Welded Titanium Bellows

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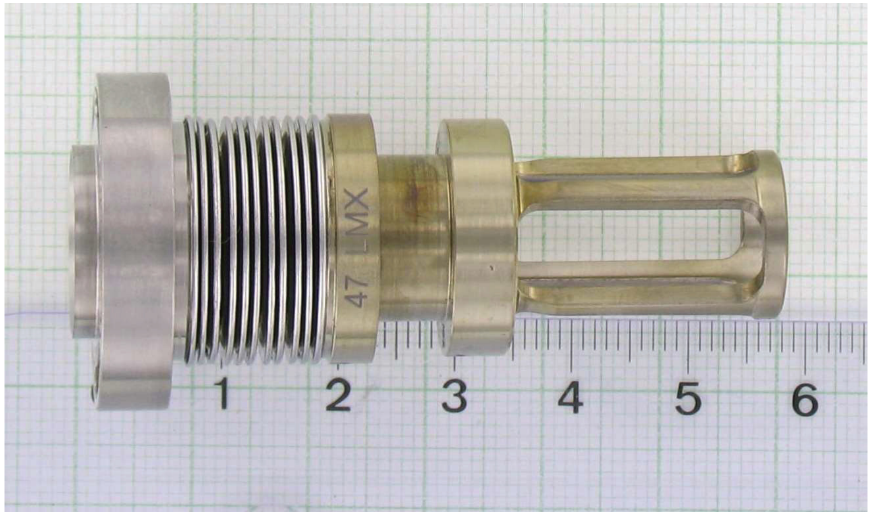
Lessons Learned, 19 November 2010

Content

- What are bellows
- Where are bellows located
- How to manufacture a bellow
- Some dramatic pictures of bellows
- What can go wrong with a bellow
- What did we learn
- The final lesson

ATV bellow details



Compensation bellow

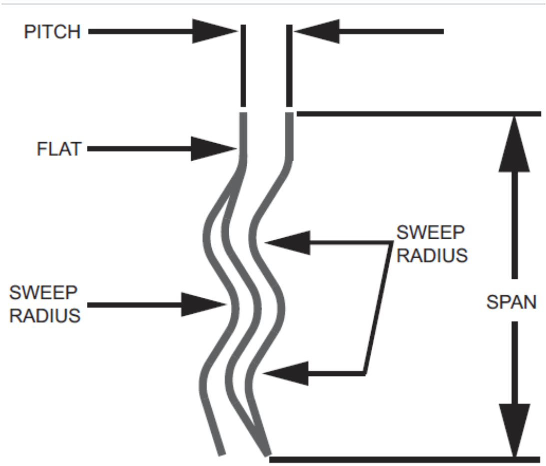
General view of the isolation bellows. The fork, the pivot arm and the upper flange are also present. Two buckles are visible

Advantages

Edge-Welded bellows have specific advantages, including:

- Higher strength with the ability to withstand greater pressures
- Wider operating temperature range
- Ability to be given precise design characteristics
- Lower spring rate (the amount of force required to compress it a given distance)
- Allow for the use of optimal plate shapes such as the Nesting Ripple design
- Lower stress in critical areas
- Large stroke

Plate shape



Tilting the bellows axis drastically reduces stresses at the welds and heat-affected zones. The stresses at the welds are predominantly bending stresses. With increasing tilt angles, the bending stresses are lowered. With a 45-deg tilt angle, bending stresses are directed away from the heat-affected zone of the weld.

Three sweep design optimizes stress distribution, thus increasing resistance to fatigue fracture. The tilted bellows axis distributes bending stresses away from the welds and through the sweep radius.

The sweep radius is optimized at 20 to 25 percent of span and it prevents a phenomenon known as *oil-canning / ballooning*—the inversion of the plate geometry that results in a bulging in and out of the plate,

The nesting ripple plate shape is more effective in achieving maximum flexing, long (axial motion) stroke with short operating lengths and a low spring rate.

Metal properties

Unalloyed titanium is available as four different ASTM grades, which are classified by their levels of impurities (primarily oxygen) and the resultant effect on strength and ductility ASTM Grade 1 has the highest purity, lowest strength, and best room-temperature ductility and formability

ASTM grade	Minimum tensile strength - MPa	0.2% yield strength - MPa	Elongation at break %
Grade 1	240	170	24
Grade 2	345	275	20

S-basis properties in both the longitudinal and long-transverse direction

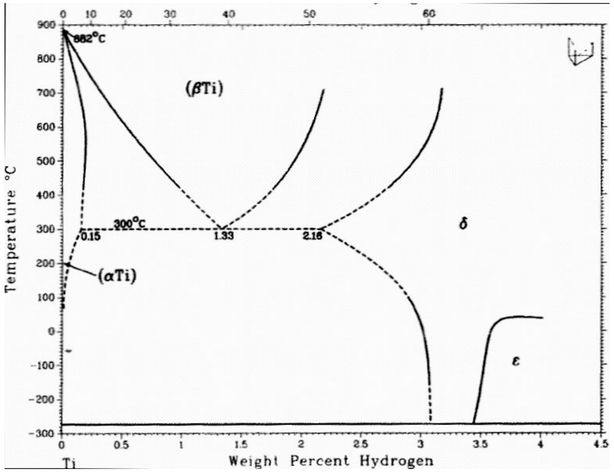
Designation	Chemical Composition (%max), Rem Ti			
	C	O	N	Fe
Grade 1	0.10	0.18	0.03	0.20
Grade 2	0.10	0.25	0.03	0.20

ASTM Grade 1 and 2 were used in the manufacturing of the bellows
Grade 2 will be used, due to higher properties

Hydrogen embrittlement

Hydrogen reduces the service life of many metallic components. Such reductions may be manifested as blisters, as a decrease in fatigue resistance, as enhanced creep, as the precipitation of a hydride phase.

Zirconium, titanium, tantalum and other transition, rare earth and alkaline rare earth metals form hydrides when the hydrogen concentration exceeds a certain level.



A very small amount of H can dissolve in Ti. TiH_2 will form immediately at low temperature. A equilibrium exists between αTi and TiH_2

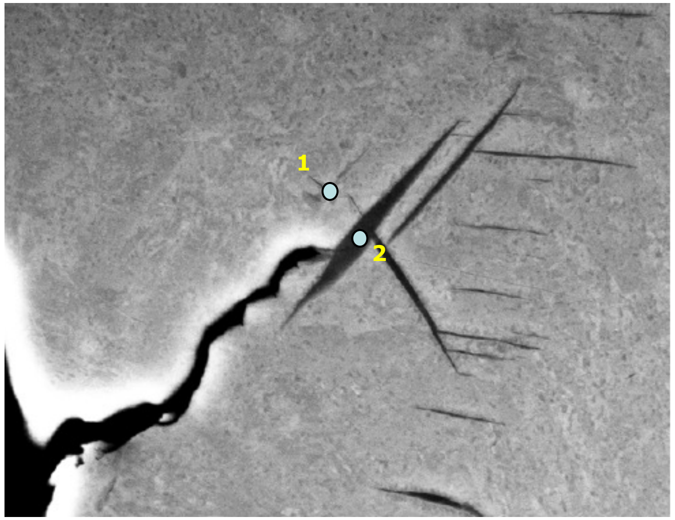
The hydrides are typically low density, brittle compounds whose presence degrades the ductility of the alloy. Additionally, applied and/or residual stresses may interact with hydride phase and effect the orientation and distribution of the hydride precipitates.

Sample	Location	Hydrogen Content [wt. %] Mean Value	Hydrogen Content [wt. %] Measurement 1	Sample 1 Weight [mg]	Hydrogen Content [wt. %] Measurement 2	Sample 2 Weight [mg]
REF. 1	Inner Weld	**0.016**	0.015	43.8	0.017	47.3
REF. 1	Bulk Material	**0.015**	0.013	49.4	0.016	59.9
REF. 3	Inner Weld	**0.014**	0.014	43.6	0.014	43.3

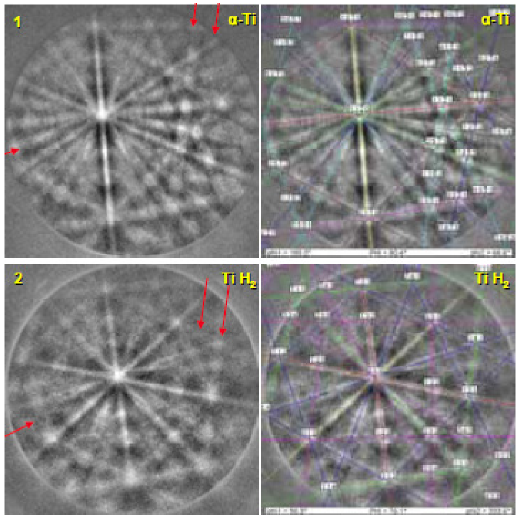
Presence of TiH_2

Needle-like structures were found in the in the microsections of failed welds
EBSD camera investigations confirmed the nature of these needles as Titanium-Hydride

Hydrogen can have a pronounced effect on the mechanical properties of titanium (Ti) and Ti alloys, such as deformation, fracture, and fatigue life. The delayed fracture of Ti alloy devices is commonly caused by hydrogen embrittlement.



