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DESIGN, PRODUCTION AND TESTING OF A TITANIUM EXHAUST DUCT FOR NOISE AND WEIGHT REDUCTION

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Abstract: Exhaust ducts for helicopters are currently mainly built out of Ni-based alloys or Commercially Pure Titanium (CpTi). With a further power increase of the engines the use of CpTi gets critical due to increased temperature and pressure of the exhaust gas stream. The increased thrust of the engines is also accompanied by an augmented noise level. The current design of a state-of-the-art exhaust duct is mostly single wall construction without any noise reduction purpose. There is a constant drive towards noise reduction of helicopters to be able to enter densely populated city areas or sensitive points like hospitals. Besides other noise sources like rotors and engine inlet the exhaust noise is important. Unfortunately the introduction of noise damping features add some weight to conventional hi-temperature ducts made from Ni-base alloys. CpTi cannot be taken due to stability problems at higher temperatures. The payload is reduced. The exchange of Ni-based alloys with Ti-alloys opens a door for a significant weight reduction. The introduction of noise reduction technology is possible without weight penalty compared to single wall Ni-alloy ducts. The material's data for long-time exposure at service temperature of 600°C and above have not yet known in detail. The forming and assembly processes were updated regarding the Ti alloys. The design, production and testing of an all-Ti-duct made from Ti6-2-4-2 and beta21S has been demonstrated successfully. The project has been funded by the EC in 5.FP under the synonym "HORTIA".

1 INTRODUCTION

Titanium alloys show an excellent combination of high strength at ambient and elevated temperatures, good corrosion resistance and low specific weight. In aerospace products like aircraft, satellites, helicopters, etc Titanium alloys play their full advantage in areas with high stresses and/ or thermal loads and/or aggressive environment. Titanium alloy parts can save half of the mass compared against Steel- and Ni-based alloys. Most amount of Titanium parts both in Commercially Pure Titanium (CpTi) and Ti-alloys are applied as machined parts made from thick sections, e.g. load carrying brackets, hinges, etc. Ti-alloy sheet metal parts are not numerous in aircraft and helicopters, which is due to the high strength, limited ductility and high amount of spring back at room temperature. Most applications are tubular parts made from relatively soft CpTi like bleed air ducts, APU-ducts or exhaust sections. Helicopter exhaust systems are made from either CpTi or from Nickel-based alloys. The decision is depending on the mission profile, the engine and the overall duct design. If the ducts is short, the resulting pressure moderate and the temperature not exceeding ~380 °C, the preferred material is CpTi. The current design of helicopters´ exhaust ducts doesn't include any noise reducing items and is single wall.

In course of increased performance level of the engines and under the hazard of future noise regulation due to environmental concerns, the current exhaust design has to be modified. In previous studies, e.g. SILENCER, the general design for a noise reduction item included in an IN625 exhaust duct structure is tested. The design is relying on the Helmholtz principle, which affords a perforated inner skin and a tight outer shell.

The approach of the actual joint development program which is partly presented hereafter is targeting on weight reduction with the introduction of Titanium Alloys Ti6-2-4-2 and beta21S. The noise reduction performance should be in the same range, ~3,8dB, as with the previous IN625 test article.

In a pre-design phase the overall design, depending on material properties, the allocation and the additional space, needed for the double skin design, was defined. With help of temperature and stress analysis and influenced by test data from materials´ tests at high temperatures and process requirements the final design has been frozen. Material tests included definition of Superplastic Forming (SPF) and Hot Gas Pressure Forming (HGPF) process parameters. The sheet metal parts are produced by SPF and HGPF. The assembly was made by different welding procedures, e,g, Laser Beam Welding (LBW), Tungsten Inert Gas Welding (TIG) and Spot Welding.

The exhaust duct was tested on a static engine test bed to verify its structural integrity and to store test data concerning wall temperatures and loads. The project has successfully been finished. On the basis of the promising results the future implementation of Titanium Alloys Exhaust Systems with noise reduction performance is possible.

