https://doi.org/10.1051/matecconf/202032111027

Comparison of different titanium alloys welded by Yb:YAG fibre laser for thin sheet applications used for T-ducts in bleed air systems

Stefan Riekehr[1)], Volker Ventzke[1)], Sabine Wagner[2)], Werner Beck[2)], Nikolai Kashaev[1)]

[1)]*Institute of Materials Research, Materials Mechanics, Joining and Assessment Department, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, D-21502 Geesthacht*

[2)]*FormTech GmbH, Mittelwendung 26, 28844 Weyhe, Germany*

Abstract

Research in aerospace applications includes the replacement of well-known materials by newly developed alloys or by new manufacturing methods for the existing materials. In the frame of TiB-Air project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) the development of a process chain consisting of deep drawing at elevated temperatures, chemical milling, contour machining by laser cutting and laser beam welding to produce pneumatic T-ducts used in bleed air systems is in focus. This production process of sheet metal parts could lower costs in terms of the process itself and the used materials: low alloyed Ti-alloys. Commercially pure titanium alloy (cp-Ti) is commonly used for these structures because of its balanced mechanical properties regarding tensile strength, yield strength, plastic strain and fatigue strength as well as good resistance against corrosion and oxidation. The possibility to substitute cp-Ti by low-alloyed Ti-alloys is examined in this work, by the comparison of two different low alloyed Ti-alloys, namely KS1.2ASN and Ti XT, with a cp-Ti alloy (Grade 4). Mechanical properties of the base materials, their weldability and the mechanical assessment of the laser beam welded butt joints in terms of static, cyclic and fracture mechanical behaviour is compared for sheet materials, with a thickness of 0.9 mm. Defect-free welding according to EN13919 acceptance criteria B was possible for all three alloys, no porosity problems occurred. The low strength alloy KS1.2ASN exhibited mechanical anisotropy between longitudinal direction and transverse direction in the tensile test, welded specimens of this alloy broke in the base material. Due to the tensile properties, both weld and base material of KS1.2ASN showed the least values for the fatigue strength and endurance limit strength. Ti XT and Grade 4 showed similar mechanical anisotropy and fractured in the base material, too. Fatigue strength of Ti XT is below Grade 4, but for the 50%-percentile the endurance limit strength is equal. Fracture mechanical testing showed that KS1.2ASN is a very promising alloy in the welded condition.

Introduction

For the manufacturing of straight or bended pneumatic tubes for bleed-air-systems, cp-Ti as Ti Grade 2 or Ti Grade 3 is mainly used [1, 2]. cp-Ti offers moderate strength up to 205 °C, high corrosion resistance, oxidation resistance up to 315 °C, low density of 4.5 g/cm³, high fatigue strength even at elevated temperatures and good weldability [3, 4, 5]. Usually titanium pneumatic tubes have wall thicknesses between 0.5 mm and 1.0 mm and diameters between 50 mm and 180 mm [1-3]. The components of a bleed-air-system are subjected to cyclic loads in terms of pressure and heat [3], the bleed air can be 200 °C to 250 °C hot at a pressure of 2.76 bar [6]. Damages in the bleed-air-systems are in sum 29% of all technical incidents in older passenger airplanes [7].

Adib et al. [4] stated that 55 % of all technical incidents in aircrafts were caused by fatigue, 16 % by corrosion and 14 % by overload. Pneumatic titanium tubes showed damages initiated by cracks near to welds [4]. Carvalho et al. [3] also reported crack initiation close to welds in titanium tubes used in flight or in simulation tests. For the welding of titanium tubes plasma arc or tungsten inert gas (TIG) welding is used [1-4]. Lync et al. [1] examined a TIG welded tube made of Ti Grade 3, which was damaged in the heat affected zone (HAZ) close to the weldment after 26600 h in service and 19275 pressure cycles. As a reason for the crack initiation the interaction of several factors was identified: embrittlement, tensile residual stresses and cyclic loading. Lynch et al. stated that the cyclic loading resulted from superposition of in-flight vibrations, cyclic pressurization and thermal cycles. Reasons for embrittlement were seen in grain coarsening and in fluctuations of the shielding atmosphere, which could lead to entrapment and solution of oxygen and nitrogen in the weld region, leading to loss of ductility and fatigue [1]. In experimentally welded Y-tubes of titanium SAE AMS 4941C, equivalent to Ti Grade 2, Baptista et al. [2] detected a through thickness crack with 35 mm length between fusion zone and base material after 20800 pressure cycles at 10.35 bar and 400 °C. Carvalho et al. [3] resumed from [1] and [2] that the crack initiation at weld flaws is a problem of the used welding processes due to the high heat input of PAW- or TIG-welding. As an alternative laser beam welding (LBW) was proposed, because of the low heat input and the resulting low distortion [3].

This work deals with laser beam welding of butt-joints of rolled titanium sheets (Ti Grade 4, Ti XT, KS1.2ASN) and the resulting mechanical properties under quasi-static and cyclic loading. The suitability of Ti Grade 4, Ti XT and KS1.2ASN to be used as substitutes for the actual cp-Ti in the manufacturing of pneumatic tubes for aircrafts is addressed.

