Influence of Shot-Peening on fatigue behavior Orbital Friction Welded Titanium Joints

U. Raab C. Becker, L. Wagner

Institute of Materials Science and Engineering, TU Clausthal, Germany

Abstract:

The usage of friction welded blisks in turbine engine compressors comprises an increase of effectiveness of the compressor and weight savings due to the omission of the disk blade attachment. The combination of the Ti-6Al-4V modifications mill annealed as the blade material and bi-modal as the disc material demonstrates a concept for a multi-material high pressure compressor blisk with operating temperatures up to 350°C. Linear friction welding (LFW) is the state of the art welding process for the production of joined titanium blisks. Orbital friction welding (OFW) represents an alternative process where the discontinuous linear motion of the LFW is replaced by a continuous circular motion, to achieve an improved heat generation. Bending fatigue tests were performed in the as-welded and stress relieved condition to demonstrate the effect of residual stresses developed during orbital friction welding on the fatigue performance of the welds. Additionally, shot peening was performed on the heat treated welds to further improve the fatigue performance.

Keywords: orbital friction welding, shot peening, Ti-6Al-4V, bending fatigue, blisk

Introduction

Linear friction welding was developed to apply the beneficial properties of rotary friction welds on non-axially symmetric components. This process was adapted for the manufacturing of blade integrated disks used in turbine engine industries [1]. The use of LFW for joining the titanium alloys Ti-6Al-4V [2 - 5] and Ti-6Al-2Sn-4Zr-6Mo [4 - 6] has been studied and has already developed into a state of the art process used in modern turbine engines [7]. Recent developments focus on the combination of nickel alloys [8] and even nickel based single crystals [9] for high-pressure compressor and turbine stages respectively.

As reported in the cited literature, LFW is capable of producing high quality titanium joints with similar and dissimilar alloy combinations. The welds can be characterized by a fine grained microstructure without oxides, inclusions or discontinuities. Depending on the welded alloys, the tensile strength of the weld can surpass the strength of the parent material or can be improved by a post weld heat treatment. Linear friction welding machines are based on typical designs of rotary friction welding machines, where the spindle is replaced by a hydraulic actuator that generates the linear reciprocating motion [10]. Orbital friction machines are equipped with rotating heads which perform a circular motion. Due to the different kinetics a faster and homogeneous heat generation can be achieved with orbital friction welding [11].Tensile residual stresses in the weld line and compressive stresses in the thermo mechanical affected zone beneath the weld line have been found in Ti-6Al-4V linear friction welds [12,13]. A PWHT at 100°C above the conventional aging temperature of Ti-6Al-4V (approximately 600°C) leads to the relaxation of tensile residual stresses to below 50 MPa [14]. Shot peening is used to increase the fatigue performance of components that have to bear cyclic loads, due to the increase of hardness at the surface to delay surface crack nucleation and induced residual compressive stresses that decelerate fatigue crack propagation [15].

Experimental procedure

Ti-6Al-4V in the mill annealed and bi-modal condition have been joined using orbital friction welding. SEM pictures of both microstructures are presented in Figure 1. The mill annealed microstructure is characterized by a duplex structure consisting of primary alpha grains with an average gain size of about 10 µm, lamellar alpha+beta phase and intergranular beta. The primary alpha grains are partially elongated and the lamellar phases are distributed heterogeneously. The bi-modal microstructure has a primary alpha content of 40 % with an average grain size of about 20 µm. The remainder consist of lamellar alpha-beta phase. In contrast to the mill annealed structure the bi-modal material appears to be fully recrystallized.

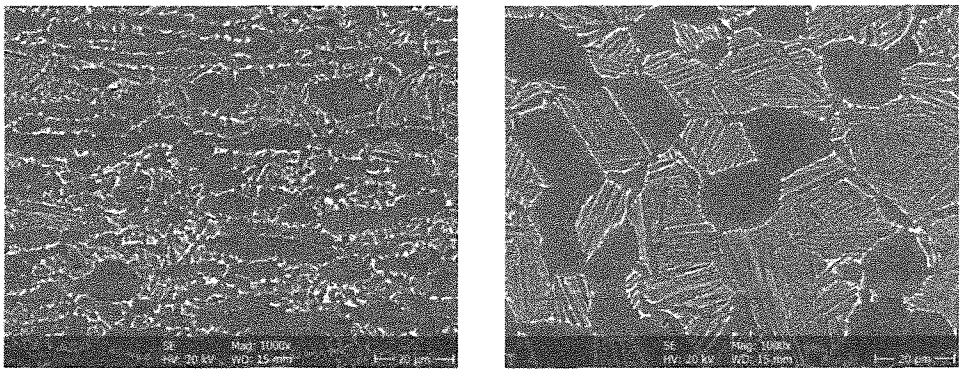

Figure 1: Ti-6Al-4V in the conditions mill annealed (left) and bi-modal (right)

Orbital friction welding was performed in the force displacement mode. The process consisted of three friction phases followed by a single forging phase. Only the mill annealed Ti-6Al-4V, representing the blade, conducted the circular relative motion to simulate the blisk welding process where the blade is subjected to the relative motion only. Welding samples with the dimension of 7 x 14 x 50 mm³ were used. The welding surfaces were turned and cleaned with acetone before welding. Figure 2 shows the flesh formed during welding.

