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FORMABILITY OF TITANIUM TI 6AL-4V SHEETS AT MODERATE TEMPERATURE COMBINED WITH HIGH PRESSURE

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Abstract

Current Hot Forming processes for sheet forming of titanium Ti-6Al-4V are surrounded by high processing cost, rigorous procedures for processing, severe quality inspection and still requiring a fair amount of manual corrective measurements, with for example a frequent need for pickling or chemical milling after the forming. Hence other methods have been explored to potentially overcome said hurdles and to reduce manufacturing cost.

An alternative new forming method has in this paper been evaluated, where an elevated pressure is used, combined with only a fraction of the temperature required at Hot Forming (HF) or at Super Plastic Forming (SPF).

This paper will review the forming limits, the forming repeatability and the process predictability of the high pressure warm forming process. The forming results will be compared with forming simulation results by the usage of the ESI PAM-Stamp software.

Tests are carried out in the Quintus High Pressure Application Centre in Sweden. Two different demonstrators have been used to form Ti-6Al-4V sheets at a moderate temperature, 270°C (520°F), combined with a high-pressure, 140 MPa (20,000 psi).

The process has demonstrated a capacity to form titanium sheets into intricate shapes, at high accuracy and with excellent repeatability, indicating a good fit for typical aerospace parts, but only using a fraction of the temperature required at Hot Forming.

Keywords:
Titanium; Nacelle; Hydroforming; Hot forming; Superplastic forming

1. Introduction

Due to the low temperature used (below 300°C) the risk of oxidation may be eliminated and the process may as one advantage therefore significantly simplify the production process, eliminating the need for surface preparations and for any post process surface cleaning steps. Further the investment in forming tools is greatly reduced in the evaluated process vs. hot forming tools, the life of the forming tools may be extended and the tool maintenance is significantly reduced when applying the low temperature processing. Finally, due to processing time counted in minutes the evaluated high-pressure warm forming process indicate a significant potential for productivity and production capacity improvements [1]. This compared with alternative hot forming processes, where cycle time typically require several hours.

2. Process technology background

Fluid cell pressing is a hydroforming high pressure technology, used by the airframe industry for decades. The technology requires only one single rigid tool half as the bottom tool and a pressurized flexible re-usable rubber diaphragm as the upper tool. The technology is used for low volume production where a high mix of parts and shapes are required, providing a low tool cost and a rapid lead time for new product development. The technique allows sheet metal to be formed at high quality and to intricate shapes. The process is typically used to form double-curved surfaces. The flexible rubber diaphragm, or fluid cell, will also ensure a gentle forming, providing excellent sheet metal surface quality. Several tools, sheet metal qualities and thicknesses may be used simultaneously in the pressing operation.

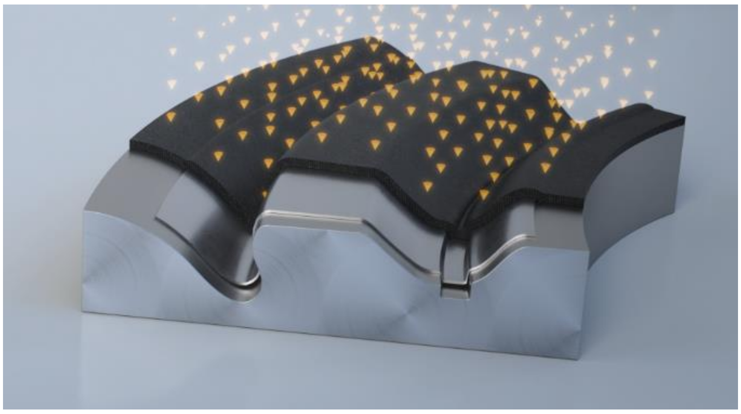


Figure 1 – The principle of the Quintus fluid cell pressing process, where a flexible rubber diaphragm is facing and separating the sheet metal blank from the pressurizing fluid. The technology requires only one rigid tool half, the other being the flexible rubber diaphragm.