Materials

Ti Grade 2 has a maximum content of 0.03 mass-% N, 0.25 mass-% O and 0.30 mass-% Fe [5, 8] and a minimum tensile strength of 345 MPa, minimum yield strength of 275 MPa and strain to fracture of 20 % [8]. b-eutectoid elements, e.g. Fe, lead to the formation of intermetallic phases, interstitially soluted elements as O, N and C stabilize the a-phase [8]. Increase of amount of these elements leads to higher yield and ultimate tensile stress, as shown by the comparison of Ti Grade 4 and Grade 2 (Tables 1 and 2). TIMET and Kobe Steel enhanced the oxidation resistance and the hot tensile strength of a-Ti-alloys by alloying with Si, Al and Nb [9, 10].

TIMETAL®Exhaust XT (Ti XT) from TIMET contains Si, which is a b-eutectoid element as Fe and usually added to Ti-alloys for high temperature applications. The enhancement of creep strength results from the precipitation of intermetallic Ti_5Si_3-phase [8]. The α-Ti-alloy KS1.2ASN contains beside Si, Al and Nb. Al stabilizes the α-phase and the b-isomorphic Nb enhances the oxidation resistance. TIMETAL® Exhaust XT (Ti XT) and KS1.2ASN were developed for applications in exhaust systems of motor cycles and automobiles and for the manufacturing of tube systems [9, 10]. The chemical composition and the mechanical parameters of Ti XT and KS1.2ASN are shown in Tables 1 and 2, note that a Nb content below 0.3 mass-% is not stabilizing the b-phase.

Table 1: Chemical composition of Ti Grade 4, Ti XT and KS1.2ASN [5, 9, 10](mass-%).

Alloy	H_2 (max.)	O_2 (max.)	N_2 (max.)	Fe (max.)	C (max.)	Si	Al	Nb

Ti Grade 4	0.0125	0.40	0.05	0.50	0.08	-/-	-/-	-/-
Ti XT	0.015	0.15	0.03	0.50	0.10	0.15-0.45	-/-	-/-
KS1.2ASN	0.0013	0.15	0.05	0.20	0.08	0.30-0.60	0.30-0.70	0.10-0.30

Table 2: Mechanical parameters of Ti Grade 4, Ti XT and KS1.2ASN [5, 8, 9, 11]

Alloy	Direction	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]
Ti Grade 4	-/-	480 (655)	550	15
Ti XT	L	489	591	30
	T	533	590	31
KS1.2ASN	L	323	457	32
	T	394	437	34

The microstructure of Ti Grade 4 is homogenous and consists of elliptical grains (Fig 1a), whereas Ti XT exhibits a finer microstructure of elongated a-Ti-grains and homogenously dispersed Ti_5Si_3-phase (Fig 1b). In comparison the grain morphology of KS1.2ASN is more heterogenous (Fig 1c).

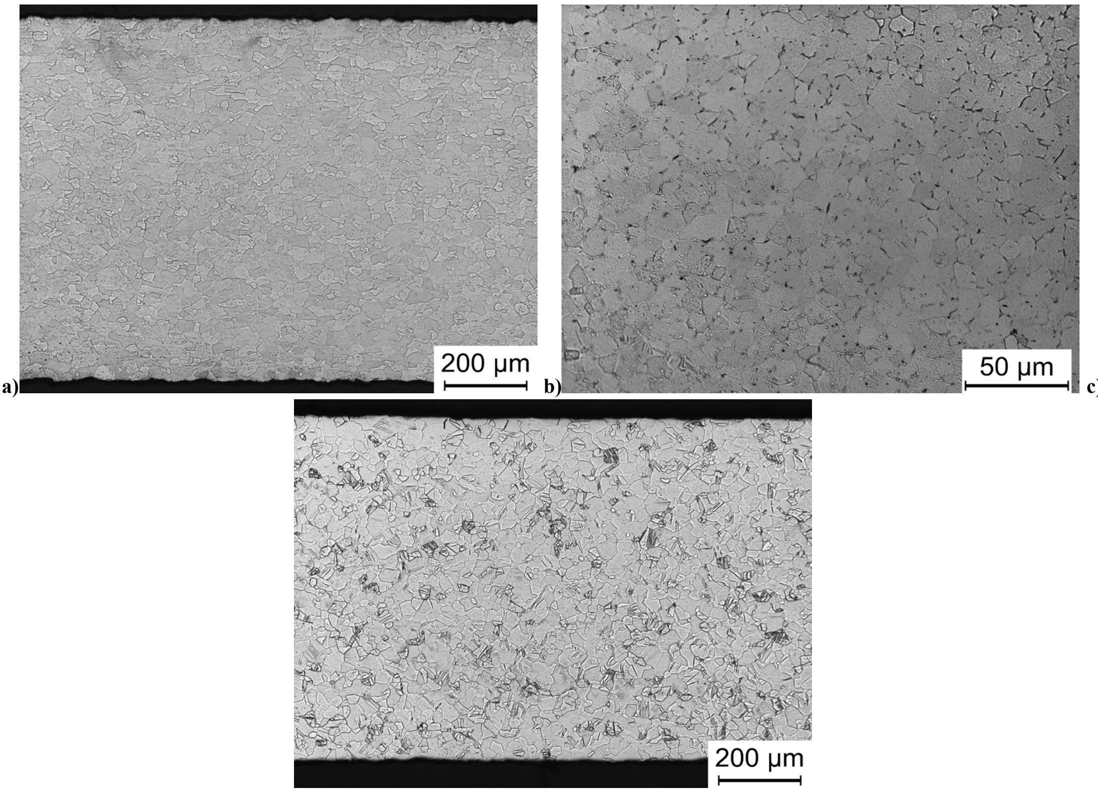


Fig 1: Microstructure of a) Ti Grade 4, b) TIMETAL®Exhaust XT (Ti XT), c) KS1.2ASN

