Formability of Titanium Ti-6Al-4V sheets at moderate temperature combined with high-pressure

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Abstract

Innovative process breaks the cost barrier

Costly and time-consuming high-temperature forming methods have limited the use of Ti-6Al-4V to highly stressed components in narrowly specialized and small volume applications, ideal for applications where less than ~1000 parts per year is required, and in vide varieties. A new forming technology, High Pressure Warm Forming process (HPWF) combines high pressure with a moderately elevated temperature for a more rapid and cost-effective forming of aerospace-grade titanium parts.

Combining moderate temperature with high pressure forming

A moderate temperature elevation to approximately 270°C (520°F), combined with a high-pressure forming step at 140 MPa (20,000 psi) has proven to form Ti-6AI-4V sheet parts with high accuracy and excellent forming repeatability. The research indicates a possibility to significantly reduce the temperature from levels required in current hot-forming processes, i.e. ~700°C / 1,300°F.

Keywords: Titanium, Hydroforming, Hot forming, SPF, High-pressure

1. Introduction - Innovative process breaks the cost barrier

Costly and time-consuming high-temperature forming methods have limited the use of Ti-6Al-4V to highly stressed components in narrowly specialized and small volume applications. A new forming technology, High Pressure Warm Forming process (HPWF) combines high pressure with only a moderately elevated temperature for a more rapid and cost-effective forming of aerospace-grade titanium parts.

Figure 1 – Photo of a 2mm thick demonstration sheet metal part in Ti-6Al-4V, formed with the HPWF process.

1.1 Background

Figure 2 – Example of the traditional hot forming process

Commercial forming methods for grade 5 of Titanium 6Al-4V has essentially so far been limited to Superplastic Forming (SPF) and to Hot Forming (HF), typically at process temperatures of 700-900ºC. The limitation of both of the said methods has been the relatively high cost, the handling challenge of hot parts and the low productivity of the processes.

1.2 New opportunity - Combining moderate temperature with high pressure forming

A moderate temperature elevation to approximately 300°C (570°F), combined with a high-pressure forming step at 140 MPa (20,000 psi) has proven to form Ti-6Al-4V sheet parts with high accuracy and excellent forming repeatability. The research indicates a possibility to significantly reduce the required temperature from levels required in current hot-forming processes [2].

1.3 The principle of the high-pressure Quintus Flexform process

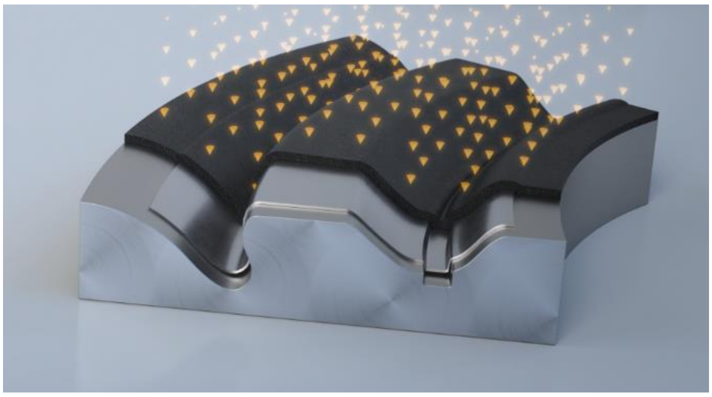

Figure 3 – The principle of the Quintus Flexform process

Sheet metal may be formed over a single shape-defining tool half by a flexible rubber diaphragm, supported by high hydraulic pressure. The high pressure allow the ~50mm thick rubber to act very much like a liquid, allowing intricate shapes to be formed with close tolerances. The technology has been used as a cold forming process for decades for structural part manufacturing in the aerospace industry.

When combined with moderate heating, this process is now also viable for material requiring elevated temperature, such as Titanium Ti-6Al-4V [3]. In this process the tool and the blank are preheated to the set temperature, the pressure is then ramped up for a period of ~1 minute. The complete pressure process being complete within a few minutes.