Figure 2 – Example of a Quintus fluid cell press cold forming operation, where several forming tools are loaded in a shuttling tray, then processed inside the pressure chamber, all tools at the same time in one and the same forming operation.

2.1 Combining moderate temperature with high pressure forming

In this study a moderate temperature elevation to approximately 270°C (520°F), has been introduced and combined with a high-pressure forming step at 140 MPa (20,000 psi), a temperature significantly lower than the temperature required in current hot-forming processes, which typically operate at some ~700°C / 1,300°F.

Figure 3 – Example of a traditional hot forming process, now challenged by a lower temperature high pressure process. Cycle times for hot forming are typically hours, producing one part at the time.

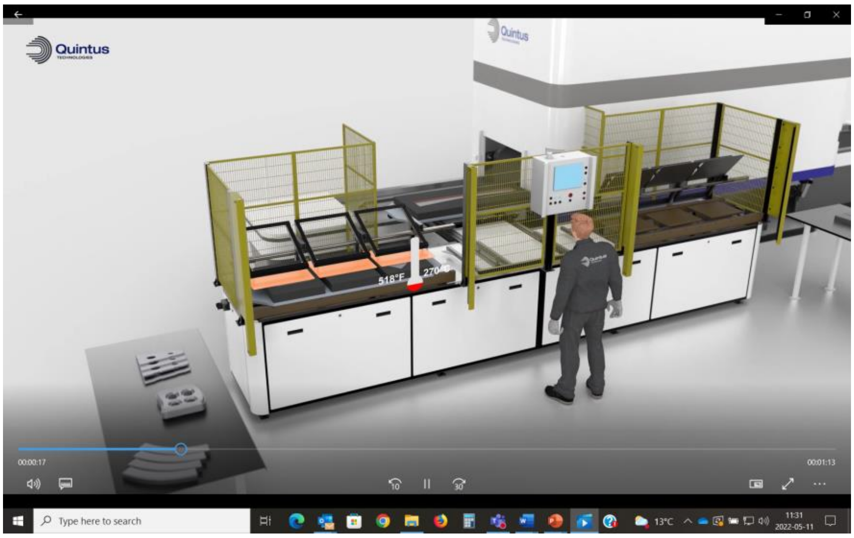


Figure 4 – Illustration of a high pressure heating station set-up, linked to a high pressure fluid cell press. The forming process may be executed in minutes, where up to three forming tools may be processed at the same time.

3. Process evaluation

The main objective in this study has been to evaluate the forming limits, the forming repeatability and the process predictability of the the discussed high pressure warm forming process. Sheet material from titanium grade 5, or Ti 6Al-4V has been evaluated.

The study also includes an evaluation of the potential opportunity to use the high pressure warm forming process to form aluminium 2024 sheets, in T3 condition, without changing its temper during the forming process.

In all titanium process tests the tool and the blanks are pre-heated to 270°C (520°F), then kept at the set-temperature by isolation during a high-pressure forming operation at 140 MPa / 1400 bar

(20,000 psi). The time to reach full pressure and back to room atmospheric pressure again is approximately 2 minutes, equal for all tests.

The forming results have also to so some degree been compared with forming simulation results by the usage of the LS-Dyna software.

3.1 Process demonstrators

In this study demonstrators with two different shapes have been used for evaluation purpose. One main objective for the study has been to evaluate the material spring-back, in order to potentially compensate the tool design correspondingly in future tool designs.

General demonstrator tool

A general demonstrator tool including several formability challenges has been used, where for example the radii formability has been evaluated.