2 EXHAUST DUCT DESIGN

The envisaged model exhaust duct is for an ARRIUS engine installed in a bi-engine helicopter. The shape of the existing single-wall duct is relatively simple. The attachment on the engine side is circular. The length of the duct is about 1,2m. It opens conically with an angle of 5°. The centre line is raked to guide the hot fumes away from the helicopter body. The geometry where the duct is cutting through the loft line of the helicopters outer body panel is oval

The addition of an acoustic treatment onto a gas exhaust nozzle implies a more complex design due to the double skin design and a direct increase of the weight. The part count is more than doubled. With help of Titanium alloys the weight can be kept down to a level of about the same weight as the conventional Ni-based duct. The design work was heavily influenced by the specific requirements of the new forming and welding techniques like Superplastic Forming (SPF), Hot Gas Pressure Forming (HGPF) and Laser Beam Welding (LBW). With help of these processes it is possible to keep production cost of Titanium alloys

parts at an acceptable level. Especially the forming techniques made it simple to foresee "integrated" parts with a complex shape. This avoided much assembly work.
The service loads and the service temperatures have been analyzed by simulation methods. With load and temperature predictions and the materials´ data from sample tests at high temperature the wall thickness and the load carrying elements were defined. In order to guarantee the necessary lifetime for this component the minimum thickness was set to s=0.8 mm. A modeling tool was developed in order to optimize the design of the component.

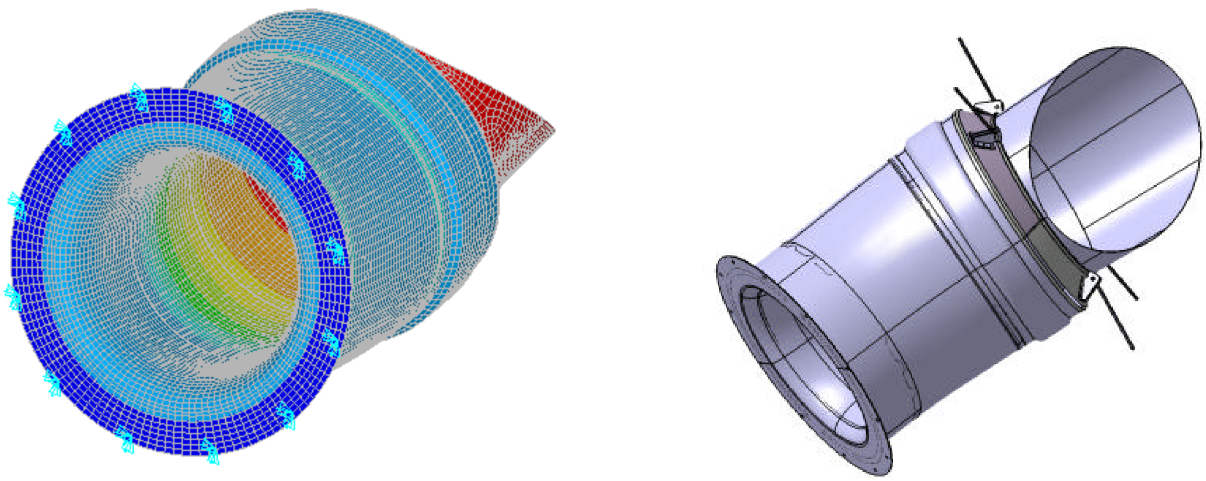


Figure 1: Design of the silent exhaust

After identification and localization of potential critical areas, some iteration loops lead to an optimization. Final design see Fig. 1. Due to suitable design modifications the heat flow could be reduced. The parts´ temperature and/or the stress level has been reduced considerably.
The design tool was validated during the nozzle tests.

3 FORMING PROCESS

3.1 SPF versus HGPF process

Forming of Titanium alloy sheets is particularly difficult because of the high strength of the material and the large spring back at ambient temperature. At temperatures between 800 and 950°C however the flow stress is much lower and the resulting strain can be some hundred percent if the right set of parameters, e.g. temperature and strain rate is applied. The mentioned material's forming properties are exploited with the SPF or the HGPF process. Essentially both processes are working with a shielding gas. With controlled gas pressure the blank is forced into a mould. The process has its name SPF if the material has SPF properties and is formed under application of SPF parameters. If the process is put outside of the SPF range or if it is a non-SPF-material the name HGPF has been established. A typical sequence for SPF and HGPF is shown in Fig.2.