2. The High Pressure Warm Forming production lay-out

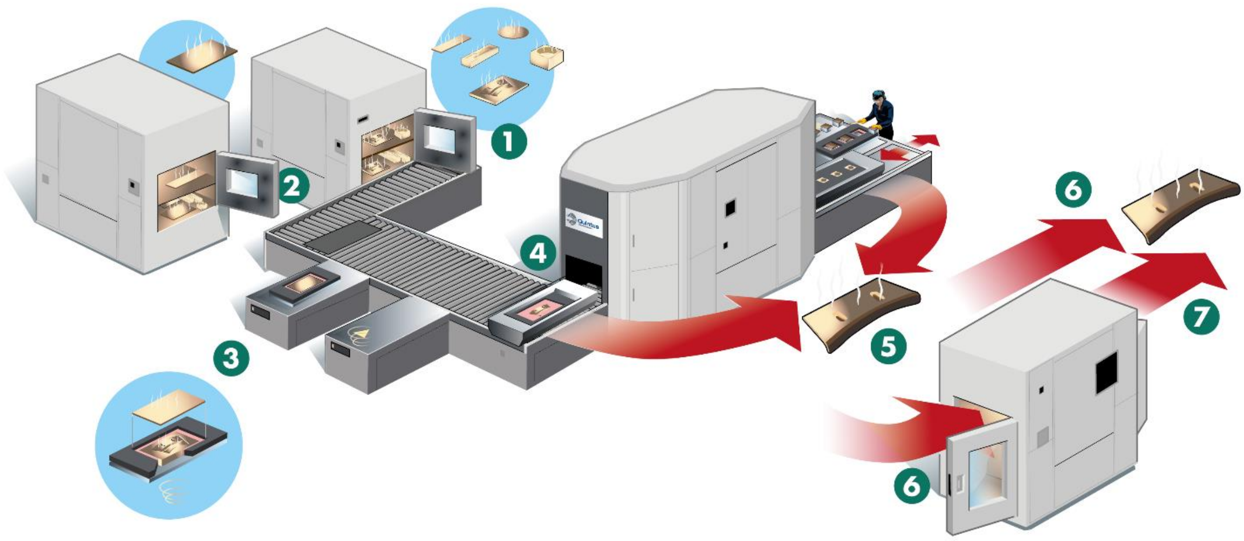

Figure 4 – The principle of the High Pressure Warm Forming production lay-out [2].

1 & 2) The tools and blanks may be pre-heated to maximize productivity

3) The blank is mated with the forming tool and heating is applied by induction. The system can handle more than one forming tool in each forming operation.

4) Kept together as a package, the blank/s and forming tool/s are automatically transported into the press and exposed to the high pressure, then returned to a part unloading station. The process parameters are carefully monitored, controlled and tracked.

5) The press may be equipped with a 2nd shuttling tray, either used for traditional cold forming or to increase the capacity of the warm forming system.

6) After forming and cooling, typically in open air condition, the parts are ready for assembly…

7) …alternatively, if required, the parts are ready for final heat treatment or for hot forming calibration.