Titanium-hydride needles present at crack tip in cracked bellow



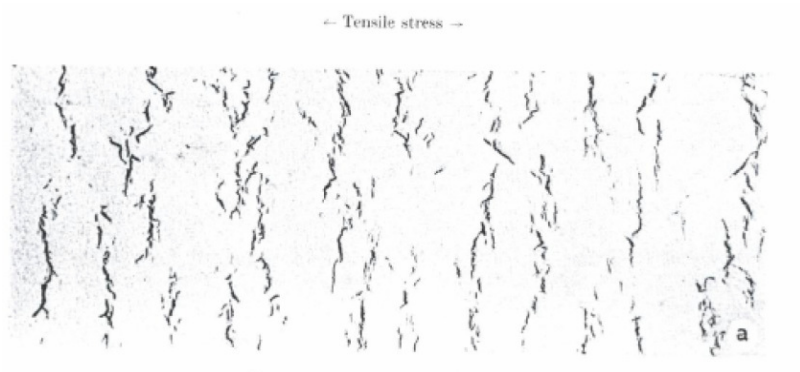
Electron backscattered diffraction (EBSD), also known as backscattered Kikuchi diffraction (BKD) is a microstructural- crystallographic technique used to examine the crystallographic orientation. Here it shows the presence of TiH_2

Hydride reorientation

The orientation of the hydride precipitate at a crack tip is seldom random. Because of the large volume expansion that accompanies hydride nucleation and growth, hydride platelets tend to precipitate perpendicular to tensile stresses and parallel to compressive stresses.

Hydrogen in most hydride forming metals and alloys is mobile at room temperature, thus hydride reorientation may occur during service.

Hydride Precipitation in Non-stressed Sample

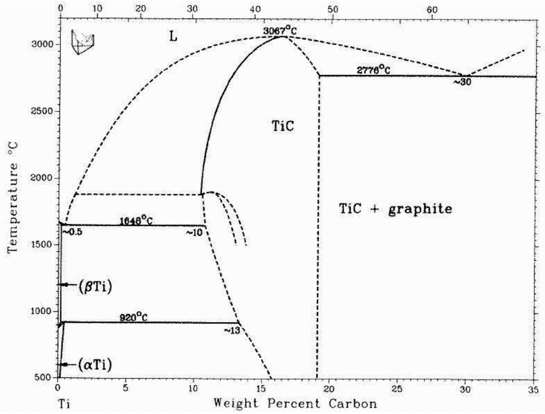


Hydride Precipitation in Stressed Sample

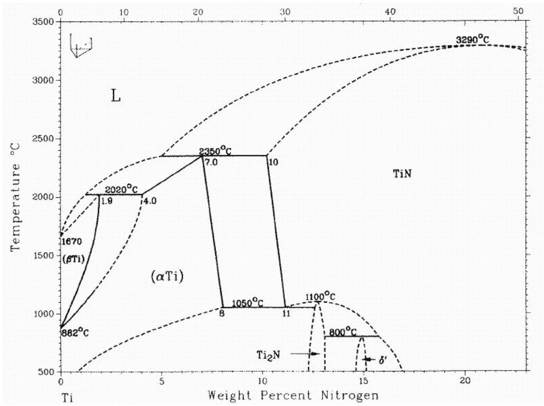
Lessons learned Hydrogen embrittlement

- The hydrogen containing material may be placed in service and the stress (either applied or residual) with the service may cause hydrogen redistribution.
- Hydrogen will accumulate at the regions of high dilatational stresses and eventually precipitate as a hydride
- Weld cracks can be driven by the welding residual stresses and may not develop until weeks after the weld has been completed.
- Hydrogen pick-up during welding should be avoided
- Starting hydrogen content of the material should be as low as possible. Is 150 ppm low enough
- Hydrogen content measurement should be performed after pickling of the material
- After ATV bellows welding process improvement Argon shielding has been required also in the opposite side w. r. t. the welding beam. Planck bellows have been welded with no Argon protection at all! This explains the discolouration observed.

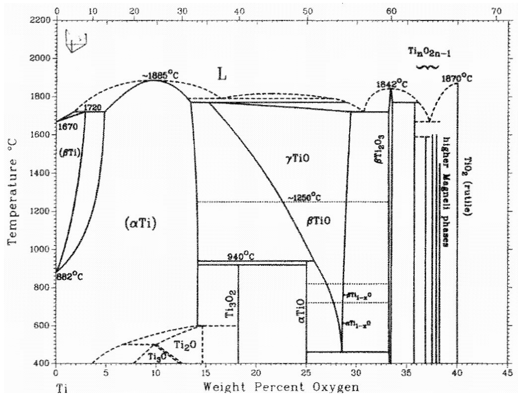
How about Carbon, Oxygen and Nitrogen



Only 1.6a% C can dissolve in Ti. Beyond that TiC will form. At low temperature a equilibrium exists between αTi and TiC



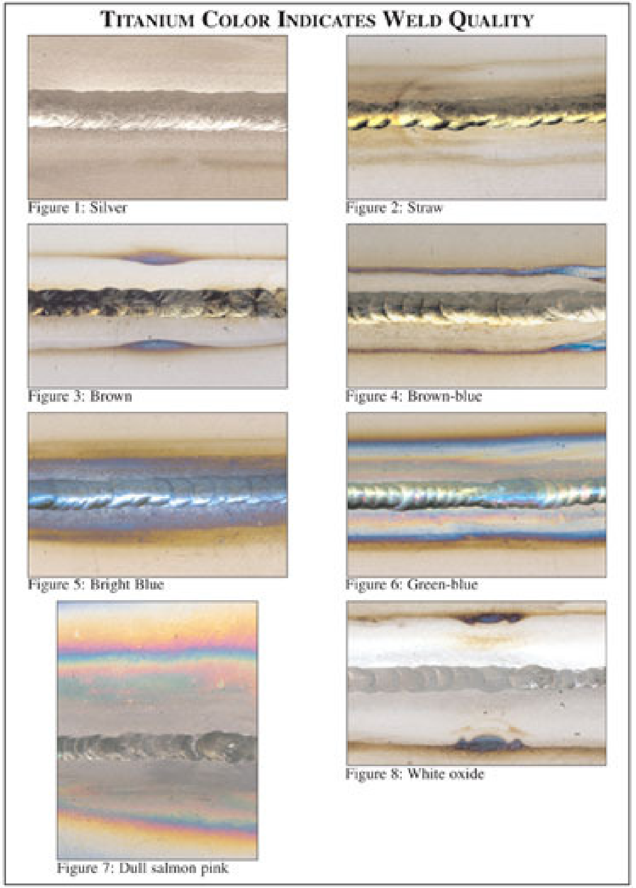
At high temperature a considerable amount of N can dissolve in Ti. At low T this will precipitate out and forms Ti_2N



Oxygen has a large solubility in αTi. This lowers when going down in temperature and Ti_2O and Ti_3O forms