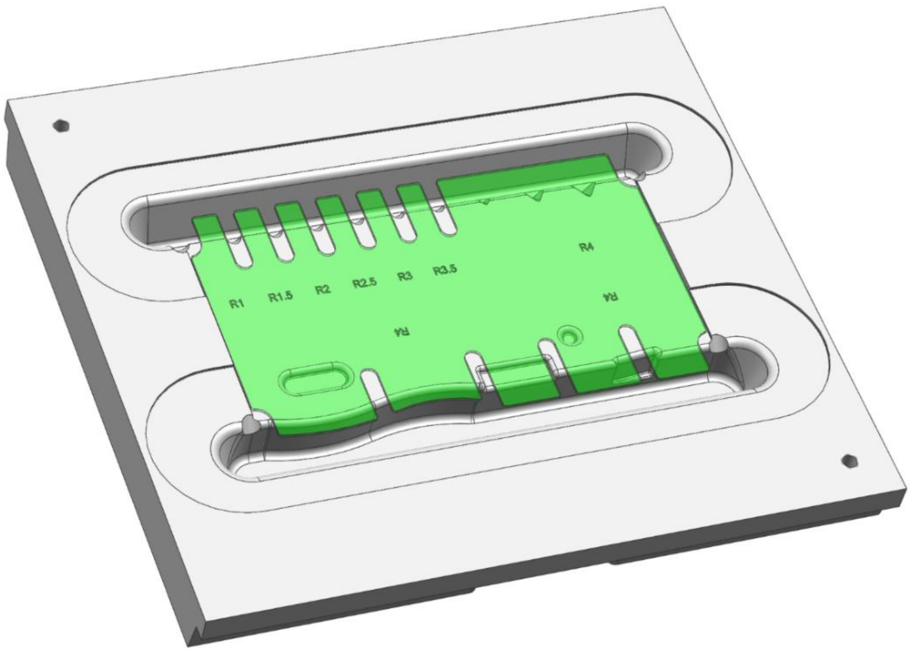


Figure 5 - Tool for testing several aspects of forming, radii, stretch-flanges, shrink-flanges, dimples and joggles. Tool size 450x500 mm.

Nacelle shaped demonstrator tool

In order to further evaluate the material formability a larger sized aerospace related demonstrator was also introduced.

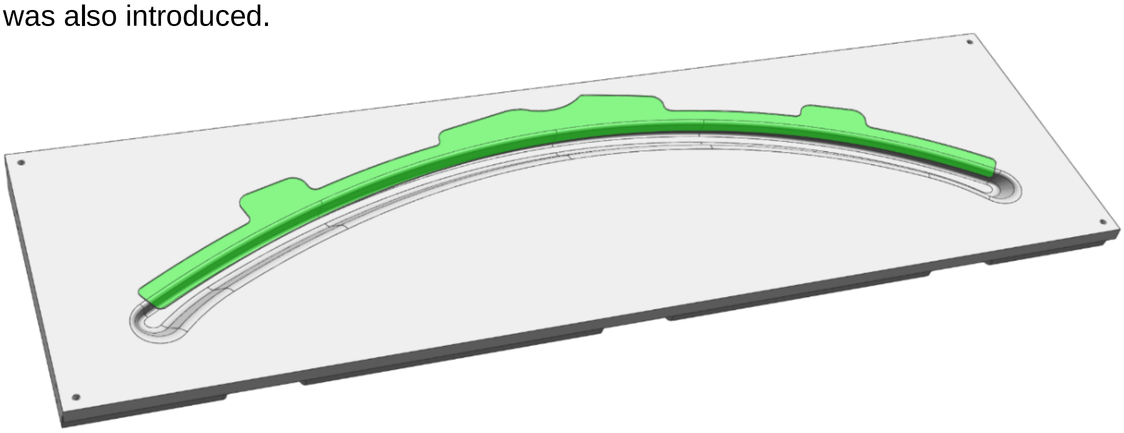


Figure 6 - Shrink flange with undercut. Tool size 1500x450 mm.

3.2 Challenges at cold forming

Both the evaluated materials are perceived impossible to form in cold/ambient condition. The objective with the study was to evaluate the formability at a lower temperature than typically used for hot forming, and/or used for superplastic forming.