2.1 Hot Forming vs. Warm Forming

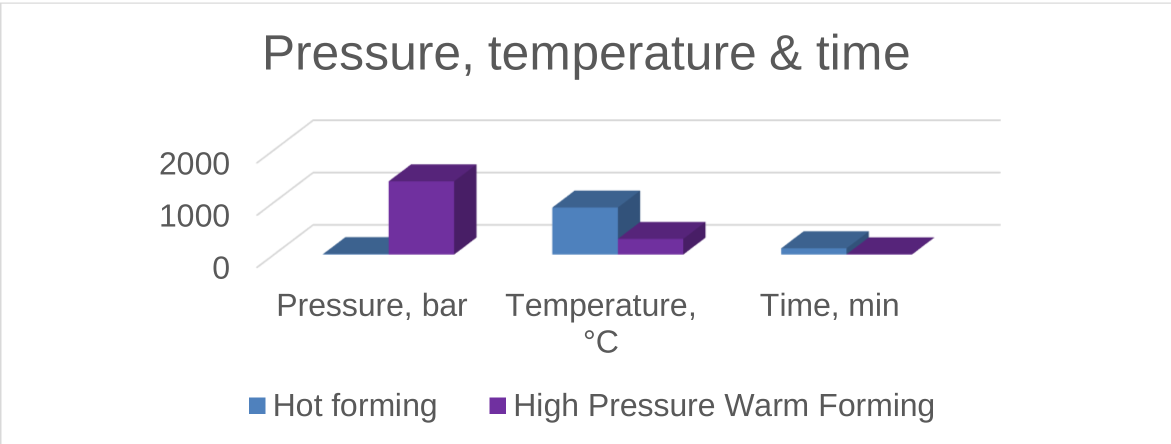

Figure 5 – A general process comparison between Hot forming and HPWF

	Hot Forming / SPF	**HPWF, High Pressure Warm Forming**
Temperature	600-900°C	< 300°C
Pressure	<1 MPa / 10 bar	140 MPa / 1400 bar
Process time	up to 120 min	< 5 min

3. Process time for HF and SPF vs. Quintus HPWF

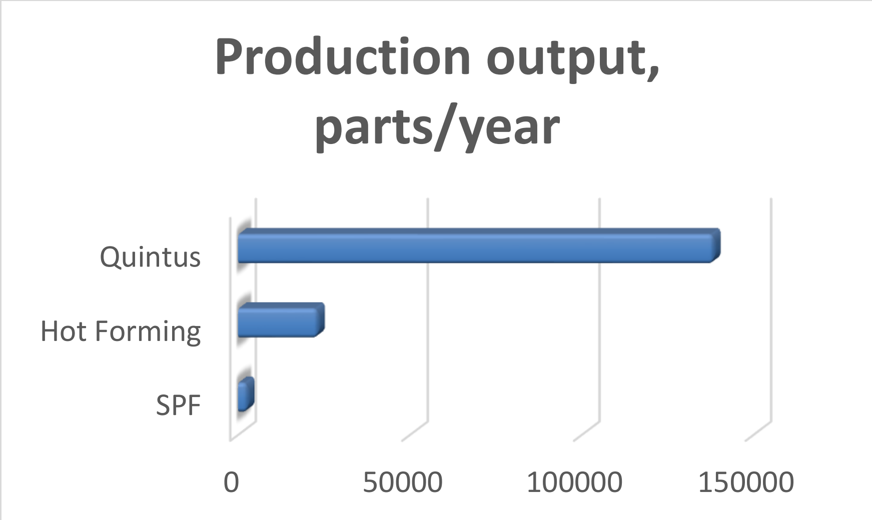

Figure 6 - Estimated annual part production capacity for a comparable production system, assuming 2 shift production at 240 working days per year [3].

4. Analysis of Ti-6Al-4V sheet metal part formed at 140 MPa/20,000 psi and at a temperature of 270°C / 520°F

The following are the result from an analysis made by the Advanced Forming Research Centre, AFRC, in Glasgow, Scotland [1], on the behalf of Quintus Technologies.

Test sample

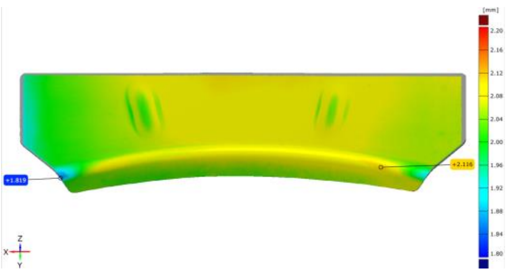

Figure 7.1 – Digital model of test part

Figure 7.2 – Photo of actual test part

The following analysis is the result from the optical and scanning electron microscope analysis made by a GOM Aramis 3D motion and deformation sensor, a non-contact and material-independent measuring system based on digital image correlation. Camera resolution 2,448 x 2,050 px, frame rate 15 Hz up to 29 Hz.