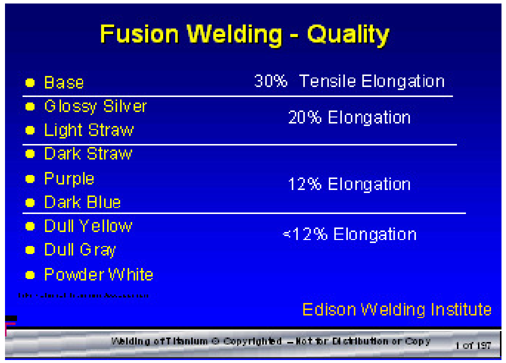
This means that we should avoid these

Welding of Titanium

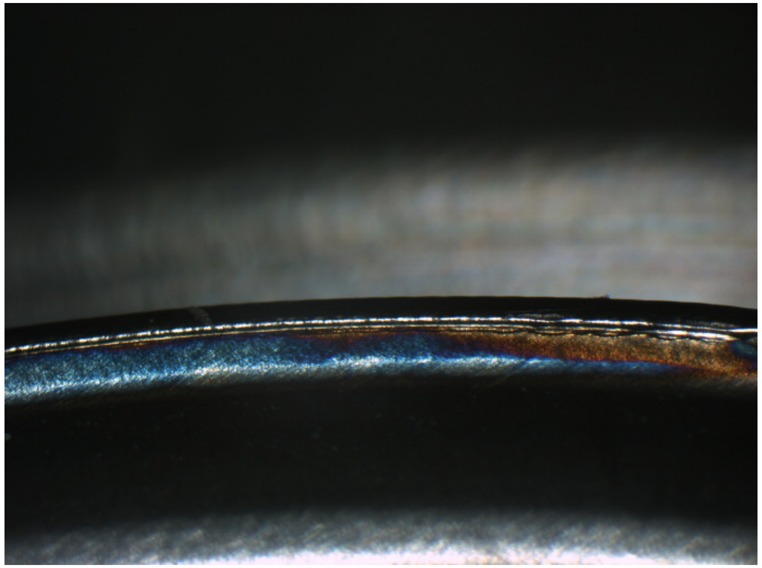


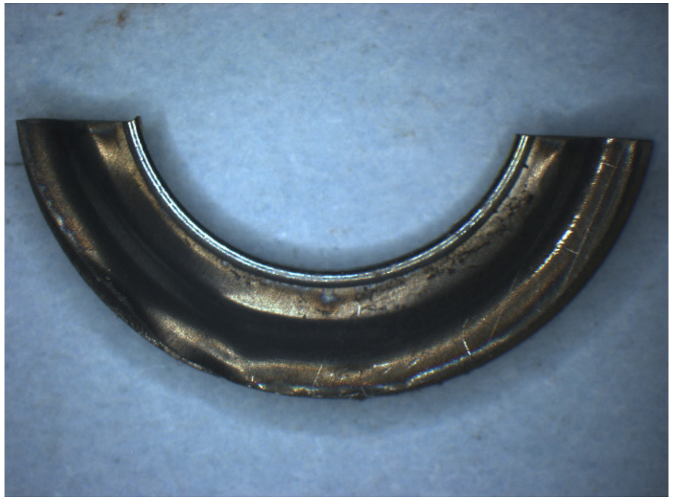
When heated, titanium becomes highly reactive and readily combines with oxygen, nitrogen, hydrogen and carbon to form oxides (titanium's famous colours actually come from varying thickness of the oxide layer). Interstitial absorption of these oxides embrittles the weldment and may render the part useless. For these reasons, all parts of the heat-affected zone (HAZ) must be shielded from the atmosphere until the temperature drops below 425°C

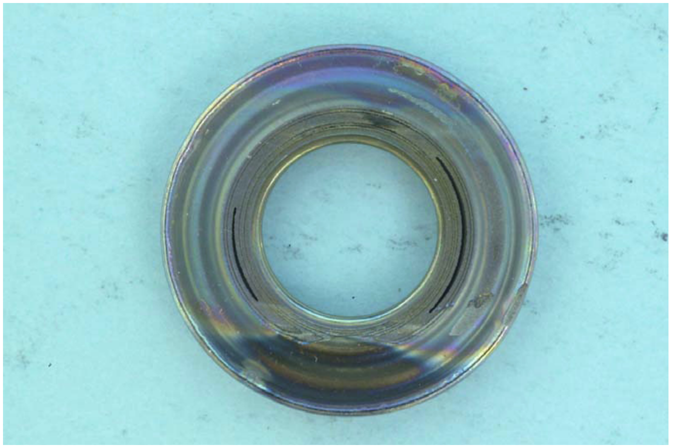
Colour acceptance criteria	
Weld colour	Quality indication
Bright silver	Acceptable
Silver	Acceptable
Light Straw	Acceptable
Dark Straw	Unacceptable
Bronze	Unacceptable
Brown	Unacceptable
Violet	Unacceptable
Dark Blue	Unacceptable
Light Blue	Unacceptable
Green	Unacceptable
Gray	Unacceptable
White	Unacceptable



Discoloured bellow parts





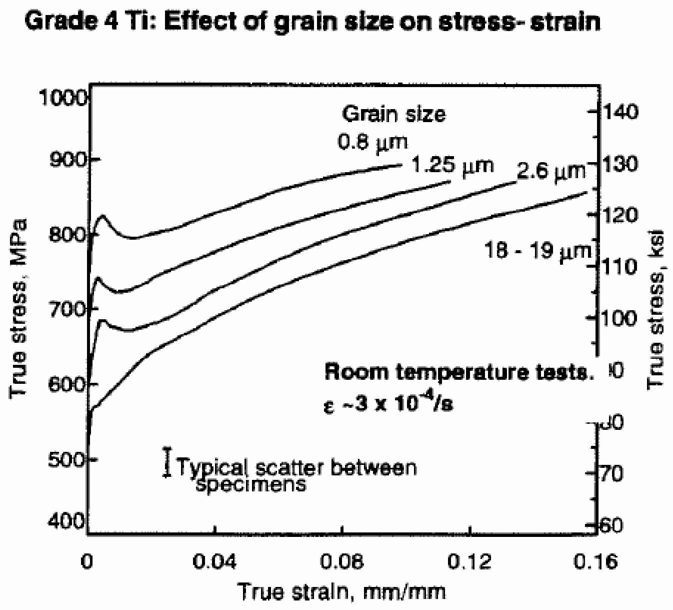


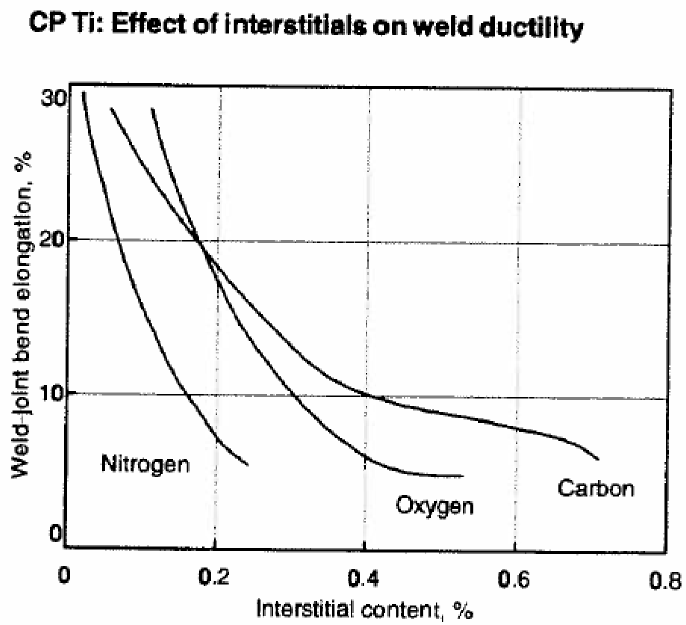
Detail view of one welded convolutions. Discoloration is visible. Discoloration of this material linked to contamination due to bad Argon shielding of the weld beam during welding process.

Also convolutions adjacent to the one welded are heated to above the discolouration temperature before they are welded

Effect of impurities and grainsize on mechanical properties

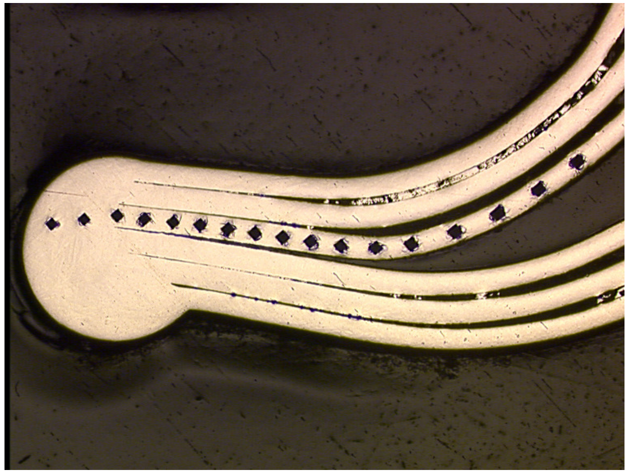
Commercially pure titanium is considered ductile and tough.
Titanium does not exhibit a ductile/brittle transition temperature

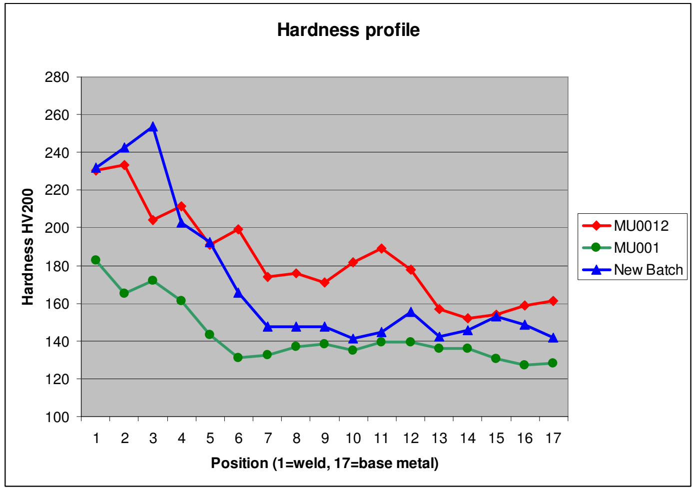




Source: *Metals Handbook*, Vol 3, 9th ed., American Society for Metals, 1980

Hardness tests





Hardness measurements on weld vs. base metal are also sometimes used as an indicator of weld quality. Normally, uncontaminated weld hardness is no more than 30 points greater on the Vickers hardness scales than the hardness of base metal of matching composition.