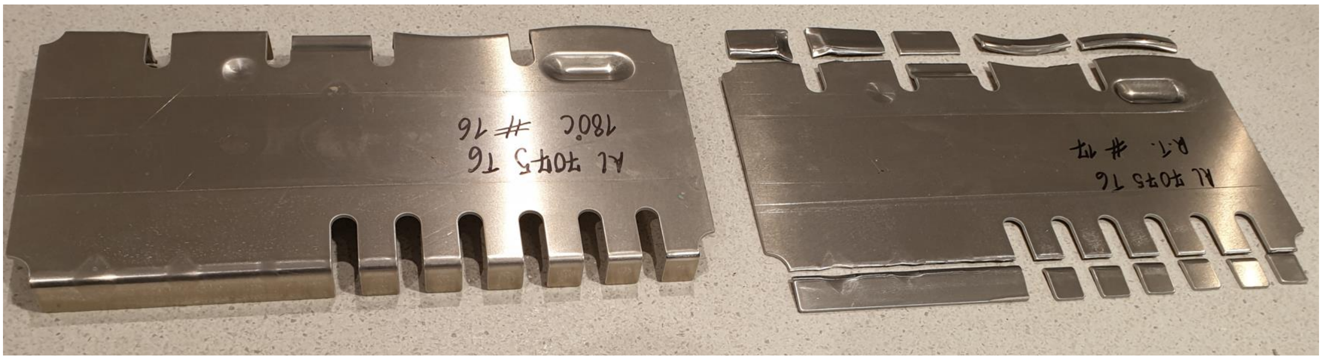


Figure 7 – Illustration of the difference in formability of Al 7075-T6, t=1.6mm, at ambient temperature and at 180°C. A similar effect is visible also for Ti 6Al-4V and for Al 2024-T3.

3.3 Process evaluation titanium grade 5, Ti 6Al-4V – General airframe demonstrator

Material evaluated

Supplier: Baoji Titanium Industry Co., LTD
Material specification: AMS 4911N

Mechanical properties (double tests):

Testing direction	Tensile strength (MPa)	Yield strength (MPa)	Elongation A50 (%)
Transverse	1 110 / 1 113	1 073 / 1 076	13 / 10.5
Longitudinal	1 105 / 1 100	991 / 989	11.5 / 11.5

Tabe 1

The test illustrated that bending radii of 2mm and larger could successfully, at a blank thickness of 2mm, be formed at the high pressure warm forming process. Fluid penetrant detection analysis only indicated ome crack and crack initiation at bend radii of 1.5mm and smaller. I.e. a forming relation of Ri/t of ~1 may be achieved.

Figure 8 – General demonstrator designed with several features, like joggles, dents, various bend radius, shrink and stretch flanges, typical challenges in airframe part manufacturing.

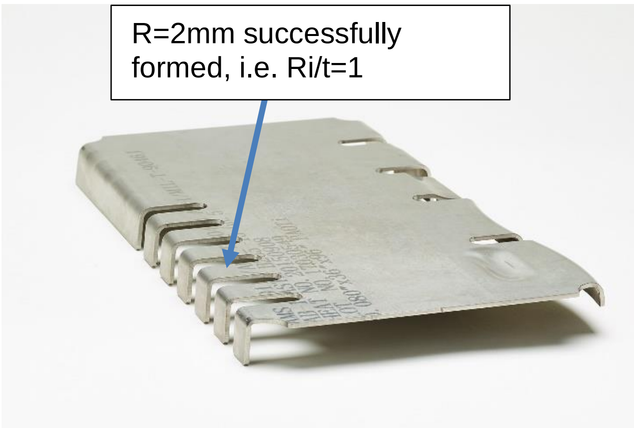


Figure 9 – In order to check the material formability the test tool is designed with a bend radii, ranging from 1mm to 3.5mm, in steps by 0.5mm.

At the flange having a 2mm radii a standard deviation of 0.2 degree was measured in a test batch of five samples and a max variance of 0.4 degree. The standard variation of the spring back of the shrink and the stretch flange was 0.2 respective 0.3 degree. All measurement well within typical required tolerances for this type of shape and part.