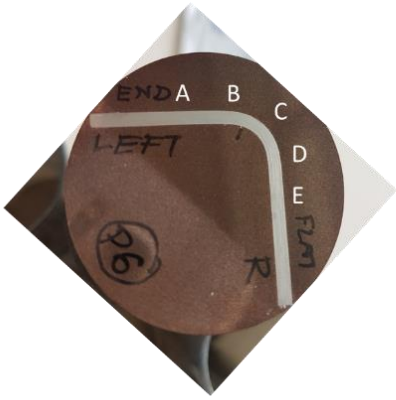

Figure 8 – Test set-up

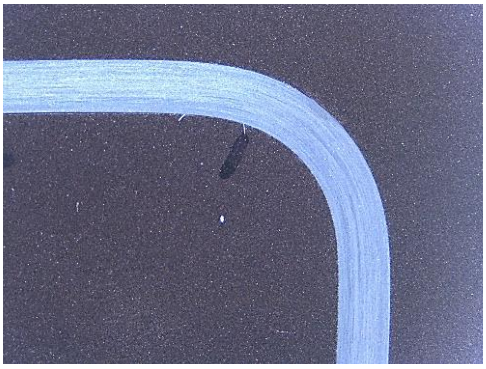

Figure 9 – Macro image

Section sample mounted and macro optical image showing material flow.

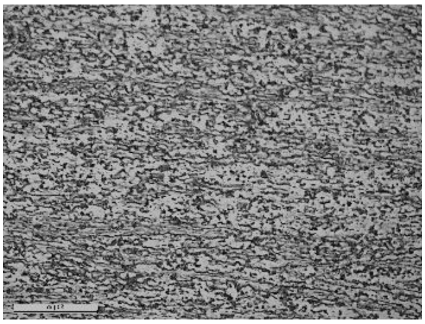

Figure 10 - Optical image location A
Fine and extended grains

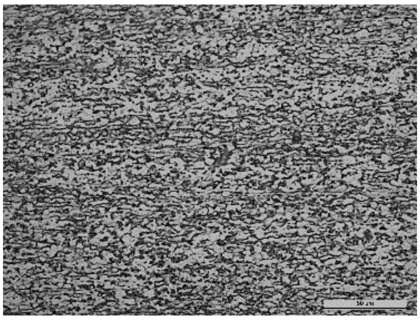

Figure 11 - Optical image location B

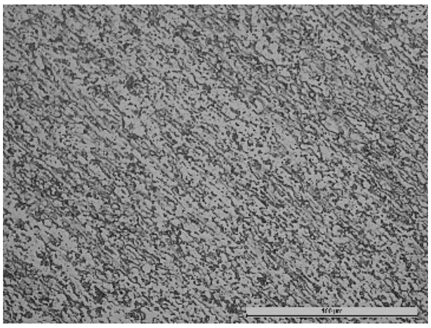

Figure 12 - Optical image location C
Direction of grain flow has oriented direction along around 15-20°

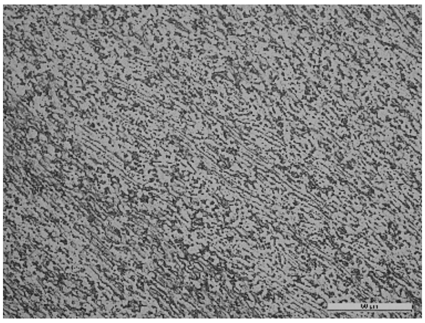

Figure 13 - Optical Image location D
Direction of grain flow transition point bending from curve to flat zone

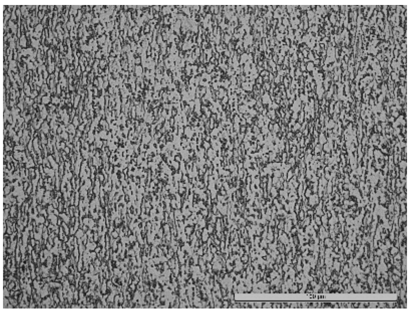

Figure 14 - Optical image location E.
Microstructure appears to be of elongated alpha grains as a result of rolling process.