Laser beam welding

For the LBW of the 0.9 mm thick butt joints of Ti Grade 4, Ti XT und KS1.2ASN an 8 kW Yb:YAG-fibre laser (IPG YLS-8000) was used. Via a fibre optic with 300 µm diameter the beam was delivered to the welding head with a focal length of 300 mm, mounted on an industrial robot KUKA KR30HA. Argon was used as shielding gas with 15 l/min for all welds. For titanium an absorption level of 37% at a wavelength of 1.06 µm is found in [12], so the Yb:YAG-fibre laser is efficient. Prior to welding the edges were prepared by milling, deburring and rinsing with acetone, to achieve a clean zero gap. Fig 2 shows the reproduction of a standardized radiograph of KS1.2ASN butt-joint. The laser beam weld is free of pores and cracks what proves the suitability of the edge preparation.

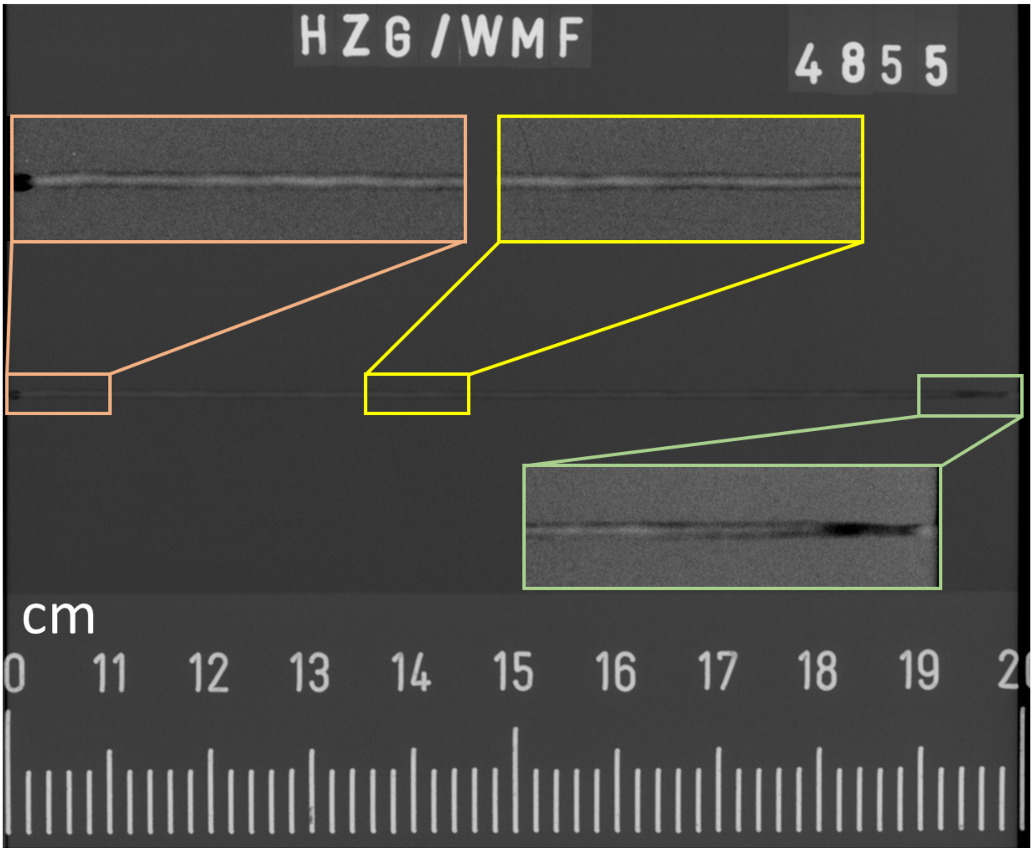


Fig 2: Reproduction of standardized radiograph of a KS1.2ASN butt-joint.

Butt-joint welding was performed for all three alloys with a continuous laser power of 1.4 kW, focal plane on the surface of the sheets, and a welding velocity of 5.0 m/min transverse to the rolling direction of the sheets. The basic welding parameters were extracted from studies of Nd:YAG- and Yb:YAG-laser beam welding of Ti6Al4V sheets with thickness between 1.0 and 2.54 mm and Ti Grade 1 sheets with 2.0 mm [13-15]. A ratio of 1.6 to 2.1 kW/mm thickness was identified. Higher laser beam power led to spatter and undercuts.

The following macrographs (Fig 3a-3c) display that with the selected parameters are a good combination of laser beam power and welding velocity. Neither the radiographs, nor the macrographs show any pores and cracks. In addition, no spatter was observed. The butt joints of Ti Grade 4 and Ti XT are characterized by a fine lamellar structure, the lamellae of KS1.2ASN are more coarse. Distinct fusion lines are not detectable. Vickers micro hardness line measurements from base material (BM) over the fusion zone (FZ) delivered hardness profiles showing a hardness increase for all three alloys in FZ and heat affected zone (HAZ). (Fig. 4).