Tool shape	Average angle, degree	Standard variation, degree	Max variance, degree
Joggle	96.0	0.3	0.7
Shrink flange	96.6	0.3	0.6
Stretch flange	96.1	0.2	0.5
2mm bend radii	94.3	0.2	0.4
3mm bend radii	94.7	0.2	0.4

Table 2 – The tool having a bend radii of 90 degree.

The forming repeatability was demonstrated being very stable. Hence, a tool may in future studies be compensated for the expected spring back, potentially allowing for a final part shape within tolerances directly out of production.

3.4 Process evaluation titanium grade 5 / Ti6Al-4V – Nacelle demonstrator

The introduction of larger sized parts provides new forming challenges. A nacelle-shaped design was for this purpose chosen as a demonstrator.

Nacelle demonstrator

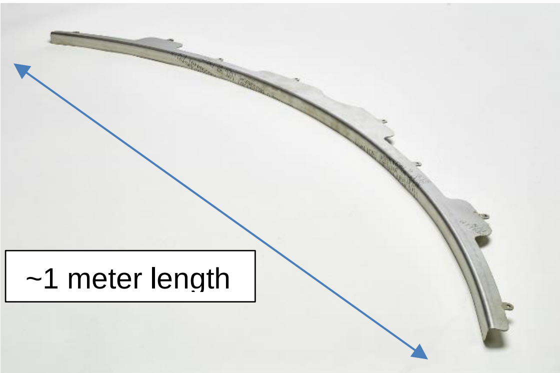


Figure 10 – A demonstrator designed to represent an engine Nacelle-shape, introducing potential challenges for full-size part production.

Test results for the nacelle

Ti parts could successfully be formed at the chosen process parameters and no cracks could be detected in follow-up inspections. Initial tests however provided severe spring back in all directions, x, y and z direction. The introduction of locking pins proved that the spring back could be dramatically reduced. The test also concluded that some level of hand correction was feasible after forming and after an intermediate heat treatment. The level of required and allowable part adjustment after forming yet to be evaluated and concluded.

Figure 11 – The part could successfully be formed at a temperature of only 270°C, when combined with high pressure of 140 MPa.

Measurements after forming

Process parameters	Angle in the center of the part, average	Max deviation
1400 bar, 270°C	85.6	1.9

Table 3

3.5 Forming simulation

An initial effort has also been made to establish a correlation between actual forming and a simulated theoretical result. More work is however required in this subject and a good model will be of great assistance in new tool designs, providing an estimated spring back compensation into future tool designs.

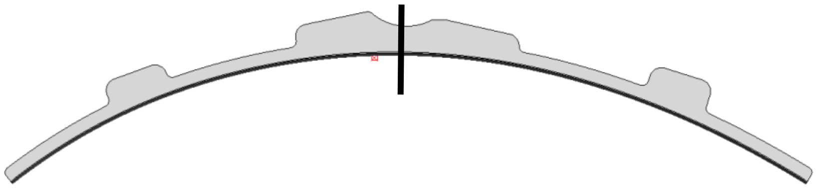


Figure 12

	Angle
Measured, actual	85.6
Simulated	82.2

Table 4

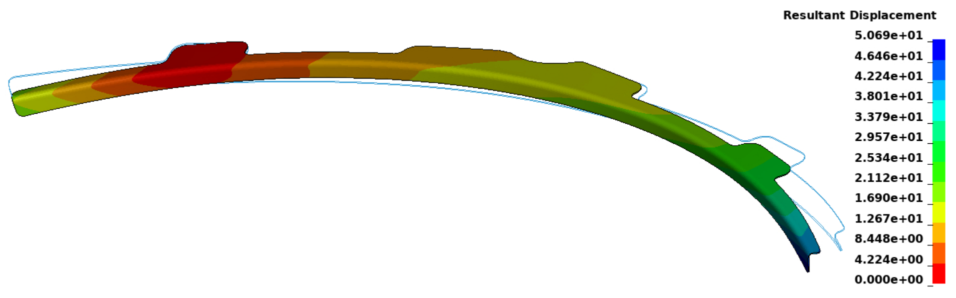


Figure 13 - Spring back in the in-plane direction could also be simulated, with a relatively good correlation to the actual values. Again, the correlation of the simulation model remains to be made.