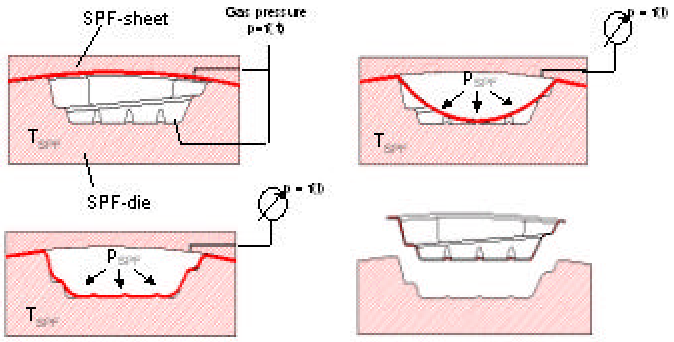


Figure 2: Forming with gas pressure under elevated temperature

The suitable set of process parameters is defined with the help of the cone cup test, Fig. 3. The material is tested on the basis of a test matrix which includes a set of temperatures and strain rates. For each combination of temperature and strain rate the cones are formed until failure.

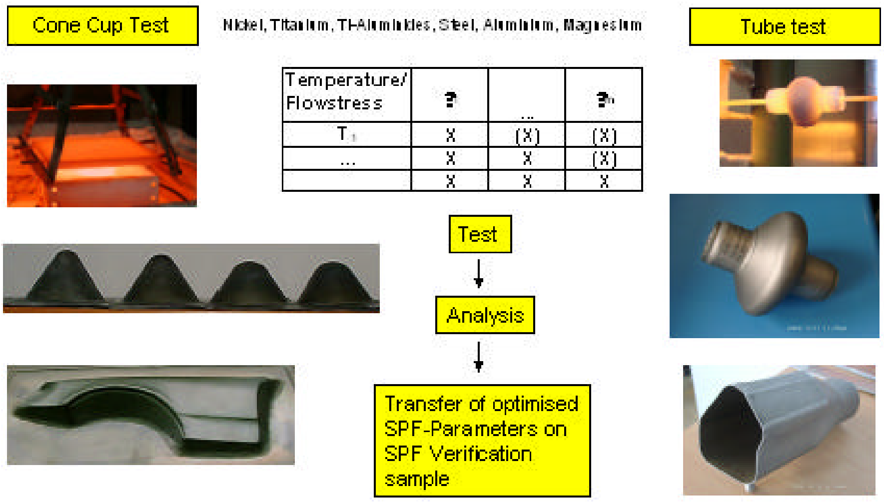


Figure 3: Cone test description

Optimum combination of temperature and strain rate allows highest cone height which is an indication for best plasticity and maximum overall strain without necking. From the results it is possible to determine the optimum set of applicable parameters for a given part geometry.

3.2 SPF Parameters

The HGPF and SPF properties of Ti6-2-4-2 have been investigated in detail with the cone cup test. The test parameters span from 820°C up to 980°C and the strain rate from $1x10^{-4}$ up to $1x10^{-2}$ s^{-1}. The results have been plotted in a 3-D-Diagram, see figure 4. From the 3-D-chart the optimum range of parameters can easily be identified.

From the selected final design every single part has to be manufactured with sheet metal forming techniques. The process studies resulted in various "hot forming"-configurations adapted to the different plasticity of the two different Ti-alloys and in reference to the complexity of the desired shape.

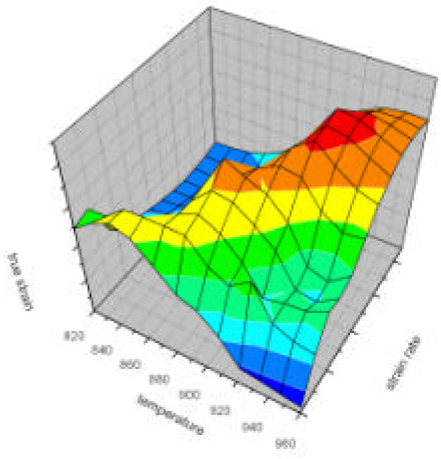


Figure 4: 3-D-plot of "Cone Cup Test"-results for SPF-parameter selection

An "industrialisation loop", starting with the initial tooling design, forming simulation analysis, iterative modification of tool geometry has been done until a good compromise was achieved. Fig. 5. The main target has been industrial feasibility, e.g. size and performance of press, extracting angle, etc but also final part properties as the thickness profile and cost analysis for future production influenced the creation of the set of dies and jigs.