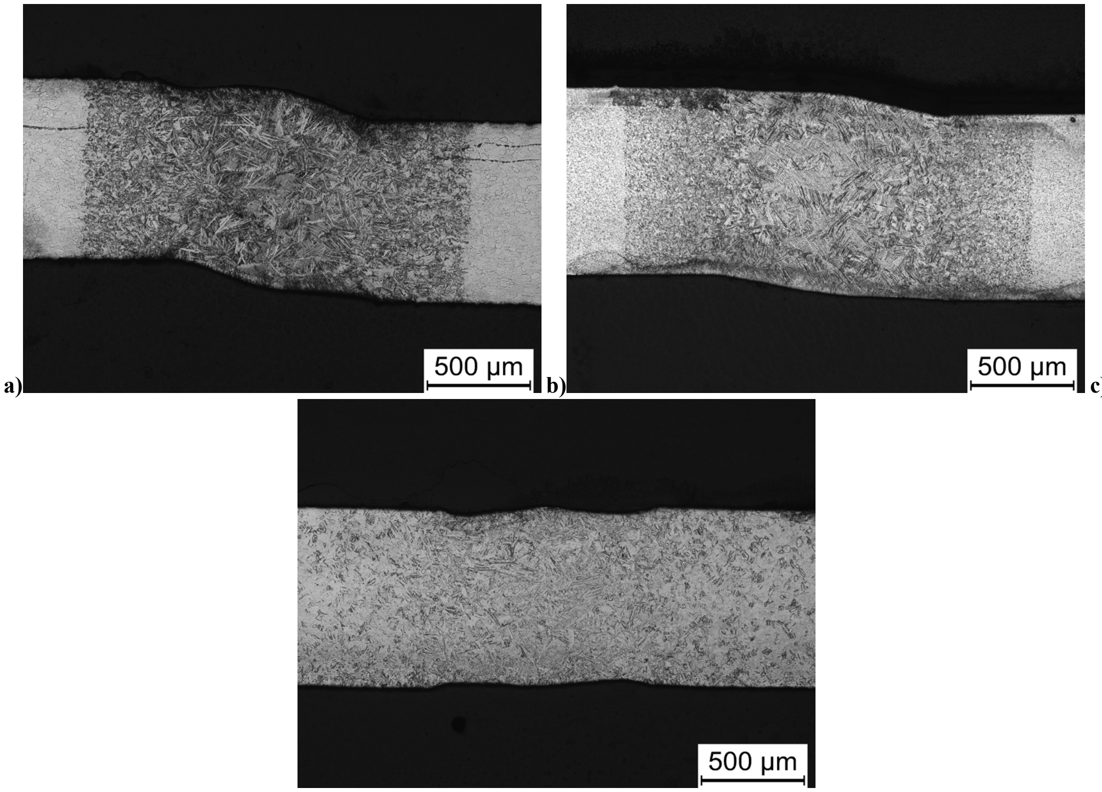


Figure 3: a) Ti Grade 4, b) Ti XT, c) KS1.2ASN

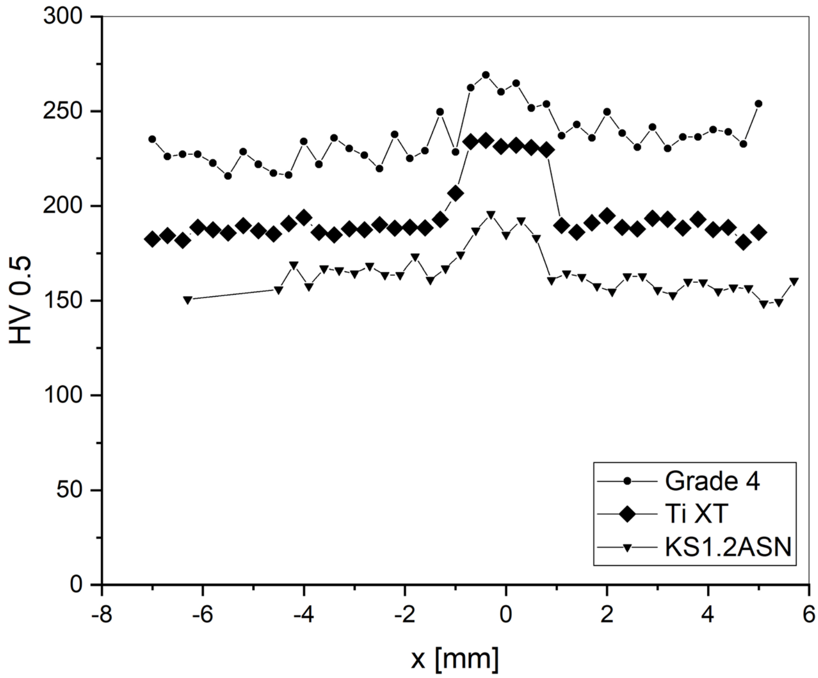


Figure 4: Micro hardness profiles of laser beam welded Ti Grade 4, Ti XT und KS1.2ASN.

Mechanical properties

Tensile tests (EN 2002-001:2005), fatigue tests (EN 6072:2010) and fracture mechanic tests (ASTM E1737) were performed in air at room temperature.

Table 3: Mechanical characteristics of Ti Grade 4, TI XT und KS1.2ASN from tensile and fatigue tests (HZG) in comparison to literature values.