Again, further simulation model work is required in order to better understand how to compensate for spring back already in the tool design phase, limiting the amount of correction work required after forming.

3.6 Process evaluation aluminium 2024-T3 – General airframe demonstrator

A forming test at elevated temperature was also made to check if aluminium 2024, t=1.6mm, could be formed in T3 condition, and if the material properties could be maintained also after forming. For this test the forming pressure of 1400 bar was used, and three different process temperatures tested. A hardness test was then performed to evaluate the result. A simple visual part inspection was made to check the material formability, as well as micrograph analysis.

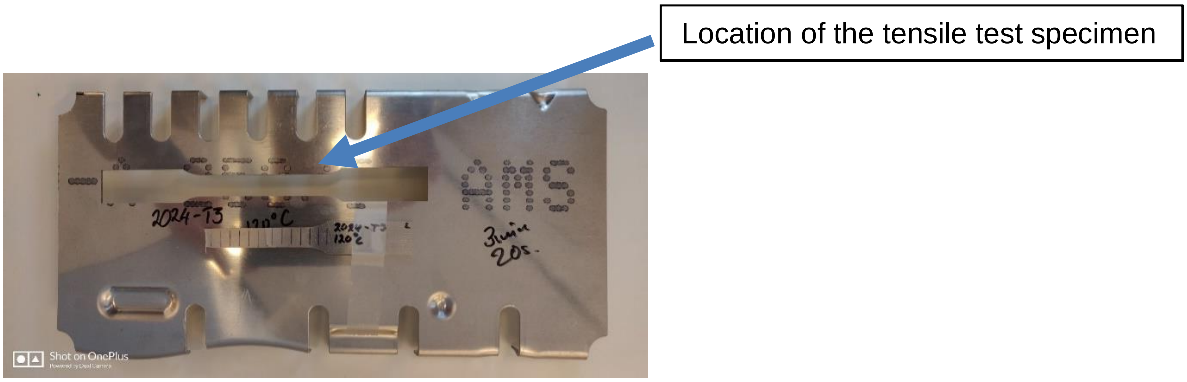


Figure 14 **-** Example of test piece and location of tensile specimens.

Indicative mechanical properties for 2024-T3, from two different references aerospace design according to MMPDS

The tensile testing results were compared with target values for the same grade and tempers. The most relevant comparison is with the MMPDS reference in case of aerospace alloys, see Figure 19 below. In the same table data from Gilbert and Kaufman is also given, which typically is more conservative.
Microhardness measurements were performed on cross sections of bend profiles in order to assess if hardness alone can be used to assess possible drop in strength during forming.

	Aerospace design according to MMPDS [2]		Gilbert and Kaufman [3]	
	Min $R_{p0.2}$ (MPa)	**Min R_m (MPa)**		
2024-T3 rolling direction	324	441	345	485
2024-T3 transverse direction	289	434		

Table 5

Overview of tensile testing results and comparison with reference MMPDS

Grade forming, temperature and reference number. Ref indicate non-formed material	**$R_{p0.2}$ MPa**	**R_m (MPa)**	**A_g (%)**	**A_t (%)**
2024 T3-Ref	**348***	**458***	13.9	15.1
2024 RT 1	**350***	**457***	14.7	17.8
2024 120°C	**345***	**454***	13.9	16.6
2024 150°C, No.1	**336***	**448***	14.4	17.4
2024 150°C, No.2	**339***	**450***	13.7	17.7
2024 150°C, No.3	**340***	**452***	13.2	16.9
2024 180°C, No.1	**323****	**445***	17.1	17.8
2024 180°C, No.2	**311*****	**435****	12.3	13.4
2024 180°C, No.3	**306*****	**428****	13.7	18.2

Table 6

* Green - The strength is within the range.
** Yellow - The strength is below the range for the respective conditions but lower than 10 MPa in yield or 20 MPa in tensile strength.
*** Red - The difference is more than 10 MPa in yield or 20 MPa in tensile strength.