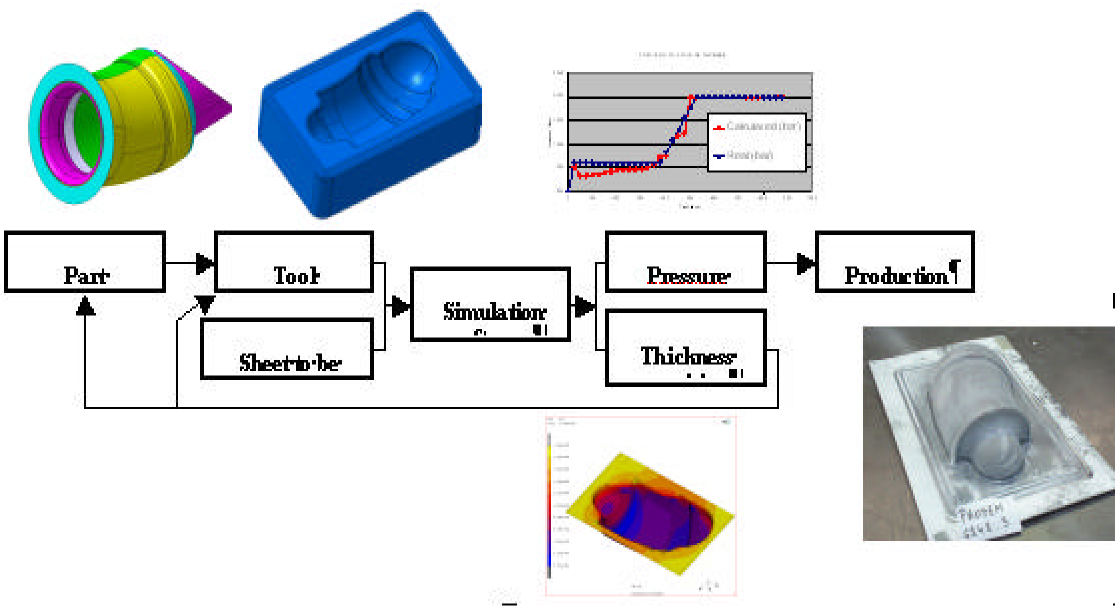


Figure 5: Typical iteration loop for SPF parts

This work led to the actual definition of the forming tools required to produce the following elementary parts. Resulting tools have been built in Stainless steel and Ni based alloy. The tools have a total mass ranging from ~300 kg up to 1.2 Tons. Fig. 6 shows the tool for the skin production in hot action.

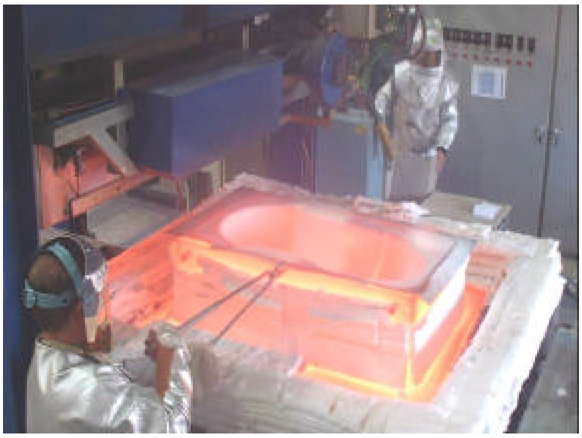


Figure 6: SPF-die for the exhaust skin half shell in action

3.3 Forming of parts

The selected final exhaust duct design resulted in 6 single parts with different and somehow complex geometry to be formed and afterwards assembled. Fig. 7.Concerning the forming operations the process studies ended up in various “hot forming” configurations respecting the ductility limitations of the different Titanium alloys in conjunction with the geometry of the parts. Process variants include SPF, HGPF and Hot forming with driver sheet.