It should be recognized that heat-to-heat variation in chemistry, within specifications, can result in hardness differentials somewhat higher than 30 Vickers points without any contamination. In any event, high weld hardness should be cause for concern because of the possibility of contamination. If the weld metal hardness is more than 40 HV greater than base metal hardness, excessive contamination is possible.

Lesson learned: the 3Cs: Clean, Clean, Clean

One of the most common mistakes when welding titanium is not verifying the many variables that contribute to good shielding gas coverage prior to striking the first arc.

- Make it a practice to *always* weld on a test piece before beginning each "real" welding session.
- To ensure that gas purity meets your requirements, measure shielding gas purity prior to welding.
- Typical specifications require that the shielding gas (typically argon) be not less than 99.995 percent purity with not more than 5 to 20 ppm free oxygen and have a dew point better than –45 to –60°C.

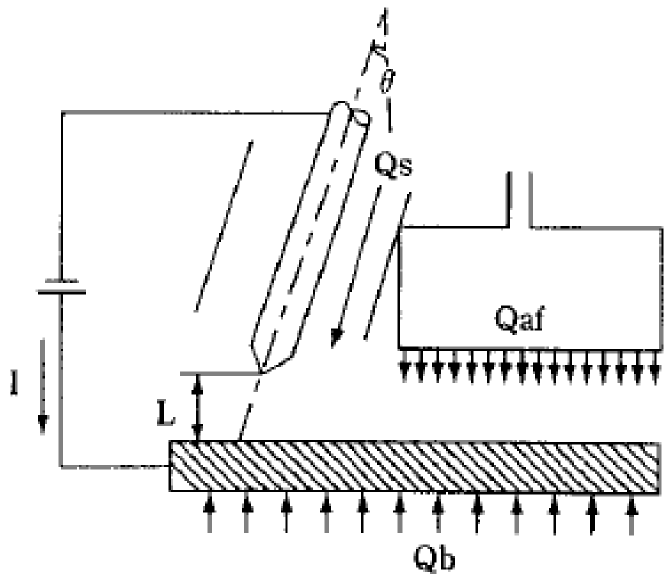
Contamination from oil on your fingers, lubricants, cutting fluid, paint, dirt and many other substances also causes embrittlement, and it is a leading cause of weld failure.

When working with titanium, follow the three Cs of welding: clean, clean, clean! Keep a clean work area, one free from dust, debris and excess air movement that could interfere with the shielding gas. Clean the base metal and bag parts not immediately welded, wear nitrile gloves when handling parts.

Chlorinated Fluoro Carbon (CFC) solvents are forbidden for cleaning titanium and titanium alloys because they produce embrittlement. Use instead only Acetone or Methyl Ethyl Ketone (MEK).

Typical arrangement for the TIG welding of titanium

Sufficient shielding effect cannot be obtained by the torch shield along the torch axis alone.
The titanium needs to be protected at temperatures > 425°C It is necessary to provide an after-shielding device at the back of the torch to shield the high-temperature weld zone of titanium. It is also necessary to provide a back-shielding device to shield the back of the weld zone



Qs : Shielding gas
Qaf : After shielding gas
Qb : Back shielding gas
L : Arc length
I : Welding current
θ : Advance angle

Gas shielding

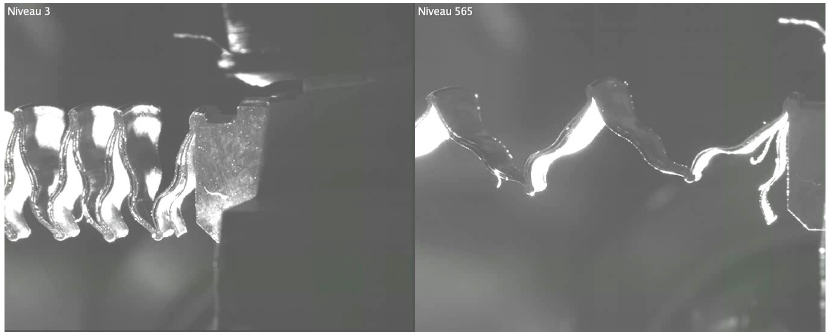
PRIMARY SHIELDING
Primary shielding of the molten weld puddle is provided by proper selection of the welding torch.
Argon is generally used in preference to helium for primary shielding at the torch because of better arc stability characteristics.

SECONDARY SHIELDING
Secondary shielding is most commonly provided by trailing shields. The function of the trailing shield is to protect the solidified titanium weld metal and associated heat-affected zones until temperature reaches 425°C or lower.

BACKUP SHIELDING
The prime purpose of backup devices is to provide inert gas shielding to the root side of welds and their heat-affected zones.

A moderate rate of inert gas should be maintained until the weld is completed.
It is important that separate flow controls are available for primary, secondary and backup shielding devices

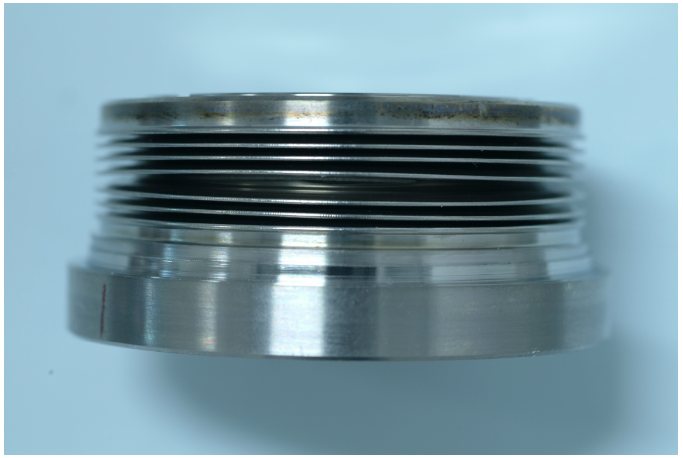
Mechanical deformation on bellows



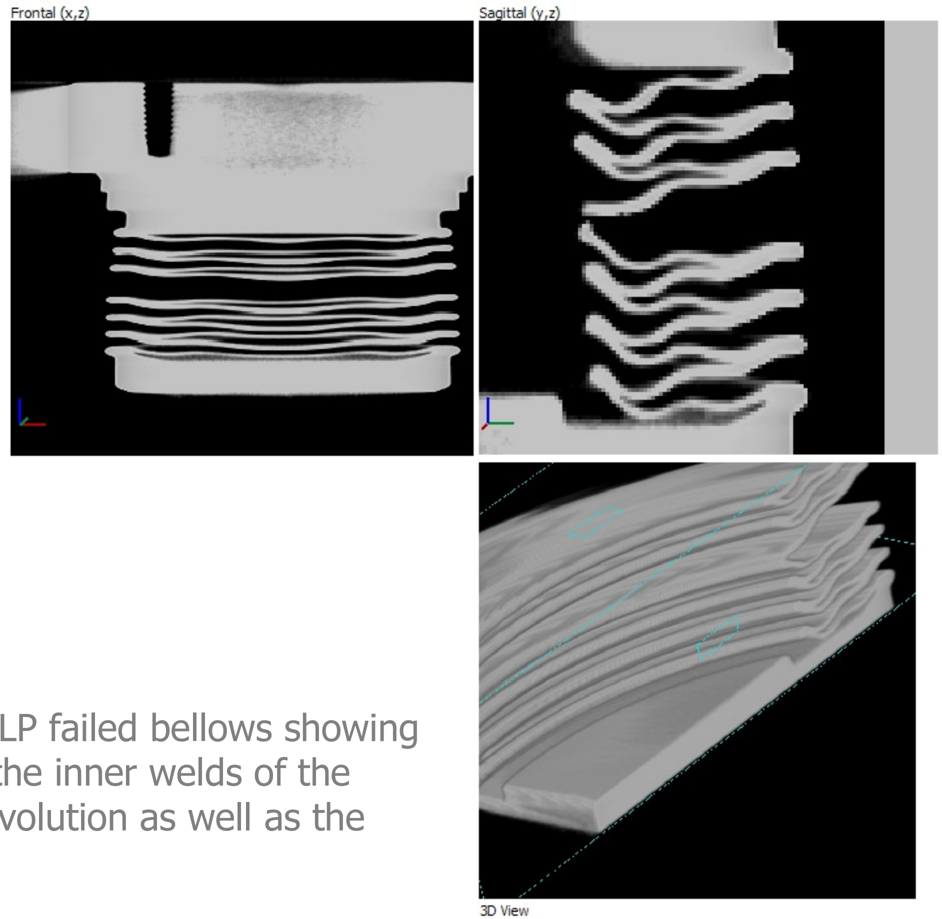
Tensile test shows that bellow that the deformation is near the weld

Loading and unloading the bellow shows elastic behaviour

Buckling on Planck bellow



Closer look at the exterior of the LP bellows, showing buckling and, just visible the crack at the centre.