[2] Reference: Metallic Materials Properties Development and Standardization Handbook (MMPDS).

Al 2024-T3 Macro photographs

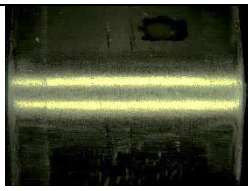
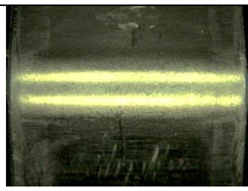
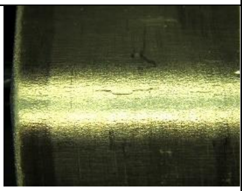
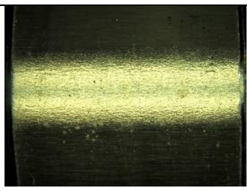
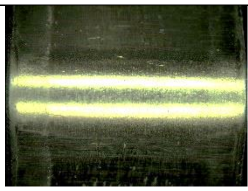
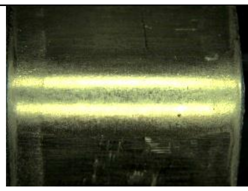
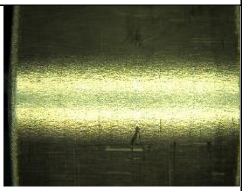
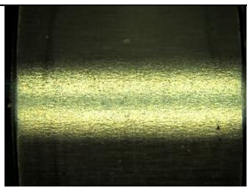
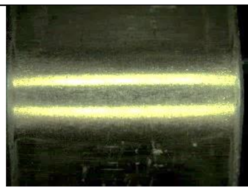
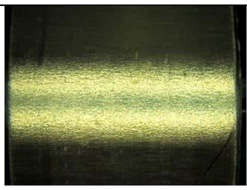
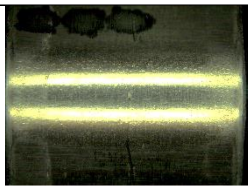
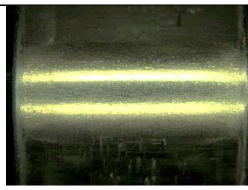
Tool radius:	**Forming temp: RT**	**120°C**	**150°C**	**180°C**
1.5	Fail	Fail		
2.0				
2.5				
3.0				

Figure 15 - Macrophotographs of the outer radius of the bend sections. Fail indicates failure during the forming operation itself.