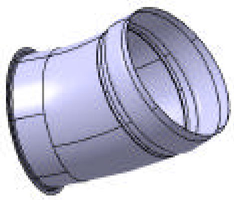
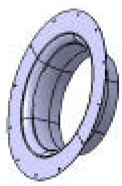
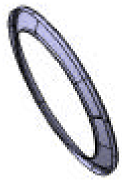
Part	Skin (L + R)	Entry lip	Ejector	Front Baffle	Rear Baffle
Part definition					
Material	Ti 6-2-4-2	Ti 6-2-4-2	B21S	B21S	B21S
Forming	SPF	driver sheet SPF	driver sheet HGPF	driver sheet HGPF	driver sheet HGPF

Figure 7: Single parts definition

During “industrialisation phase” the priority has been on technical feasibility combined with cost consideration for future production. Starting from initial tool design based on experience from other parts it was possible to achieve iterative optimisation supported by simulation analysis results for the whole set of dies and tools. A good compromise has been found to end up with a suitable thickness profile of the parts. With assistance of the simulation tool also the cycle time and the pressure cycle could be pre-determined.

4 CHEMICAL MACHINING OF TITANIUM SURFACES

Process and materials analysis previously conducted resulted in special a decontamination sequence for alpha-case removal. The alpha-case layer has to be removed because it is the origin of brittle cracking. The sequence was optimized for refractory Titanium alloys. Hydrogen adsorption and intergranular attack is a phenomenon resulting from the chemical composition of the HF / HNO_3 bath. For beta21S special chemical treatment in special condition is necessary to achieve the proper milling rate, thickness homogeneity, surface roughness, see Fig. 8, and to avoid exceeding hydrogen uptake.

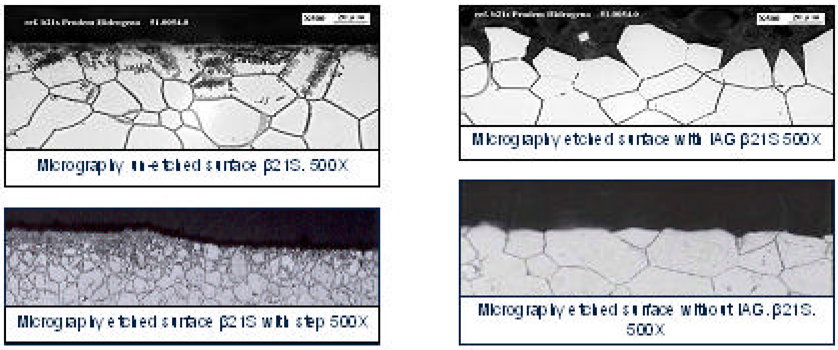


Figure 8: Different surface smoothness as a function of the chemical-mill process

5 WELDING PROCESS

Development of the welding processes to assemble the whole exhaust duct was separated in phases:

- Definition of welding parameters of each characteristic material, material condition (base material and heat treated and strained material), material combination (Ti6-2-4-2 and beta21S) and welding configuration with samples.
- Study on samples similar to the real exhaust geometry
- Transfer of experience on the real part

For the given materials and the welding conditions three different welding processes have been identified and investigated, see figure 9:

- Resistance Spot Welding in lap joint configuration
- GTAW in butt joint configuration
- LASER welding in butt and lap joint configurations

The welding operations and the QA requirements for the exhaust duct are classified following Class 2.

An appropriate surface preparation is required before welding and is put into a process spec to be reproducible. It consists of degreasing, decontamination, stripping, rinsing. The use of specific solvents required for the titanium alloys surface preparation is necessary, especially no contact with halogen solvents is required. A maximum delay between surface preparation and welding has been fixed.

Following French standards have been considered for development and validation steps:

- NF L 06-383 for RSW
- NF L 06-394 for GTAW
- NF L 06-395 for LBW

As visual acceptance criteria the appearance has to show:

- No cracks
- The seam must present a silver-grey brilliant metallic aspect.
- No white or grey or blue coloration must be seen on the melted zone.
- If a single pass welding process is realized, a light yellow in the melted zone or light blue on HAZ is permitted.

Further characterization has been done by NDT. The samples and the parts have been X-ray-ed and underwent a penetrant inspection.

		welded formed samples ß21s: 1.47mm thickness Ti-6242: 1.2 mm thickness
Material	Welding process	Tests for processes optimisation and parameters validation
? 21s/ß21s	GTA butt welding	Tests performed by EXAMECA: - NDT: X-rays, FPI -Dimensional observations -Mechanical tests: tensile tests+bending tests -Metallurgical observations -Microhardness traverses
	Laser butt welding	
Ti6242/Ti6242	GTA butt welding	
	Laser butt welding	
Ti6242/Beta21S	GTA butt welding	
	Laser butt welding	
	Resistance Spot welding	

Figure 9: Matrix for welding investigations

As an example for the total scope of the welding investigations of all the three different welding processes, the results for LBW are presented. The following micrographs, Fig. 10, 11, 12, and 13 show the integrity of the weld seam and the heat affected zone (HAZ) for the welding of same material and the combination of Ti6-2-4-2 with Ti beta 21S.