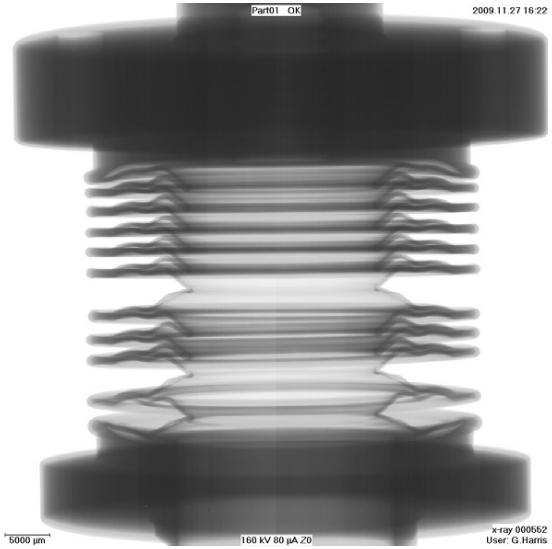


3D x-ray of LP failed bellows showing buckling in the inner welds of the cracked convolution as well as the cracking

ATV isolation bellow – Jules Verne

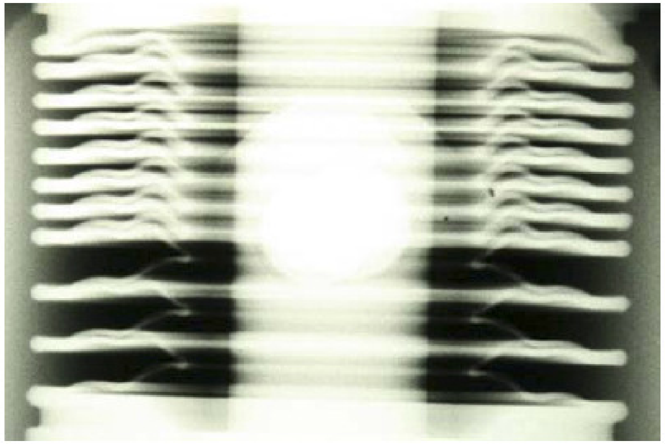
View of the isolation bellows in the as-received condition.

View of the isolation bellow, after removing the interfaces. Three buckles are visible.

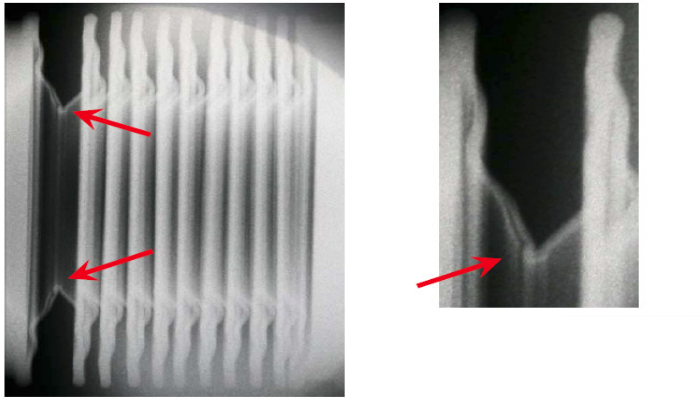


2D x-ray of buckled bellow

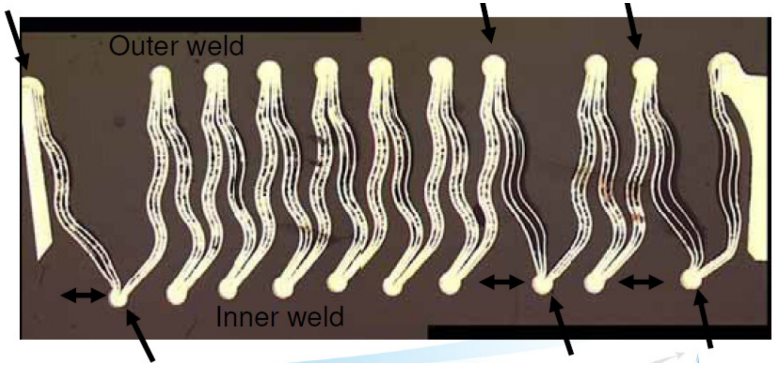
ATV-LV Johannes Keppler- FM



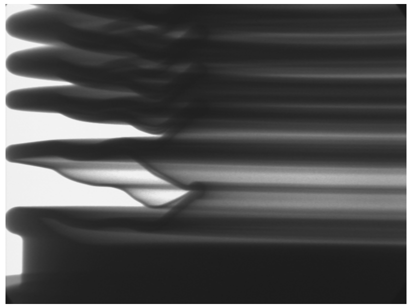
2D X-ray of bellow showing three buckles



In situ X-ray inspection on ATV-JK, showing buckling and a detached ply



Microsection through a buckled bellow showing also ply separation



One ply ballooned from its stable position

Buckling explanation
Ballooning explanation

The following buckling explanation

The loading by an external pressure will force the bellows to reduce their axial length (axial stiffness << radial stiffness) However, the bellows length is fixed at both bellows ends

When passing a certain (static) pressure level one (the weakest) convolution changes its geometry to a new stable state (buckling). Further pressure increase results in additional buckles.

Ballooning explanation

The ply layers are originally welded in parallel position and will be bended away from each other due to the buckling process, because the ply layers are squeezed in radial direction during the buckling process. The inner and outer circular welds are coming closer together and the radii are changed. The geometry of the ply is not optimal anymore to resist the oil-canning effect and the ply geometry is inverted

Lessons learned

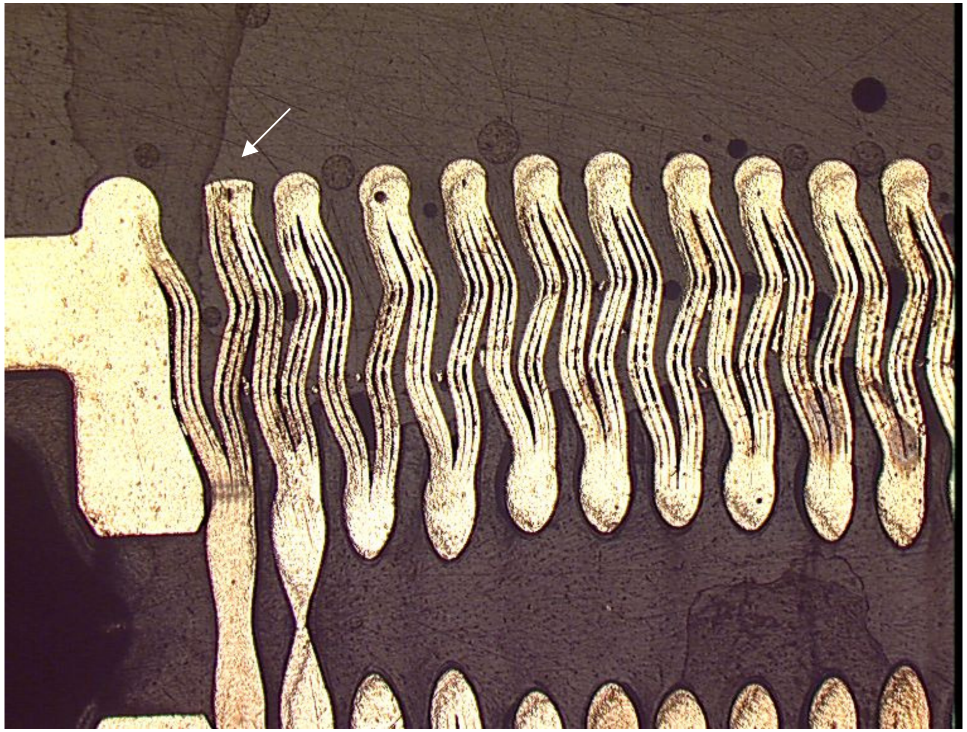
- Failures in convolution usually occur in buckled regions

- Apparently buckling cannot be avoided. Not all convolution are equal. A certain amount of buckling should be allowed.

- Buckling and ballooning appear together. Without buckling there is no space enough for ballooning.