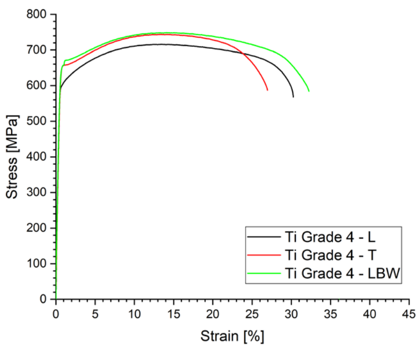
Alloy	R_m [MPa]	$R_{p0.2}$, R_{eL}/R_{eH} [MPa]	A [%]	s_D [MPa]	Lit. & HZG
Ti Gr. 2 (Ref.)	485 345	350 – 450 275	28 20	314 @ N=6·10^6 -/-	[5, 8, 19]

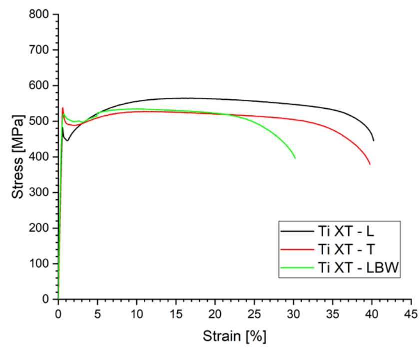
Ti Gr. 4	685 550	560 480	23 15	-/- 350 @ N=10^7	[8, 20]
Ti Gr. 4	716 (L) 744 (T) 749 (LBW)	581 (L) 650/651 (T) 650 (LBW)	29 (L) 26 (T) 32 (LBW)	401 @ N=10^7 465 @ N=10^7 184 @ N=10^7	HZG
Ti XT	591 (L) 590 (T)	489 (L) 533 (T)	30 (L) 31 (T)	-/- -/-	[9]
Ti XT	565 (L) 538 (T) 532 (LBW)	445/482 (L) 489/538 (T) 497/515 (LBW)	40 (L) 39 (T) 30 (LBW)	434 @ N=10^7 457 @ N=10^7 304 @ N=10^7	HZG
KS1.2ASN	457 (L) 437 (T)	323 (L) 394 (T)	32 (L) 34 (T)	-/- -/-	[11]
KS1.2ASN	418 (L) 421 (T) 422 (LBW)	293 (L) 369/387 (T) 368/380 (LBW)	40 (L) 43 (T) 32 (LBW)	289 @ N=10^7 289 @ N=10^7 290 @ N=10^7	HZG

The rolling texture of cp-, resp. a-Ti-sheets can be described by (0 0 0 1) ±30°- ±50° ® T [1 0 -1 0] // L with L being the rolling direction and T the long transverse. Often an orientation band can be seen in T-direction of (0 0 0 1)-pole figures [8, 15]. To assess the influence of the texture on the mechanical properties specimens were extracted both, in rolling (L) and transverse (T) direction. Displacement controlled tensile tests were performed in an electro-mechanical 100 kN testing machine (Schenck RM 100) with a cross head velocity of 0.5 mm/min. Displacement was measured with a laser scanner (Fiedler WS180). Fatigue tests were performed at 15 Hz with R=0.1 in a servo-hydraulic 10 kN testing machine (Instron 10kN). Welded specimens were not machined before testing.

The mechanical parameters as ultimate tensile strength (R_m), yield strength ($R_{p0.2}$), lower and upper yield point (R_{eL} and R_{eH}) strain to fracture (A) and fatigue strength (s_D) are shown in Table 3. For comparison literature values are juxtaposed to test data from HZG, reference material is Ti Grade 2.

Ti Grade 2 is referenced with an ultimate tensile strength of 345 - 485 MPa, $R_{p0.2}$ between 275 - 450 MPa and strain to fracture of 20 – 28 % [5, 8, 19]. Values from an S-N-curve for Ti Grade 2 leads to maximum stress of 314 MPa at 6×10^6 cycles and 393 MPa at 10^5 cycles [5].





a) b) c)

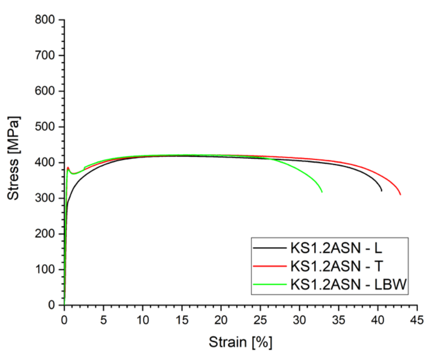


Figure 5: Stress-Strain-Curves of a) Ti Grade 4, b) Ti XT und c) KS1.2ASN sheet material resp. as-welded.

Ti Grade 4 exhibits higher values for R_m and $R_{p0.2}$ than Ti Grade 2. All Ti Grade 4 weldments showed in the tensile test fracture in the base material, due to the increased hardness in FZ and HAZ. The determined values were slightly higher than literature values [8, 20]. The fatigue strength of Ti Grade 4 is below its yield strength, but higher than the fatigue strength of the reference alloy. For the welded case, the fatigue strength drops well below 50% of the base material value, due to notch effects in the region of HAZ and FZ. Fracture location shifted to the base material, when the fatigue stress was higher than the yield strength. Here plastic deformation was superposed to damage through fatigue mechanisms.

