraordinary strength environmental degradation resistance etc ability maintain property high temperature 40 produced triple var alloy generally available aerospace industry solution heat treatment condition β structure single phase forging cold rolling process reduce thickness le 4mm direct use aircraft part 41 excellent cold formability good response aging treatment without quick workhardening make possible compressive load reduce ti 15mo 3al 3nb 0 2si alloy part 80 compression part lose inherent property sort crack initiation etc 23 first application mmcs nap program 40 number component military civil aeroengines exhausting part like plug nozzle arrangement roll royce trent 400 engine airbus a340 boeing 777 manufactured 42 practically 164 kg weight boeing 777 aircraft reduced part made inconel 625 alloy ware replaced ti 15mo 3al 3nb 0 2si alloy 36 another application thrust reverser inside wall cfm leap 1b engine boeing 737 max aircraft performs better made ti 15mo 3al 3nb 0 2si alloy material 2 4 5 ti 5al 5mo 5v 3cr alloy late 1990s time aerospace industry felt need material improved processability work performance compare ti 10v 2fe 3al alloy 43 vsmpo made compositional alteration decreased fe wt content increased cr wt content base material ti 5al 5v 5mo 1cr 1fe developed ti 5al 5mo 5v 8980 paramjit singh material today proceeding 4 2017 8971 8982 3cr alloy uniformity microstructure well macrostructure new alloy added advantage like hardenability ultimate strength compared conventional ti 10v 2fe 3al alloy ti 5al 5v 5mo 1cr 1fe alloy limited fe content wt ti 5al 5mo 5v 3cr minimizes segregation chance thermomechanical processing heat treatment type affect α β phase microstructure mechanical property alloy 44 aging treatment low temperature affect uniformity α distribution hence mechanical characteristic alloy 45 russian aircraft number component like landing gear part lift device fuselage part common application ti 5al 5mo 5v 3cr alloy forging ti 5al 5mo 5v 3cr fulfill requirement landing gear airframe boeing 787 46 part made ti55531 version ti 5al 5mo 5v 3cr added 1wt zr commonly used airbus 380 aircraft 47 2 4 6 ti 35v 15cr alloy 1980s failure noted exhaust nozzle assembly made conventional ti alloy due high thermal stress combustion pratt whitney f 119 engine f22 raptor 48 49 twca developed stable β alloy compositional element v 35 wt cr 15 wt 50 took almost five year mature alloy 49 effect aging treatment towards α precipitation ti 35v 15cr alloy maintains stability retains β phase without quenching presence cr higher wt help absorb thermal energy upto heat fusion 50 51 presence v stabilizes β phase strengthens solid solution ti 35v 15cr whereas carbon make carbonitrides 52 ti 35v 15cr alloy offer extraordinary resistance thermal burning aircraft exhausting system alloy maintains strength extreme temperature condition though recommended temperature upto 540 c 48 past decade china uk investigated lot burn resistant alloy making metallurgical alteration addition al c content 30 53 54 3 summary future work article address basic attribute characteristic ti alloy aircraft airframe engine component application cp ti commonly used ti alloy three class α α β β discussed author summarize discussion following bulleted point since inception 1950s considerable research metallurgical thermomechanical processing titanium alloy made possible increase service temperature limit 300 c near 600 c moderate specific strength ti alloy recommend use design airframe part stiffness prime requirement high resistance creep oxidation offered near alpha alloy key reason suitability elevated temperature application good formability characteristic increase share cp ti airframe corrosive environment aircraft lavatory kitchen demand use cp ti heat resistance strength attribute favor use ti alloy engine presence mo ta nb v etc alloying element hamper ductility metastable β alloy high strength level hardening rate segregation welded part major drawback limit weld ability metastable β alloy hence use welded titanium part aircraft boeing usa airbus europe leader aircraft manufacturing forecasted increasing percentage share ti alloy per plane overall aircraft industry coming year paramjit singh material today proceeding 4 2017 8971 8982 8981 4

acknowledgement k gujral punjab technical university kapurthala gratefully acknowledged research work