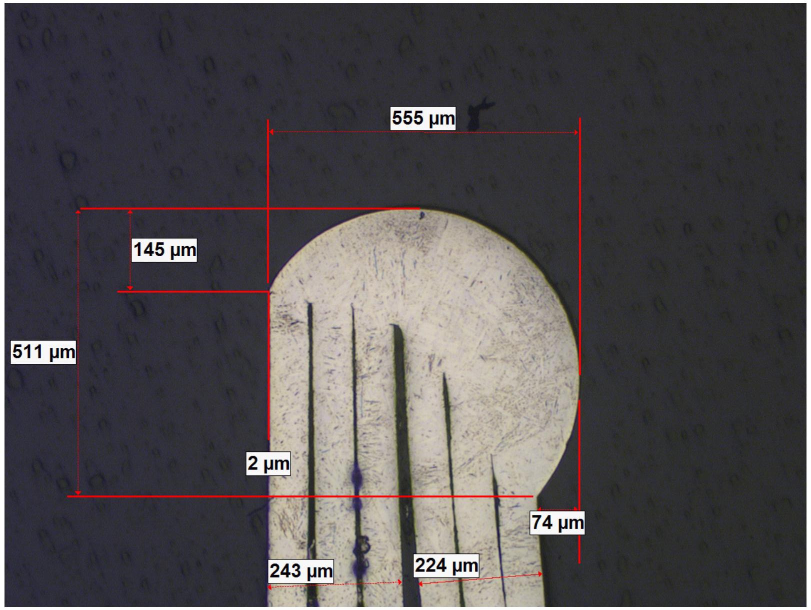
- Ballooning changes the shape of the plies and its is no longer guaranteed that the weld is not stressed. The tilt angle near the weld is no longer directing the bending stresses away from the weld. The weld can fail

Porosities and lack of weld penetration



Microsection though HP bellow (left anomaly due to polishing not in plane), showing some pores and the flat abnormal weld (at arrow)

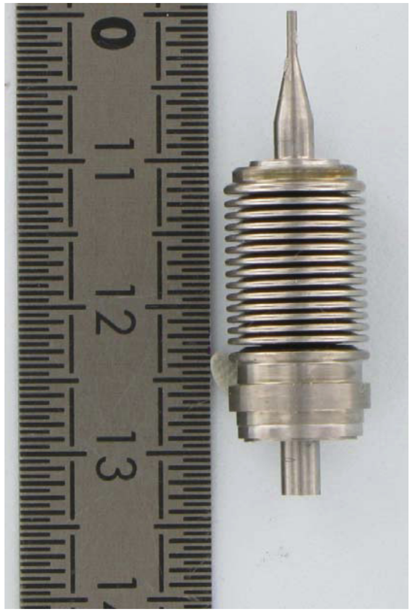
Misaligned weld

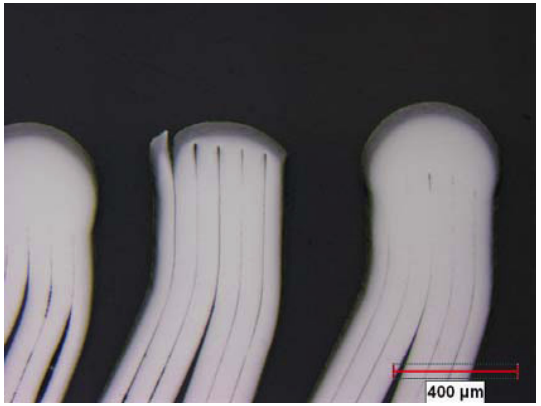


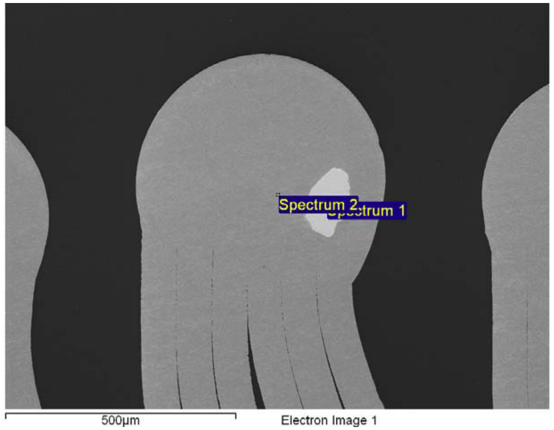
Microsection showing the measurements of the relevant dimensions of one of the weld present in the bellows

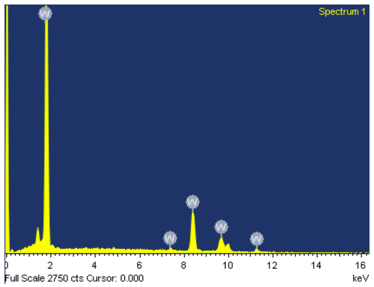
Lack of weld penetration is due to the improper alignment of the weld beam during welding process. Since the process is automated than it is more likely that the complete circumference is affected.

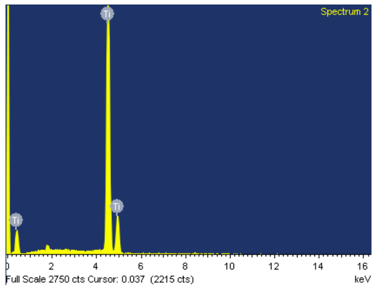
Rosetta HP bellow





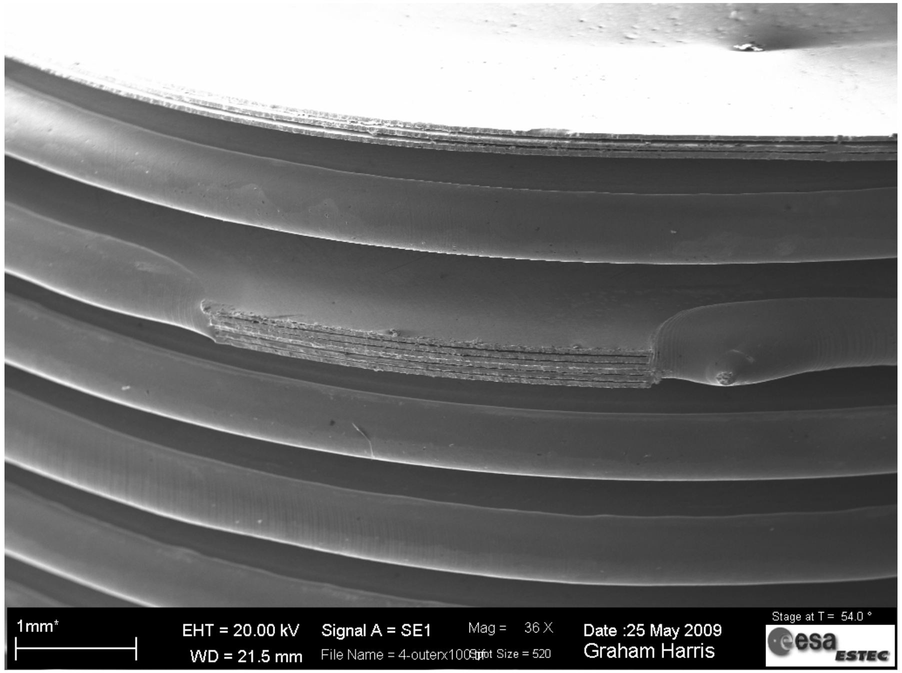




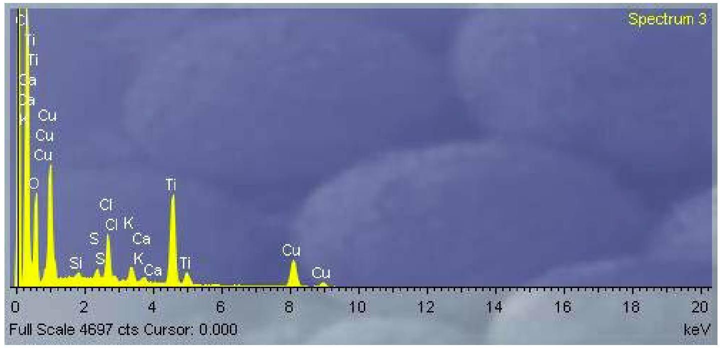


High pressure bellow. The location where the EDX spectra have been acquired are indicated. The inclusion is made of tungsten.