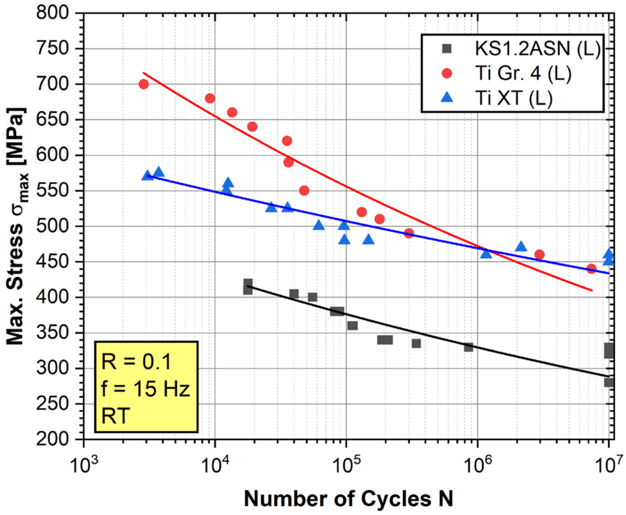
Mechanical characteristics of Ti XT in tensile test were lower as in literature [9], but between Ti Grade 2 and Ti Grade 4. Fatigue strength of Ti XT is higher than Ti Grade 4, despite the lower yield strength. The difference of yield strength and fatigue strength is much lower for Ti XT. The welded Ti XT joints showed higher fatigue strength than Ti Grade 4 and the loss in comparison to the base material was smaller. Again, fracture occurred for low stresses in the HAZ-FZ area, for stresses higher than the yield strength, fracture location was shifted into the base material, also with superposing plastic deformation to fatigue mechanisms.

Lowest mechanical values were found for KS1.2ASN, comparable to Ti Grade 2, but below literature values [11]. In the tensile tests, the welded joints fractured in the base material, again shielding effect of hardness increase was present. The fatigue strength was nearly the same for base material and welded joints.

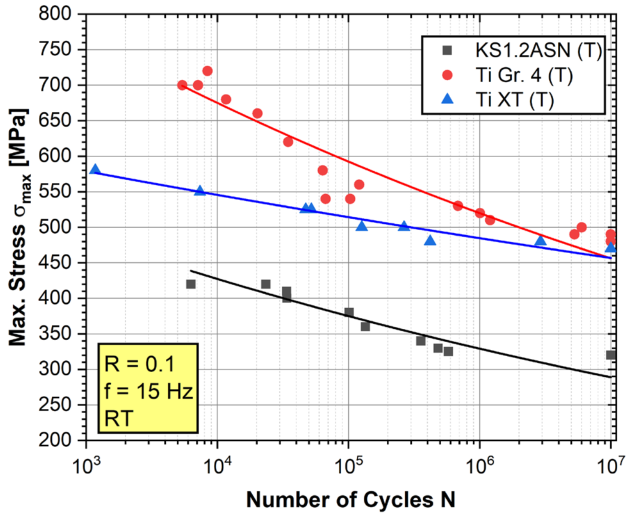
In Fig 5 the stress-strain-curves are displayed for base materials and welded joints. Due to the texture some differences between L- and T-direction occur. Pronounced yield points are found for all three alloys, but only for Ti XT in both directions, Ti Grade 4 and KS1.2ASN show this particular mechanical behaviour only in T-direction. Metallographic investigations after fracture showed deformation twinning beneath ductile deformation. CP- and a-Ti tend to the formation of deformation twins during mechanical loading [8, 18].

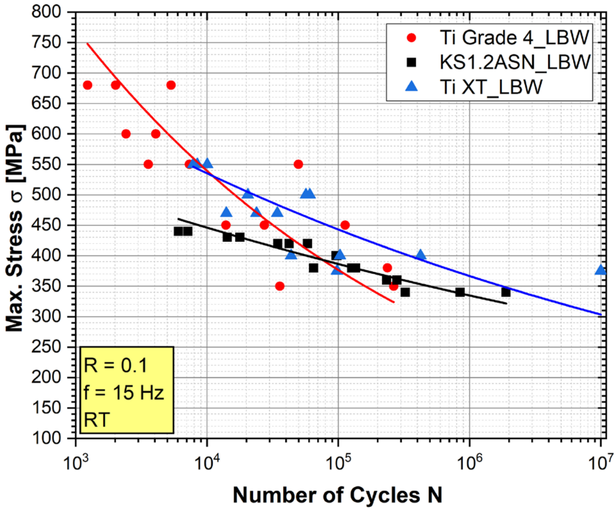
The butt-joints of the three alloys exhibit also pronounced yield points, despite the different orientation. As mentioned before, fracture occurred not in the welded joint. All joints showed higher hardness in the weld zone than in the base material. This strength mis-match shifts deformation into the base material and shields the weld zone mechanically. The slightly lower strain to fracture values are due to the lower deformable length when approximately 5 % of the deformation length cannot be deformed, due to the higher hardness. For the determination of the strain to fracture of conventional welds, this shortening of the testing length is compensated by elongating the testing length by the width of the weld. For laser beam welded joints this compensation is not recommended in the standards.

The orientation dependency of the strength values is also displayed for the fatigue endurance values of Ti XT and Ti Grade 4. KS1.2ASN shows a more isotropic mechanical behaviour, Fig 6.