4.1 Alpha case evaluation

Alpha case formation has been evaluated at three points, A, C and E, of the 'L' shape section. Both optical microscope and SEM have been used for alpha case evaluation.

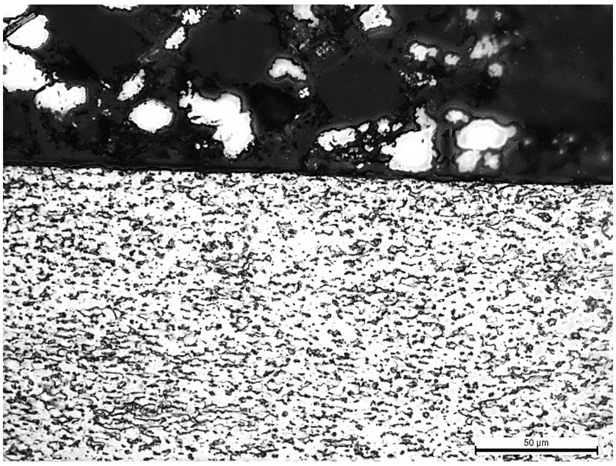

Figure 15 – Alpha case evaluation top

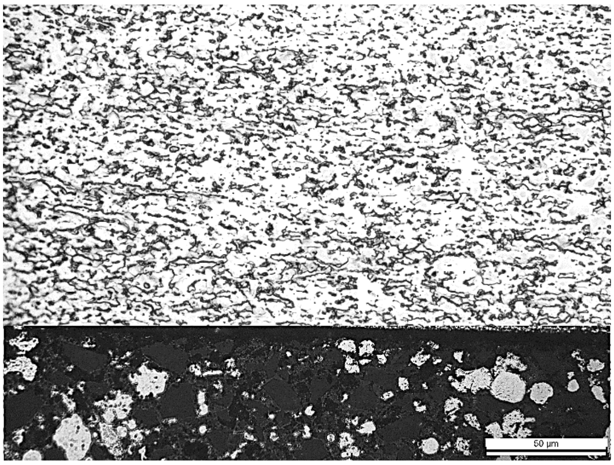

Figure 16 - Alpha case evaluation bottom

No alpha case could be observed either at the top or the bottom of point A, C or E as indicated by the optical micrographs. SEM images taken at 500X and 2000X magnifications indicates no formation of alpha case.

4.2 Crack inspection – Optical studies

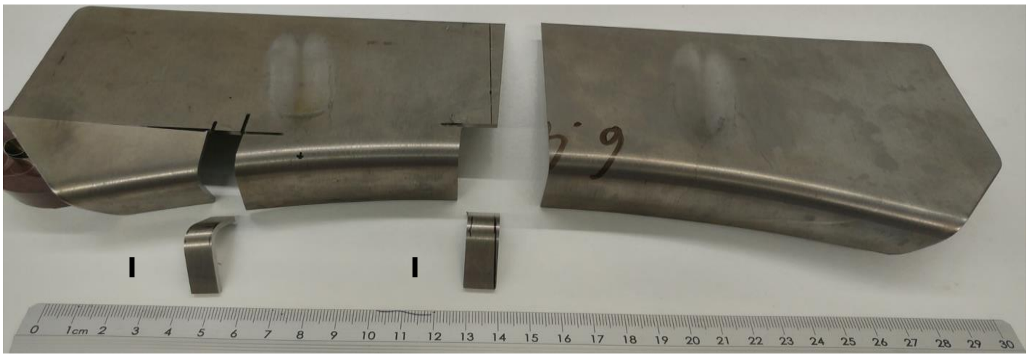

Figure 17 – Test samples

Test samples was cut 30-40 mm away from the edge and another sample close to middle of the component. The samples sectioned into two half's and mounted on 35mm holders.