Incomplete weld



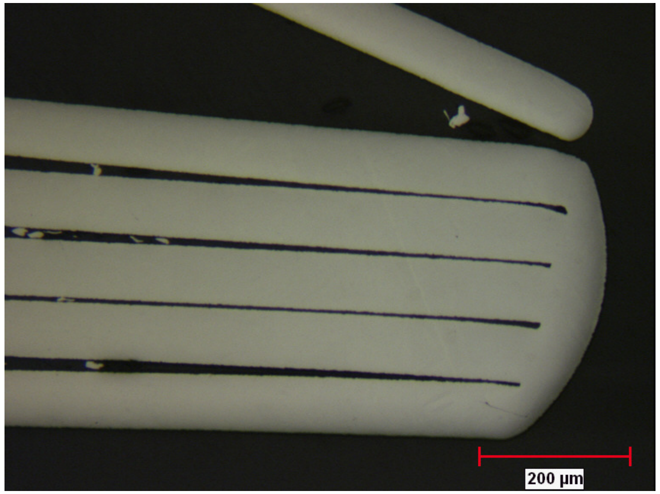
outer weld seam, incomplete weld

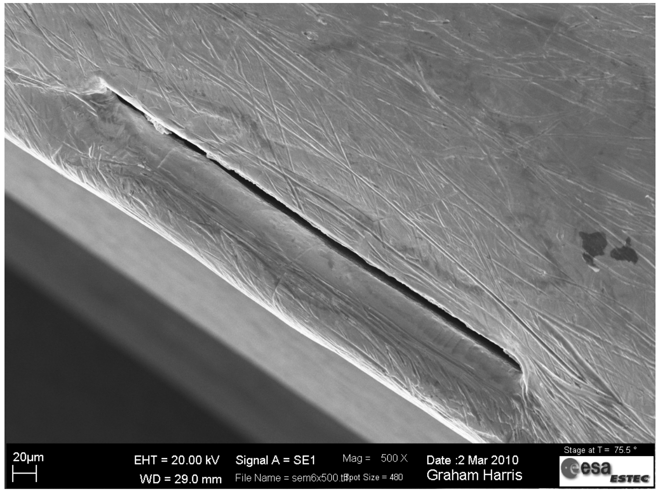


Lots of contamination found near incomplete zone

There is no overlapping of the beginning and end of the weld

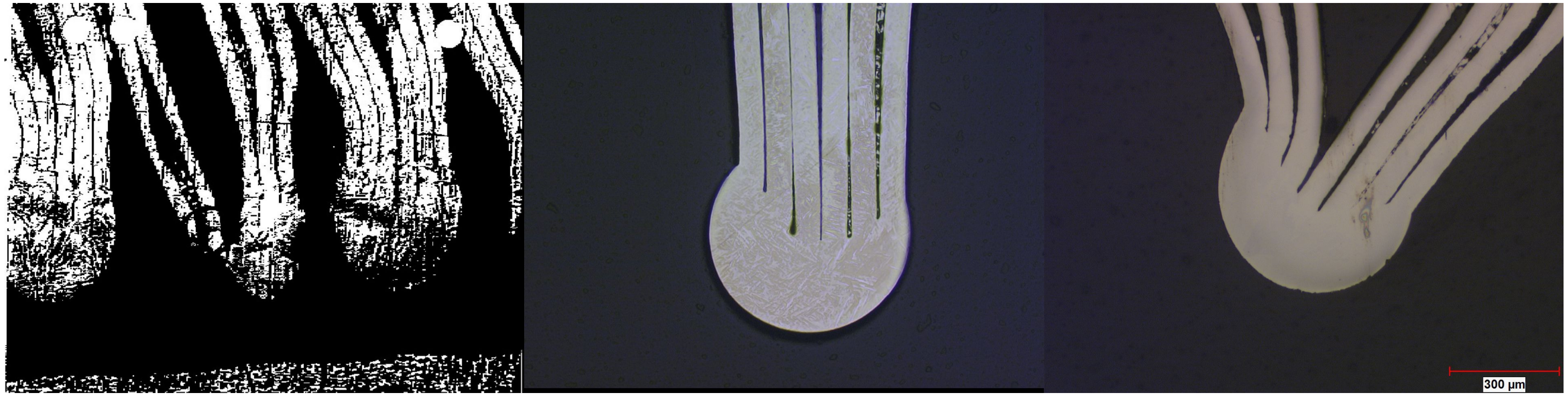
The bellows are part of the Latching Valve and are fabricated from component parts made of Titanium Grade 2, TIG welded together.





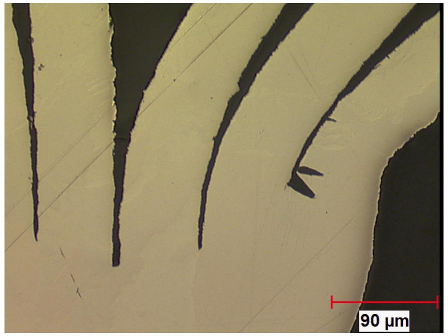
Following proof pressure testing of Latch Valve Bellow Assembly an anomaly was detected during x-ray inspection. This anomaly was identified as splitting of the buckled plies of Channel 2 Compensation bellows.

Number of plies should be six

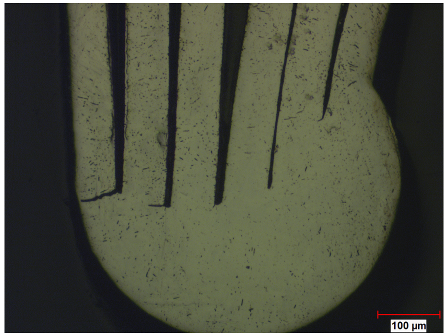


Microsection of old Rosetta bellow (left) showing 5 plies in a weld, a good weld from MU0012 (middle) showing the expected 6 plies and from the burst tested MU001 bellow showing 7 plies in a weld.

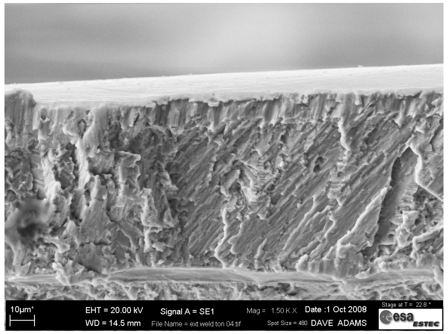
Cracks at root of plies



Detailed view showing cracks in the buckled plies of the inner. Two evident notches are present at the root of the ply nr. 1. while a smaller crack is also present. All defects are in thickness direction.

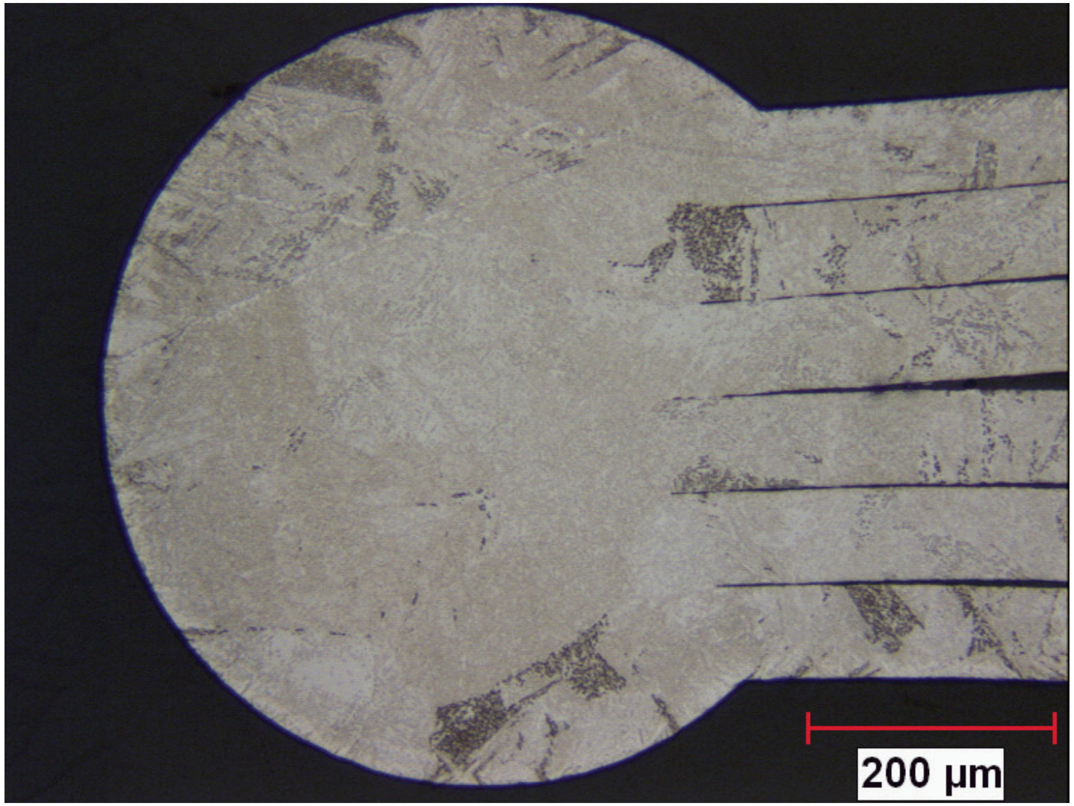


While one side present a good weld, with sufficient roll over of the plies, in the other side, lack of weld penetration is evident. No roll over of the plies is present and the plies are separated. Moreover two of them present cracks, of which the one in the first ply is almost through the thickness. (Planck investigation)



Detailed view of the fracture surface of one of the failed plies. Majority of the fracture surface shows a common mode with cleavage and tearing.