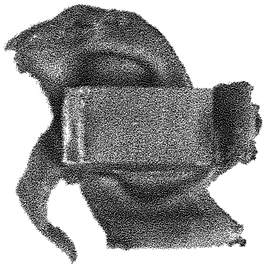

Figure 2: Top view on flash formed during welding

During welding plasticized (softened) material is extruded into the flash. The flash formation can be used as a first quality criterion for friction welds. The picture shows that material was extruded in all directions. Hence, it can be assumed that a connection along the entire cross section was generated.

The welded samples were partially subjected to a post weld heat treatment (PWHT) to relief residual stresses that may have formed during welding. The heat treatment was performed at 640°C for two hours followed by air cooling.

Tensile tests were performed on the welds and the bulk material in the PWHT condition. The tests were conducted according to EN 10002-1 with M6 samples with a strain rate of 1 mm/min at room temperature.

Shot peening (SP) was performed on the welded samples with an Almen intensity of 0.2 mmA using SCCW 14. The influence of SP on surface roughness was measured.

Bending fatigue tests were performed in the as welded (AW), heat treated (HT) and heat treated plus shot peened (HT + SP) condition. The sample geometry is presented in Figure 3. The tests were performed at a stress ration of R = -1 and a frequency of 24 Hz. The samples were fixed on the "disk side" (bi-modal microstructure) of the weld. Only the mill annealed material, representing the blade material, was deflected to simulate the bending load scenario of compressor blades. The sample geometry is characterized by a modified hour glass shape with an extended gauge length in the middle of the sample. This modification was used to enable the fatigue limiting crack to initiate and propagate either in the weld zone, the heat affected zone or in one of the bulk materials.

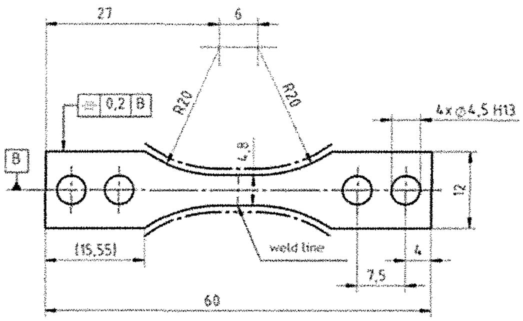

Figure 3: Bending fatigue test sample

Microhardness profiles (HV 0.1) were measured along the surface and along the weld line. The step size between the indentations was 50 µm.

Results

A SEM picture of the weld zone is presented in Figure 4. The orbital friction welding process leads to a drastic change of the microstructure. The central weld zone (CWZ) in the middle of the picture is characterized by a grain fined microstructure that developed due to dynamic recrystallization during welding. Next to the CWZ the thermo mechanical affected zone (TMAZ) shows severe plastic deformation. A heat affected zone where grain coarsening may have occurred cannot be found in the weld. Between CWZ and TMAZ the primary alpha Phase dissolved completely. In the TMAZ partially dissolved primary alpha grains are visible. Results of the tensile tests of the welded samples are listed in Table 1.

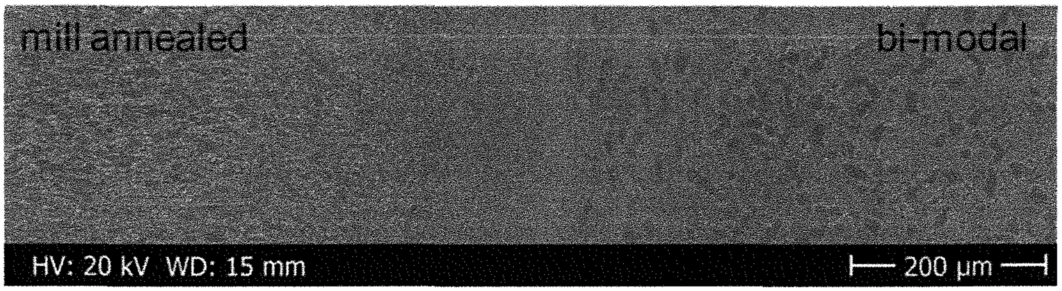

Figure 4: Microstructure of the weld

Table 1: Results of the tensile test of the welded and heat treated (640°C/2h/AC) samples

Sample	YS [MPa]	UTS [MPa]	A [%]	E [GPa]	Fracture site
1	997	1034	7,6	103	bi-modal
2	955	993	15	108	mill annealed
3	947	989	10,1	104	bi-modal

Fracture occurred twice in the bi-modal material and once in the mill annealed material outside of the weld and heat affected zone. In comparison to the tensile properties of the heat treated bulk material (Table 2) the welded samples exhibited higher strength but lower elongation which can be attributed to a strengthened weld zone due to grain boundary hardening and plastic deformation.

