MATEC Web of Conferences **321**, 01005 (2020)
The 14th World Conference on Titanium
https://doi.org/10.1051/matecconf/202032101005

Titanium in France: research activities, industrial developments and applications

P.-F. Louvigné

The French Titanium Association (www.titane.asso.fr), France

pierre.francois.louvigne@gmail.com

The French titanium community has been very active in the past four years for developing new applicative opportunities in all traditional sectors: aerospace, industrial, medical, defence etc. Thanks to good connections between academia and industry, the research activities are supporting the main priorities: improvement of efficiency, reduction of cost and control of the quality. This presentation will give an overview of the most significant progress made in France during the period.

1. The Titanium Community in France

The French Titanium Association

Since its creation in 1994, the French Titanium Association brings together companies and laboratories interested in titanium and in it implementation. This organisation regroups the industrial and academic experts of this metal which has remarkable properties, but whose implementation is very demanding. The Association is a place of exchange and collective work around the issues specific to titanium and its alloys. In particular, it organises technical committees to work on issues of interest to the members. Also, the Association aims to contribute to a better diffusion of technological information on the characteristics, privileged uses and methods of implementation of titanium and its alloys. Furthermore, for the benefit of its members, it leads an action to capitalise on the knowledge of this metal, which has given rise to many works in previous decades. The Association relies on about a hundred academic and industrial structures, representing 200 to 300 people around titanium. Since 2004, the Association organises Technology Days bringing together about 100 people for a scientific 2-day symposium with about 20 presentations.

Market, Surveys and Governmental Initiatives

Since 2001, the French Ministry in charge of raw materials policy has put in place an economic and geostrategic watch on the titanium market. The objective of this watch is:

- to ensure regular monitoring of supply and demand highlights
- to capitalise market information and analysis in a report updated every 3 years [1],
- to provide an exchange forum for titanium-using manufacturers to assist them on their procurement strategy.

Aware of the difficulties faced by companies in terms of access to raw materials, the French authorities created the Committee for Strategic Metals (COMES), forum for consultation between the French actors: ministries, public bodies, industry and professional federations representing the industry. The mission of COMES is to assist the minister responsible for mines in the development and implementation of the strategic metals management policy, in order to strengthen the security of supply necessary for the sustainable competitiveness of the economy. France’s action is divided into three main areas:

- awareness of the risks (geopolitical, environmental and economic) of raw materials and the sharing of knowledge on raw material markets with industrial players,
- the development of primary and secondary territory resources,
- the diplomacy of raw materials.

For more information on COMES, the reader can visit the official website of Mineral Info [2].

Thesis, research and development funding

The French academic community involved in titanium research has produced about 1648 theses over the period 2015-2019. This research is funded by ministries, research bodies, local authorities, foundations, associations, etc. Private companies also contribute through industrial research training agreements (CIFRE) sometimes co-financed by public bodies such as the Ministry of Higher Education and Research, the French Defence Procurement Agency (DGA) and the Defence Innovation Agency (AID). The European Union also offers universities the opportunity to train young researchers in partnership with the private sector through a funding action entitled "European Industrial Doctorate". Thesis work is often carried out in larger projects involving research organisations, technical centres and industrialists. They are funded by National or European public bodies such as:

- National Research Agency (ANR – Agence Nationale de la Recherche) whose mission is to implement project research funding in France;
- Support schemes financed by the Future Investment Programme (PIA - Programme d’Investissements d’Avenir), which aims to select innovation projects with particularly strong potential for the French economy;
- The Inter-Ministry Fund (FUI - Fonds unique interministériel) which is a programme to support applied research, to assist in the development of new products and services that can be placed on the market in the short or medium term;
- The European Regional Development Fund (ERDF), which aims to strengthen economic and social cohesion in the European Union and which in particular supports innovation and research projects in Small & Medium Enterprises;
- Specific support for defence research and innovation works (ASTRID - Accompagnement Spécifique des Travaux de Recherches et d’Innovation Défense) which aim to support dual research projects, that is, with potential benefits for both civilian and military fields (funding by the DGA and implemented by the ANR);
- Support Scheme for Dual Innovation (RAPID - Régime d'Appui pour l'Innovation Duale) is a program put in place by the DGA and the DGE (Direction Générale des Entreprises), which funds industrial research or experimental development projects of interest for the defence sector.

2. Thesis

Every year, the scientific committee of the French Titanium Association awards a prize to the best thesis that has been presented over the past year.

In 2015, this award was presented to Dorian Depriester for his work on “Characterization and modelling of Backward cold flowforming of Ti-6Al-4V” [3]. Ti 6-4 is well known for its poor ductility at room temperature, which is the main reason why the flowforming of this alloy is a real challenge. Following the objective to increase the "tube spinnability" of the Ti-6Al-4V, Dorian first carried out an extensive microstructural and mechanical analysis of the alloy. He learnt about the strain mechanism occurring during flowforming by performing experiments with a specific laboratory set-up designed by himself. In consequence, he was able to build an adequate constitutive law for the plastic flow of the alloy. This law has been used to optimise the processing parameter, in order to avoid failure during the process. The 2014 nominees were Fabien Grange for his work on “Experimental and Numerical investigations of mass Finishing processes on titanium Ti17” [4] and David Prat for “Development and modelling of finish Milling strategies in 5 axis - Application in the Machining of closed veins” [5].