How it should be



Lessons learned

esa

- Lack of weld penetration is due to the improper alignment of the weld beam during welding process. Since the process is automated than it is more likely that the all circumference was affected.

- The severe lack of weld penetration appears to be out of the bellows acceptance specification and should have been flagged during inspection at the manufacturer

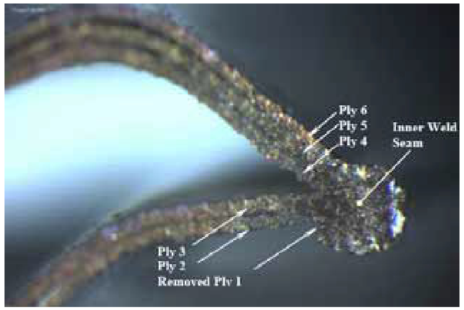
- The shape of the electrode was not measured. The parameters were not documented as well; only the welding speed. There was no traceability of the weld parameters

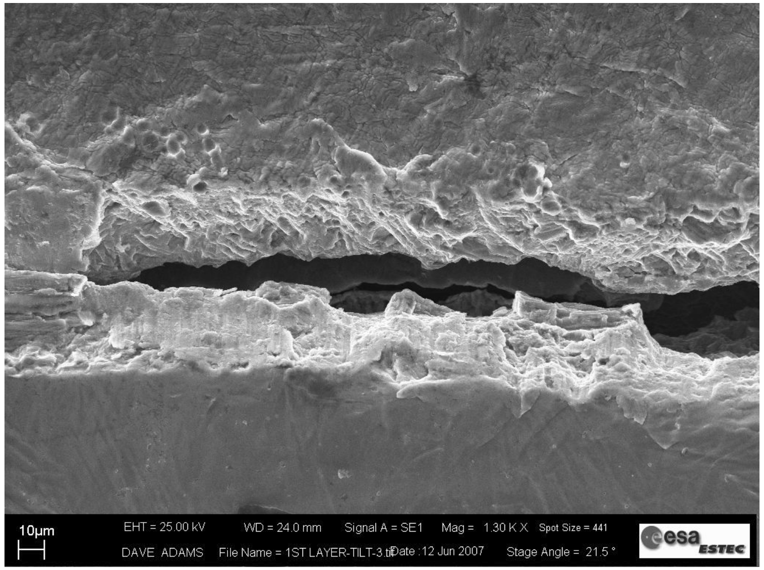
ATV bellows

During delta qualification of a spacecraft system, bellows leaking was observed

The bellows was made of Titanium and had 10 welded convolutions in total. Each convolution is made with 3 plies of 60 µm wall thickness

Failure investigation first identified the location of the cracks in the 3 plies of a deformed convolution



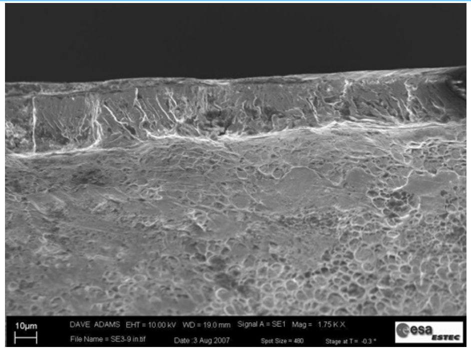


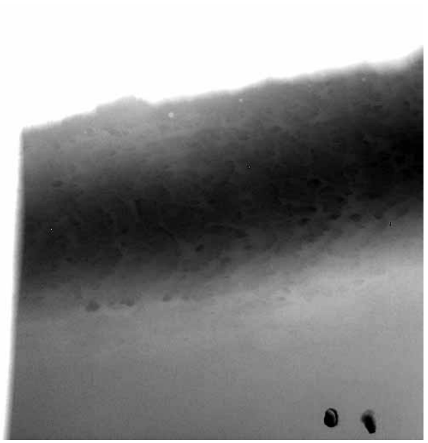
Vega Ti welds failure

A demonstration model Titanium tank was manufactured to demonstrate the validation and readiness of the welding process and to verify the maturity of the entire welding process
During proof testing, before reaching 2 x MEOP failure occurred

Vega Ti welds failure

Porosity, caused by improper setting of welding process parameters and leading to poorer mechanical performances is also present





The presence of brittle alpha-phases on the tank surface refers to oxygen contamination. Oxygen contamination has been most probably produced due to insufficient argon shielding in the trailing edge as well as in the underside of the work pieces

Weld shielding by argon should be improved either by using leading, trailing argon protection as well as at the under side, or by using a plastic/Perspex chamber around the tank filled with argon during welding
The welding parameters have been optimized to produce non porous welds

After implementing the recommendations two further demonstrators have been successfully tested at values higher than 2 x MEOP.

Major findings during process audit

The in-Process control of the bellows at the time of manufacturing was inadequate for full proof detection of this type of weld deficiencies. This includes the welding process itself and quality control.

The weld deficiencies do not meet the today's bellow manufacturer's acceptance specification for weld quality and should have been scrapped

Not all dimensional parameters can detected with a stereozoom visual inspection at 10x and micrometer measurements on the welded bellows.

Lack of weld penetration due to e.g. improper alignment of the weld beam during weld process can only be detected by in process micro-sectioning on sample basis. Sampling on weld quality was however limited to once a year.

In-situ inspection techniques of bellows already mounted on pressure regulators are not always capable of detecting inferior weld quality in bellows. Consequently there is a risk that bellows with inferior quality welds are mounted on flight pressure regulators.

The risk that bellows with inferior quality welds have passed the acceptance and are mounted on units used for flight hardware on different projects.

Lessons learned

The defective welds in pressure regulators results in considerable program impacts

There are unavoidable schedule slips due to the re-procurement and replacement of parts and welded modules.

Flight hardware quality is jeopardized by the resulting rework and retest effort.

Proper process controls during the welding processes is essential.

Contractor process controls may not be adequate for providing flight components capable of meeting mission requirements.

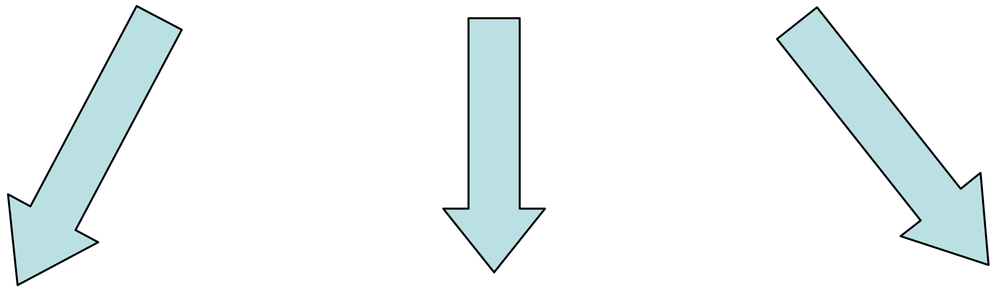
Bellow manufacturers usually tell you that bellow manufacturing is an art.
This actually means that the process is not under control

Recommendations

- Procurement of parts with a prior history of problem/failures should be specifically re-evaluated prior to re-use on a subsequent flight program.
- Special screening tests such as CT-scans and X-ray may also be warranted.
- Ensure that PA managers are aware of welding problems with titanium
- Enough resources should be available to monitor the contractor-specified manufacturing processes and test procedures.
- Ensure that supplier quality assurance controls and inspections are adequate, and that quality control standards are enforced over sub-tier suppliers (i.e., welding subcontractors).
- The use of titanium in bellow applications should be carefully reviewed or avoided due to its highly reactive nature during welding.
- Consider an alternative material such as stainless steel and non-welded bellows
- The behaviour of the bellows should be investigated by test:
  - by analysis: only relatively approximate assessment is considered feasible;
  - verification by means of testing

Final Lesson - It is all in the title

Welded Titanium Bellows



Process + Material = Product

Do not evaluate a process without knowing the material

Processes can change the material properties

Acknowledgement

- The following persons/organisations and companies have contributed to this presentation by discussion or performing the actual practical work in the TEC-Q laboratories.

- QTM: Dave Adams, Gianni Corocher, Graham Harris, Renee Dohmen
- QEC: Tony Denham
- MSS: Gerben Sinnema

- Project collaboration
- Rosetta, Planck, ATV, LPF

- Companies and organisations:
- EADS Lampolzhausen-D, Eaton-F, Idrosapiens-I, CNES-F