Max. Stress σmax [MPa]
Number of Cycles N
KS1.2ASN (L)
Ti Gr. 4 (L)
Ti XT (L)
R = 0.1
f = 15 Hz
RT

a) **b)**


Max. Stress σmax [MPa]
Number of Cycles N
KS1.2ASN (T)
Ti Gr. 4 (T)
Ti XT (T)
R = 0.1
f = 15 Hz
RT



c) d)

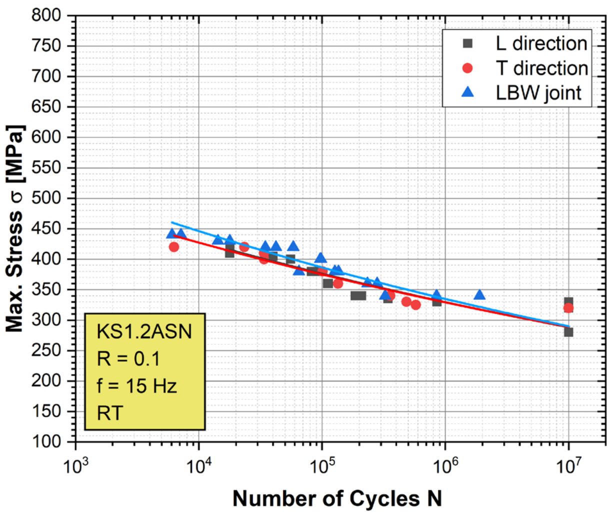


Figure 6: S-N-curves of Ti Grade 4, KS1.2ASN and Ti XT; a) L-direction, b) T-direction, c) "as-welded", d) KS1.2ASN sheet material and "as-welded".

For comparison of the fracture behaviour under static loading KS1.2ASN and Ti Grade 4 were selected. Small panels with a centre crack were manufactured, to reduce buckling to the minimum. Specimens were 120 mm wide M(T) specimens. For the test an anti-buckling guide was mounted, crack mouth opening was measured directly with a clip gauge from mounted knife edges. To compare the fracture behaviour, as ASTM E1737 is only valid for bending specimens, the fracture resistance J was calculated according to EFAM GTP94 [21] for the maximum load values and collected in Table 4. The original load versus CMOD (crack mouth opening displacement) curves are shown in Fig. 7.

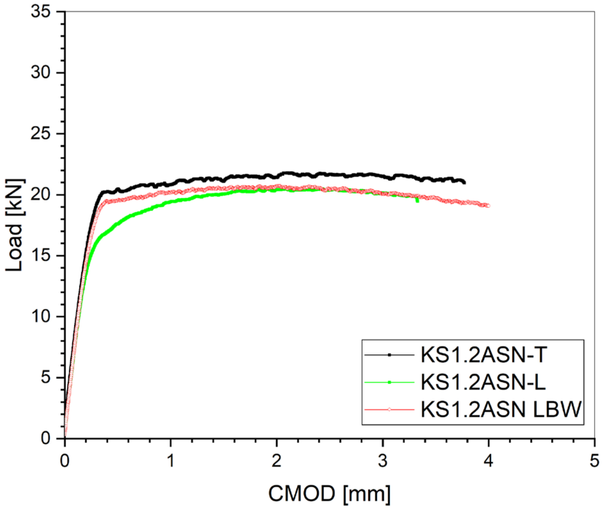
Again, KS1.2ASN shows only a slight orientation dependency, J_{max} values between differ by 10 % (323 and 354 MPa*mm) between T- and L-direction. The laser beam weld of KS 1.2ASN exhibits a J_{max} of 334 MPa*mm, as the F-CMOD curve shows, it is an intermediate value between the base material specimens in the two directions.

Ti Grade 4 is anisotropic for fracture resistance, also the welded joint offers very few amount of crack extension after maximum load. Whereas KS1.2ASN shows a long plateau of the load for crack extension, Ti Grade 4 has not enough ductility due to its higher strength. Especially the welded Ti Grade 4 exhibits very few stable crack extension.

Table 4: Fracture resistance J_{max} and relevant parameters for the calculation after EFAM GTP94

Alloy	Crack length to width ratio [mm]	Thickness [mm]	Max Load [kN]	CMOD at max. load [mm]	J_{max} [MPa*mm]
KS1.2ASN					
T-dir.	0.5	0.9	21.4	2.004	354.3
L-dir.	0.5	0.9	20.5	2.092	323.4
LBW	0.5	0.9	21.4	2.005	334.5
Ti Grade 4					
T-dir.	0.5	0.9	32.9	1.250	286.3
L-dir.	0.5	0.9	30.4	1.005	199.2

LBW	0.5	0.9	31.2	0.693	122.5



a) b)