Tensile testing of 2024-T3

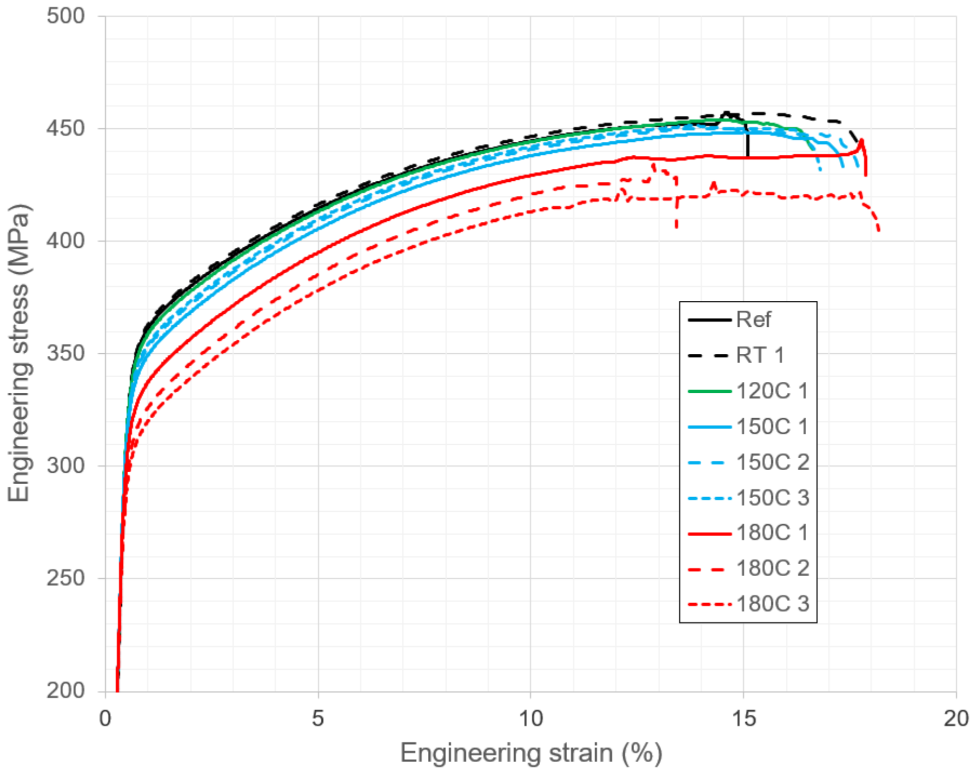


Figure 16 - Tensile testing of 2024-T3 taken out from the flat, nondeformed parts after hot forming. Sample "Ref" is not formed.

Crack inspection in the bend radii

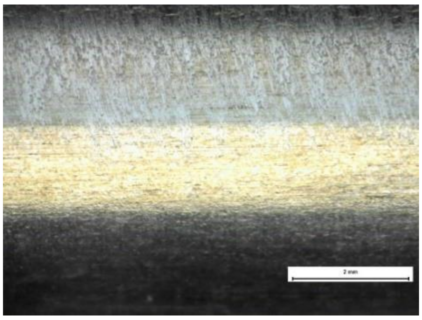


Figure 17 - Macrophotographs (4x) of the outer radius of the 2mm bend section for a sample formed at 150°C. [4]

Al 2024-T3

As a conclusion the forming at 150°C resulted in significantly better formability compared to room temperature. The material qualify for the same tempers according to the reference values used for aerospace applications, MMPDS. There is however a ~14MPa loss in strength meaning that a starting material closer to the limit could fall below the limit after forming. Forming at 180°C resulted in good bending performance, but too low strength to meet the same temper. Forming at 120°C, performed for a single sample of 2024-T3, did not improve the bendability significantly.

The results were overall satisfactory and promising forming window likely to be in the range of 130 to 140°C. Suggested future work at the said temperatures should also include the studying of the reproducibility and more accurately any loss in strength as a function of the used temperature. Reproducibility could include both mechanical properties and shape tolerance.

4. Discussion and conclusion

The study indicate that the formability is good when combining high pressure forming with a relatively low temperature process, significantly lower than temperatures typically used for SPF and for hot forming. The evaluated process thereby provides an interesting alternative to the said hot forming process methods. For simple shapes the study indicate that parts may be formed to close and to final tolerances directly from the process. For more complicated part shapes, the high pressure warm forming process, HPWF, may still require a down-stream final hand correction step, which in this study proved possible after an intermediate heat treatment.

The technology indicates a significant cost reduction and a high productivity improvement opportunity for Ti 6Al-4V parts, formed from sheet metal vs. currently used hot forming processes [1].

Further efforts need to be made in order to properly calibrate forming simulation data with actual formability data, as this will be an important feature in future tool design efforts.

The study further illustrated the capacity to form Al 2024 directly in T3 blank condition, with no major change in the material properties after the forming step, potentially simplifying the production process and eliminating manufacturing steps vs. the current quite complex manufacturing process. This may be a very interesting topic for future deeper forming studies.

References

[1] Formability of Titanium Ti-6Al-4V, paper presented at ICAS 2020 by Sture Olsson, Quintus Technologies

[2] Metallic Materials Properties Development and Standardization Handbook (MMPDS).

[3] Gilbert and Kaufman, (2000), DOI:10.1361/iaat2000p039

[4] Results from mechanical analysis by Swerea, Sweden

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