Laser Beam Welded samples in butt joint configuration.

Ti6-2-4-2/Ti6-2-4-2

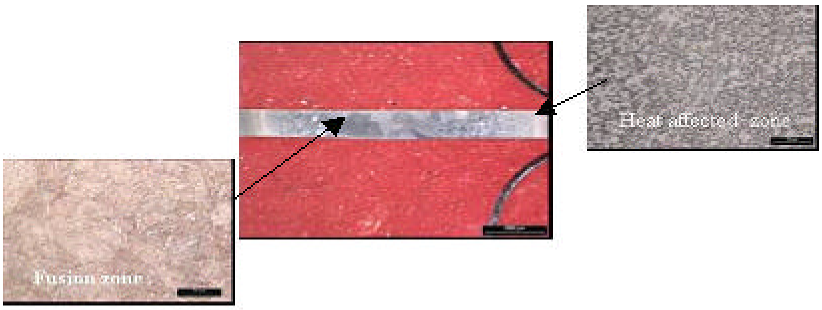


Figure 10: LBW of SPF`ed Ti6-2-4-2 to Ti6-2-4-2 in as-received condition

Beta21S/Beta21S

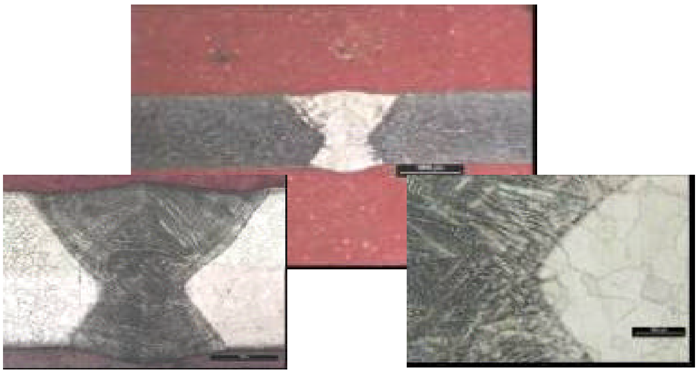


Figure 11: LBW of SPF`ed beta21S to beta21S with H_2 contamination

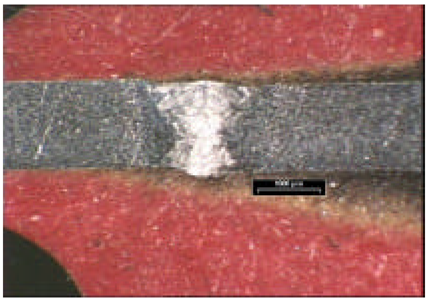


Figure 12: LBW of SPF´ed beta21S welded to beta21S in as-received condition without H_2 contamination

Ti6-2-4-2/beta21S

Figure 13: LBW of SPF`ed Ti6-2-4-2 welded to Hot formed beta21S

The welding experiments show the performance of the different applied welding processes. Both the welding of Ti-material of the same alloy and the combination of Ti6-2-4-2 with beta21S proved to be successful. The additional tensile tests referring to the different combinations of alloys and heat-treatment conditions clearly show an influence of the welding operation on tensile strength. As usual, there is a small reduction of Ultimate tensile strength (UTS). Some hydrogen pick-up during GTAW and LBW of beta21s cannot be avoided. This contamination leads to a reduction of mechanical performance data. Tensile strength is reduced by~ 15%. Special attention has to be paid on unacceptable hydrogen content which results in brittle failure at low strength level.

If the heat- and the surface treatment and the welding operation has been kept inside the specified conditions, the failure always occurs in the base metal. The elongation to failure is similar to the delivery condition.
The specified give satisfactory results according to the QA requirements and to the standards cited above.

6 TESTING AND RESULTS

The assembly of the complete test item following the construction plan and the given tolerances has successfully completed.
The completed demonstration part was tested in full scale on an engine test bed regarding both the temperature distribution under full engine load and the emitted noise level. The documented temperatures confirmed the simulation results. The noise emission of the exhaust gas flow was measured. The noise was reduced to ~the same level as with the IN625 component.