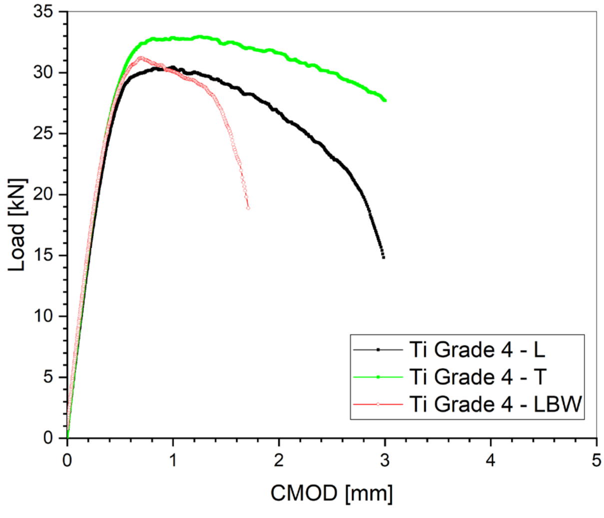


Figure 7: Load-CMOD curves of a) KS1.2ASN and b) Ti Grade 4

1. Conclusions

- Ti Grade 4, Ti XT and KS1.2ASN with sheet thickness of 0.9 mm are defect free weldable with 1400 W laser power, 5 m/min welding velocity, 0 mm focal position and 15 l/min Ar-flow.
- Yield strength, ultimate tensile stress and fatigue strength are orientation dependent for Ti Grade 4, Ti XT and KS1.2ASN because of the crystallographic texture.
- Under cyclic loading (15 Hz, RT), with maximum stress below the yield strength, the LBW joints fractured in the area between fusion zone and heat affected zone.
- Ti Grade 4 shows the highest notch sensitivity, due to the superior tensile strength.
- The difference in fatigue strength between LBW-joint and sheet material becomes smaller in the row Ti Grade 4, Ti XT and KS1.2ASN.
- KS1.2ASN offers higher fracture resistance than Ti Grade 4.
- In terms of mechanical strength, fatigue strength and fracture resistance KS1.2ASN exhibits well-balanced parameters. The replacement of Ti Grade 2 by KS1.2ASN or Ti XT is possible.

1. Acknowledgement

The work was carried out under the auspices of the TiB-Air project (project number: 20W1522C), funded by the German Federal Ministry of Economics and Technology (BMWi) under the LuFo V-2 program. The authors would like to thank the BMWi for the financial support as well as R. Dinse, F. Dorn, M. Erdmann and P. Haack for their valuable technical support.

1. References

[1] S. P. Lynch et al: Failures of welded titanium aircrafts ducts, Engineering Failure Analysis, Vol. 2, No. 4, 1995, pp.257-273.

[2] C. A. R. P. Baptista et al: High temperature cyclic pressurization of titanium ducts for use in aircraft pneumatic systems, Materials and Design 30 (2009), pp. 1503-1510.

[3] S. M. Carvalho et al: Simulating the damage accumulation in aircraft bleed system ducts joined by laser and arc welding processes, Procedia Engineering 10 (2011), pp. 1321-1326.

[4] A. M. L. Adip et al: Aircraft engine bleed system tubes: Material and failure mode analysis, Engineering Failure Analysis 14 (2007), pp.1605-1617.

[5] R. Boyer et al (Eds): Materials Properties Handbook: Titanium Alloys, ASM International, 1994.

[6] https://www.skybrary.aero/index.php/Bleed_Air_Systems (accessed 20.04.2019)

[7] W. Yonggang et al: Summary and Analysis of the Aging Aircrafts' Failure, The 2nd International Symposium on Aircraft Airworthiness (ISAA 2011), Proceedia Engineering 17 (2011), pp. 303-309.

[8] G. Lütjering, J. C. Williams: Titanium, 2nd Edition, Springer-Verlag Berlin Heidelberg 2003, 2007.

[9] Properties of TIMETAL® Exhaust XT, Sheet + Tubes for Automotive Exhaust Applications, April 2010, Henderson Technical Laboratory, TIMET.

[10] S+D Speciality Metals UK Limited: KSTI-1.2 ASN

[11] S. Jurendić, S. Gaiani: Deep drawing simulation of a-titanium alloys using LS-Dyna, 8th European LS-DYNA Users Conference, Strasbourg, May 2011, pp.1-8.

[12] K. H. Leong, H. K Geyer (1998, November). Laser beam welding of any metal. In International Congress on Applications of Lasers & Electro-Optics (Vol. 1998, No. 1, pp. F242-F250). LIA.

[13] N. Kashaev et al: Microstructure and Mechanical Properties of Laser Beam Welded Joints between Fine-Grained and Standard Ti-6Al-4V Sheets Subjected to Superplastic Forming, Advanced Engineering Materials 17 (3) 2015 pp. 374 - 382.

[14] F. Fomin et al: Effect of Microstructure Transformations on Fatigue Properties of Laser Beam Welded Ti-6Al-4V Butt Joints Subjected to Postweld Heat Treatment, in: Tanski, T.; Borek, W. (Eds.): Study of Grain Boundary Character. 2017. pp. 111 - 141.

[15] E. Maawad et al: Influence of crystallographic texture on the microstructure, tensile properties and residual stress state of laser-welded titanium joints, Materials and Design 101 (2016), pp. 137-145.

[16] S. T. Auwal et al: A review on laser beam welding of titanium alloys, The International Journal of Advanced Manufacturing Technology, 97 (1-4) (2018) pp.1071-1098.

[17] S. Panda et al: Orientation dependent mechanical properties of commercially pure (cp) titanium, Materials Characterization 98 (2014), pp. 93-101.

[18] S. Sinha, N. P. Gurao: The role of crystallographic texture on load reversal and low cycle fatigue performance of commercially pure titanium, Materials Science and Engineering A 691 (2017), pp. 100-109.

[19] Titan Grade 2/Titane Grade 2, thyssenkrupp Materials Schweiz, www.thyssenkrupp.ch. (accessed 20.04.2019)

[20] Titan Grade 4/Titane Grade 4, thyssenkrupp Materials Schweiz, www.thyssenkrupp.ch. (accessed 20.04.2019)

[21] K.-H. Schwalbe et al: EFAM GTP 94: The GKSS test procedure for determining the fracture behaviour of materials, GKSS External Report 94/E/60 , 1994, Geesthacht, Germany