Shot peening lead to an increase of the surface roughness from R_a = 0.12 µm to R_a = 1.3 µm (N = 3). Results of the bending fatigue tests are presented in Figure 5. The left graph shows the influence of PWHT on the fatigue performance of the welds. The AW samples cracked in the weld zone, most probably because of tensile residual stresses developed during welding.

The applied heat treatment resulted in a shift of the fracture site into the bi-modal parent material and the exhibition of a normal shaped S-N curve. Based on this S-N curve a stress amplitude was chosen to compare the HT with the HT + SP condition. Three samples of each condition were tested at 500 MPa bending stress. The results are shown in the right graph of Figure 5. Shot peening increased the fatigue performance of the welds up to 750 %. The crack nucleation shifted from the surface (HT) into subsurface regions (HT + SP).

Table 2: Tensile properties of the bulk materials, mill annealed and duplex in the heat treated (640°C/2h/AC) condition

Sample	YS [MPa]	UTS [MPa]	A [%]	E [GPa]
mill annealed	888	927	19	102
duplex	897	940	12,5	110

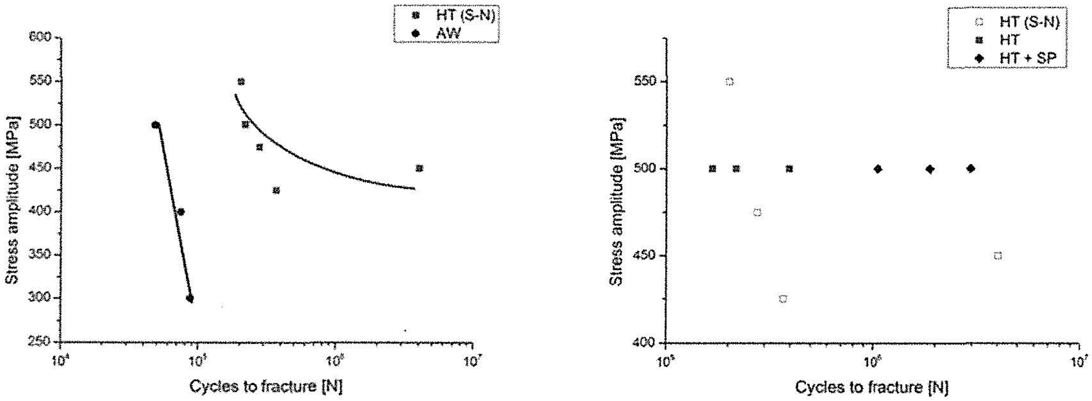

Figure 5: Results of the bending fatigue tests (R = -1)

The microhardness profiles are presented in Figure 6. The surface hardness (left) increases up to 50 HV 0.1. It appears that the weld line (0,0 +/- 200 µm) is less affected by the peening process. The bulk hardness measured along the weld line shows that shot peening lead to a slight hardness increase through the entire materials thickness of 2mm.

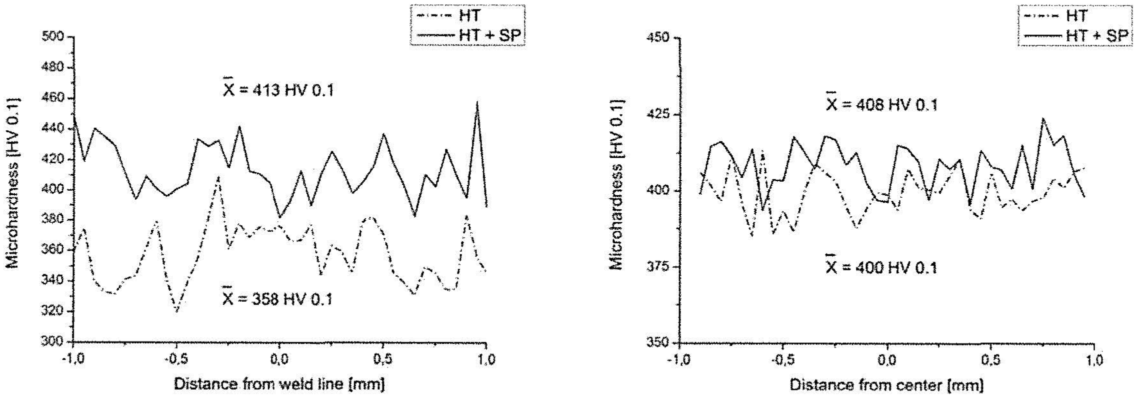

Figure 6: Microhardness profiles: Surface hardness (left) and bulk hardness (right)