reference 1 peter j kumpfert c h ward c leyens titanium alloy aerospace application adv eng mater 5 2003 419 427 2 flightpath 2050 europe vision aviation report high level group aviation research publication office european union luxembourg 2011 3 mitsuhiro k masashi making lighter aircraft engine titanium aluminide blade ihi eng rev 47 1 2014 10 13 4 p mouritz introduction aerospace material first ed woodhead publishing suite philadelphia usa 2012 5 koul et al proc asme turbo expo orlando fl 2009 6 h ozaltun j seidt et al proc asme turbo expo orlando fl 2009 7 c leyens peter c leyens peter ed titanium titanium alloy fundamental application wiley vch verlag gmbh weinheim 2005 8 kuttolamadom j jones l mears kurfess choragudi sae technical paper 2010 01 0022 2010 9 banerjee dipankar williams j c perspective titanium science technology acta materialia 61 2013 844 879 10 r r boyer attribues characteristic application titanium alloy jom 2010 62 5 21 24 11 j fanning titanium alloy composite intensive airframe timet presentation conference titanium san diego 2006 12 v r henriques titanium production aerospace application j aerosp technol manag 1 1 2009 7 17 13 f h froes titanium physical metallurgy processing application asm international first ed p 354 14 new material next generation commercial transport committee new material advanced civil aircraft national academy press washington c 1996 15 specification book fourth ed international titanium association broomfield usa 2005 16 titanium pamphlet japan titanium society ed 4 2007 17 c veiga j p devim j r loureiro rev adv mater sci 32 2012 133 1481 18 r jaffee j min met mat 7 247 1955 19 ikeda komatsu sowa niinomi aging behavior ti 29nb 13ta 4 6zr new beta alloy medical implant metallurgical material transaction 33 3 2002 487 493 20 abasi momeni nonferr metal soc 21 8 2011 1728 1734 21 r r boyer jom 44 5 1992 23 25 22 eylon proc int workshop beta titanium alloy paris france 1994 75 82 23 james cotton robert briggs rodney r boyer sesh tamirisakandala patrick russo nikolay shchetnikov john c fanning state art beta titanium alloy airframe application june 2015 volume 67 issue 6 pp 1281 1303 24 am 4914f titanium alloy cold rolled sheet strip 15v 3al 3cr 3sn solution heat treated 25 am 4957e titanium alloy round bar wire 3ai 8v 6cr 4mo 4zr consumable electrode melted solution heat treated cold drawn 26 am 4897c titanium alloy sheet strip 15mo 3 0al 2 8cb 0 20si sae 2011 27 paul j bania beta titanium alloy role titanium industry jom july 1994 volume 46 issue 7 pp 16 19 28 w parris h w rosenberg u patent us3 802 877 9 april 1974 29 g w kuhlman beta titanium alloy 1990s proceeding symposium metallurgical society aime ed eylon r r boyer kos new york mineral metal material society 1993 pp 485 512 30 g lutjering j c williams titanium second ed springer verlag 2007 283 336 31 r r boyer jom 46 7 1994 20 23 32 r r boyer h w rosenberg proc symp annual meeting metallurgical society aime ed r r boyer h w rosenberg new york american institute mining metallurgical petroleum engineer 1984 pp 441 456 33 r r boyer g w kuhlman processing property relationship ti 10v 2fe 3al metallurgical transaction december 1987 volume 18 issue 12 pp 2095 2103 34 harry w rosenberg ti 15 3 new cold formable sheet titanium alloy jom 1983 volume 35 issue 11 pp 30 34 35 e rosenblum shame w b treppel proc symp annual meeting metallurgical society aime ed r r boyer h w rosenberg new york american institute mining metallurgical petroleum engineer 1984 pp 307 329 36 l fleming titanium prod appl proc tech program int conf 2 1990

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alloy: 0.4709711682830289
ti: 0.44346920225190306
aircraft: 0.271581914557367
titanium: 0.271581914557367
material: 0.23376671126456908
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