Figure 14: Exhaust nozzle after first campaign with Max Take off Power (MTP)

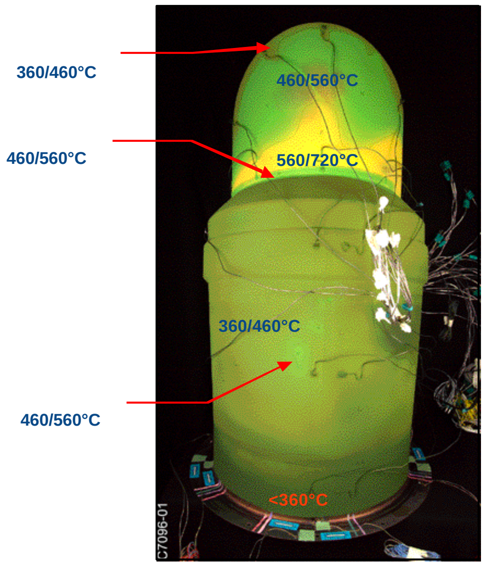


Figure 15: First campaign. Exhaust nozzle after coloration test at MTP

As it can be seen in Fig.14, the engine ejector, which is located at the back, leads the fumes directly in the HORTIA gas exhaust nozzle. The acoustic treatment is located in the center area of the nozzle.
Three different campaigns of engine bench tests were performed with a TM333 gas turbine.

- First campaign suited for thermo mechanical tests. Fig. 15. Temperatures and mechanical stresses were measured for three different engine running conditions as Max take-off power, stabilized power and emergency power. The maximum occurred temperature was lower than 700°C. Fig. 16 shows the comparison between the predicted and the measured values. The predicted data have been validated. A predictive design tool for such a component was not available before.
- Second campaign targeted on endurance test. 1000 cycles at Max take-off power have been performed. A full control of the nozzle did not reveal any defects.
- Third campaign was realized to measure the acoustic performance. Fig. 17. Four different engine running conditions, Maximum continuous power, stabilised power, Twin-engine take-off power and Idle power have been applied. A comparison between the HORTIA gas exhaust nozzle and an existing helicopter ejector resulted in a significant noise reduction.

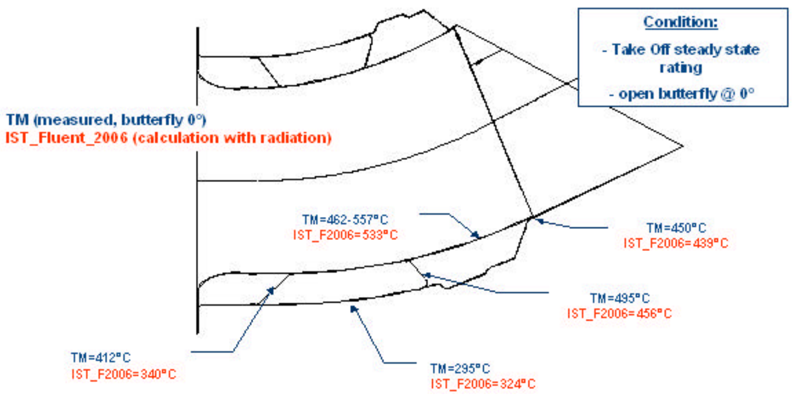


Figure 16: Second campaign result. Validation of temperature simulation with measured data

Figure 17: Test set-up for acoustic measurements

7 SUMMARY

The development work has been finished successfully and provided the information for the potential replacement of heavy Ni-base exhaust ducts by Titanium alloys. The Titanium alloys Ti6-2-4-2 and beta21S have been investigated in detail related to the mission spectrum of the helicopter and the defined engine concerning high temperature strength, aging behaviour due to long-time exposure, oxidation characteristic, material's properties after forming and welding etc, etc. Concerning the production techniques for the complex shape of the noise damping exhaust duct the applicable processes and parameters for forming, chemical machining and welding, have been elaborated. Superplastic Forming and Hot Gas Pressure Forming techniques have been applied for the complex shapes of the integral parts. The assembly was by different welding processes as resistance spot welding TIG and laser beam welding.
The described work has been conducted in the framework of EC FP.5 under the project title HORTIA="Heat and Oxidation Resistant Titanium alloys Application.

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