Figure 18 – Test set-up

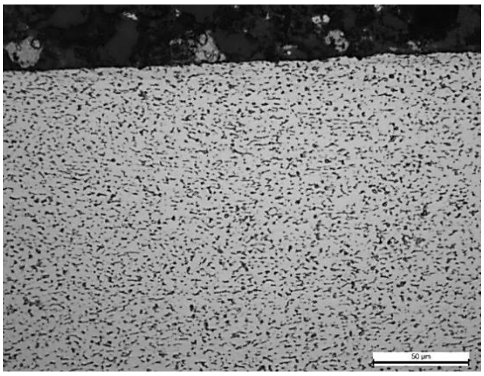

Figure 19 – Optical image of the structural integrity after processing

Optical studies confirm that the structural integrity after the HPWF process is intact. The analysis revealed no cracks within the macrostructure or along the edges of the section. Further, optical micrographs show uniform microstructure along the thickness of the sample, also confirming no formation of alpha case. This observation is further supported by SEM [scanning electron microscope] images.

5. Additional forming limit analysis

In addition to the above analysis, performed by the AFRC, other tool configurations have also been used to evaluate the forming limitation, the material/process spring back and the repeatability of the process.

Figure 20 – Forming limit analysis of R/t Forming at various bend radii.

Figure 21 – Demo part for spring back analysis

Measurements document an impressive forming spring-back deviation of less than 0.5 mm and a forming relation of the achievable radius vs. the blank thickness, R/t, at a relation value of as low as approximately 1. As a comparison a corresponding target value of the R/t-value for hot forming is typically not less than 2.

5.1 Tool design compensation

The high level of process repeatability is encouraging, which initiated additional work to evaluate how to implement spring-back data into compensated tool design.

Figure 22 – Tool compensation for material spring back

Example of parts formed to final tolerance, where the forming tool has been compensated for the theoretically expected spring back.

5.2 Forming simulation

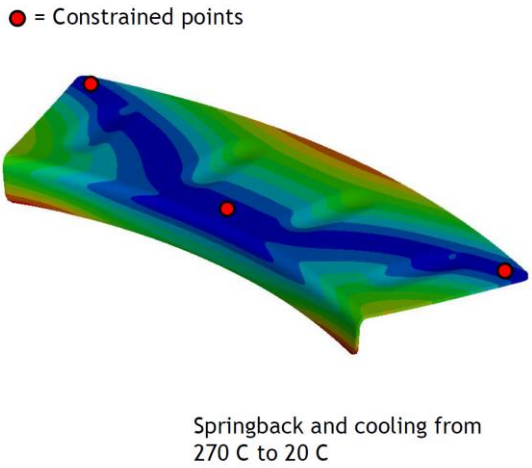

Figure 23 – Example from ongoing forming simulation correlation work

Work is ongoing to correlate forming simulation models with the actual forming process. The limited availability of good material properties for Ti 6Al-4V is somewhat limited at this stage. Further work is required allowing the optimization of tool design for the production process.

6. Conclusion

The High Pressure Warm Forming process indicate a potential capacity to significantly lower the fabrication cost and to improve the productivity of parts formed from sheets of Titanium 6Al-4V.

Analysis of the HPWF process has proven to produce test parts well within required tolerances. The process has proven a capacity to compensate the tooling and the forming process for spring back of the sheet material, leading to minimal distortion in the final part angularity. The measurements document an impressive forming spring-back deviation of less than 0.5 mm and a forming relation of the achievable radius vs. the blank thickness (R/t) at ~1.

The HPWF process also open the door to additional materials to be processed, currently being cold formed, but where the HPWF process provide an opportunity to potentially eliminate current timely and costly heat treatment steps and manual correction steps.

Additional process validation required
The results are encouraging, indicating an alternative process opportunity to traditional Hot Forming methods for grade 5 of Ti 6AL-4V, for suitable part configurations. Additional validation is required to further identify material forming limits and spring back behavior. Further, the impact of the pressure vs. time and temperature needs further investigation, securing proper control and repeatability of a final commercial process.

7.1 References

[1] Courtesy to the input by the Advanced Forming Research Centre, AFRC, University of Strathclyde, UK.
[2] Sture Olsson, *High-pressure warm forming takes off, takes on titanium*, www.StampingJournal.com, May/June 2018
[3] Web site: https://quintustechnologies.com July 2021

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