Summary

Following conclusions can be drawn from this study:

- PWHT is necessary to release tensile residual stresses in the weld region,
- Shot peening further increases fatigue life due to increased hardness and subsurface crack nucleation at 500 MPa bending stress

It is noteworthy that the PWHT may not lead to an entire relaxation of the tensile residual stresses which developed during welding. Therefore it is possible that the compressive residual stresses induced by shot peening superposed the remaining tensile stresses from the welding process. Additional residual stress measurements are necessary to clarify the interdependency of SP induced residual stresses and stresses that formed during orbital friction welding.

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Literature

[1] Antonio M. & Mateo García (2011). BLISK Fabrication by Linear Friction Welding, Advances in Gas Turbine Technology, Dr. Ernesto Benini (Ed.), ISBN: 978-953-307-611-9

[2] Wanjara, P., & Jahazi, M. (2005). Linear Friction Welding of Ti-6Al-4V : Processing , Microstructure , and Mechanical-Property Inter-Relationships, 36(August).

[3] Vairis, a, & Frost, M. (1999). On the extrusion stage of linear friction welding of Ti 6Al 4V. Materials Science and Engineering: A, 271(1-2), 477–484. doi:10.1016/S0921-5093(99)00449-9

[4] Vairis, a., & Frost, M. (2000). Modelling the linear friction welding of titanium blocks. Materials Science and Engineering: A, 292(1), 8–17. doi:10.1016/S0921-5093(00)01036-4

[5] Guo, Y., Chiu, Y., Attallah, M. M., Li, H., Bray, S., & Bowen, P. (2012). Characterization of Dissimilar Linear Friction Welds of α-β Titanium Alloys. Journal of Materials Engineering and Performance, 21(5), 770–776. doi:10.1007/s11665-012-0129-z

[6] Pederson, R., Niklasson, F., Skystedt, F., & Warren, R. (2012). Microstructure and mechanical properties of friction- and electron-beam welded Ti–6Al–4V and Ti–6Al–2Sn–4Zr–6Mo. Materials Science and Engineering: A, 552, 555–565. doi:10.1016/j.msea.2012.05.087

[7] Guo, Y., Jung, T., Chiu, Y. L., Li, H., Bray, S., & Bowen, P. (2013). Microstructure and microhardness of Ti6246 linear friction weld. Materials Science and Engineering: A, 562, 17–24. doi:10.1016/j.msea.2012.10.089

[8] Bußmann, M.; Kraus, J. & Bayer, E. (2005). An Integrated Cost-Effective Approach to Blisk Manufacturing, Proceedings of 17th Symposium on Air Breathing Engines, Munich, Germany, 4-9 September 2005

[9] Vishwakarma, K. R., Ojo, O. A., Wanjara, P., & Chaturvedi, M. C. (2010). Linear Friction Welding of ALLVAC ® 718 PLUS Superalloy, 413–426.

[10] Amegadzie, M., Ola, O., Ojo, O., Wanjara, P., & Chaturvedi, M. (2012). On Liquidation and Liquid Phase Oxidation during Linear Friction Welding of Nickel-Base IN 738 and CMSX 486 Superalloys, 587–594.

[11] Raab, U., Levin, S., Wagner, L., Heinze, C. (2014). Orbital friction welding as an alternative process for blisk manufacturing, Journal of Materials Processing Technology, in press. doi:10.1016/j.jmatprotec.2014.06.019

[12] Daymond, M. R., & Bonner, N. W. (2003). Measurement of strain in a titanium linear friction weld by neutron diffraction. Physica B: Condensed Matter, 325, 130–137. doi:10.1016/S0921-4526(02)01514-4.

[13] Romero, J., Attallah, M. M., Preuss, M., Karadge, M., & Bray, S. E. (2009). Effect of the forging pressure on the microstructure and residual stress development in Ti–6Al–4V linear friction welds. Acta Materialia, 57(18), 5582–5592. doi:10.1016/j.actamat.2009.07.055

[14] Frankel, P., Preuss, M., Steuwer, a., Withers, P. J., & Bray, S. (2009). Comparison of residual stresses in Ti–6Al–4V and Ti–6Al–2Sn–4Zr–2Mo linear friction welds. Materials Science and Technology, 25(5), 640–650. doi:10.1179/174328408X332825

[15] Wagner, L (2006). Shot Peening. John Wiley & Sons.