The following year, Charles Tarek Sultan’s research “Abrasive Waterjet Milling of hard metals” [6] was awarded. The aim of the research was to develop a controlled depth milling on different hard metals including titanium with the abrasive water jet (AWJ) technology for pockets machining. The process is known to be used for cutting operation but Tarek has proved that, by controlling the input parameters and the geometric characteristics, it is possible to manufacture pockets with constant or variable depth. His work shows the study of elementary passages and their superposition to generate a necessary path for the realization of a pocket in AWJ. Furthermore, Tarek has proposed a variety of strategies for machining rectangular pockets and he has provided a correction of the operating parameters to obtain a controlled depth. The other nominees for the 2016 award were Emilie Lebrun for her work on «microstructures and phase transformations in the T18 quasi-beta alloy for aeronautical applications» [7] and Matthieu Salib, who presented his thesis entitled "Kinetics and crystallographic study of the α phase precipitation at β/β grains Boundaries in a titanium Alloy" [8].

In 2017, the thesis prize of the Titanium Association was awarded to Aude Mathis for her work on «Anodizing of titanium by Micro-Arc Oxidation (MAO)» [9]. Aude has studied the process set-up of the electrochemical surface treatment named MOA. She was aiming to determine the influence of parameters such as nature of the substrate (alloying elements), chemistry of the electrolytic solution and electrical parameters, on the process. She has analysed in-situ electrochemical behaviour of forming oxide layers, as well as microstructural and chemical characteristics of formed coatings by using numerous technics including voltamperometry and chronopotentiometry. Aude succeeded to differentiate three anodizing stages (I/ conventional, II/ micro-arc, III/ of arcs), characterised by a particular electrochemical response of the metal/electrolyte interface, and which impacts obtained coating properties. In particular, phenomenological models were proposed for each stage of anodizing and linked to MAO process parameters on Grade 2 commercially pure titanium and Ti-6Al-4V alloy. The 2017 nominees were Vincent Duquesnes who presented “On the effect of hydride on titanium and titanium alloys: influence of manufacturing parameters and consequence on the material durability in corrosive environments" [10] and Immanuel Freiherr Von Thugen for his work on "Cold Dwell-Effect: Relationship Between microstructure, microtexture and Mechanical Properties of Titanium Alloy Ti6242" [11].

Last year, Cedrik Brozek was awarded the 2018 prize for his thesis entitled « Development and conception of new titanium alloys with high ductility and strong work hardening » [12]. Cedrik’s research was dedicated to the development and characterisation of new high deformation titanium alloys, combining TRIP (Transformation Induced Plasticity) and TWIP (Twinning Induced Plasticity) effects. He used a semi-empirical approach, combining theoretical calculations and experimental data, as a method for designing these new alloys. By setting the parameters of the simulation, it is possible to control the degree of stability of the β phase of titanium. This metallurgy, called combinatorial metallurgy, allowed Cedrik to propose three new grades of alloys, namely: Ti-8.5Cr-1.5Sn, Ti-8.5Cr-1.5Al, and Ti-10V-4Cr-1Al. It turns out that several deformation mechanisms are triggered to plastically accommodate the material during an external mechanical stress. Among these mechanisms are the {332} ⟨113⟩ twinning, the stress martensite, and the dislocation slip. Cedrik has shown that their synergy gives rise to two effects, a microstructural refinement effect called "dynamic Hall & Petch effect", and an effect comparable to the matrix-reinforcement interactions, called the "Composite effect". He then carried out a comparative ballistic test campaign with other titanium alloys, to analyse the behaviour to damage, closest to a potential industrial application. He demonstrated that alloys with the ability to be transformable by deformation are those with the highest toughness (KIC) and resilience (KCV). Going further, he finally studied the transposition of the design method to an industrial alloy where the transposition of the TRIP / TWIP effects is applied to α+β matrices. The other nominees for the 2018 award were Héloïse Vigié for her work entitled « Microstructural evolution and mechanical behaviour of the beta21S Alloy after Aging » [13] and Marie Fischer for her thesis « In situ titanium Alloy and Lattice structures processing by additive manufacturing: application to implantable medical devices » [14].

3. Research & development projects

Aero-engines

In the domain of aero-engines, the Orbital Friction Welding technique (OFW) has been intensively evaluated. In particular, developments have been carried out for the new-generation rotors for the low-pressure compressors (LPC), the « bladed drum » also designed as « BluM® » [15]. This lightweight component developed for the future boosters is inspired from the integrally machined disks (or blisks) commonly used in high pressure compressors, where the blades are generally machined out of the same piece of material as the disk, to form a one-piece rotor stage. In the current designs, the low-pressure compressor is usually based on a cylindrical drum comprising circular channels in which the blades are slotted. With the BluM, the basic drum shape, is kept and the blades are attached on it by using the orbital friction welding. The process, which is starting to be more widely used in aircraft engines, is compliant with all assembly requirements in particular accuracy and mechanical performance. By using this design concept, the weight saving is about 20%. After preliminary evaluation of the OFW at laboratory scale, an extensive campaign of welding has been carried out on hundreds of representative samples to check the accuracy and repeatability of the process. Soon after and thanks to very promising results, a full-scale prototype has been manufactured to check the overall production feasibility.

BluMs are currently being considered on next generation aircraft engines. In view of the rapid progress in developments and the good industrial prospects, investments have been made for an orbital friction welding machine for BluMs and an inertia friction welding machine for welding massive parts for fan disks.

Also related to friction welding, the Rapid DISTIR [16] project, funded in 2014, was aimed to analyse and model the behaviour of friction-welded structures under dynamic stress (high strain rate). The study made it possible, in particular, to produce prototypes for high-speed tests performed by assemblies of different matters combining titanium alloys, aluminium-lithium alloys or even heterogeneous assemblies of aluminium/steel. Still in the domain of the FSW, the Rapid IMPAACT [17] project funded in 2016 focused on the production of aeronautical parts implementing titanium assemblies with aluminium alloys 2169 and 6063 (heterogeneous assemblies), while the JOSEFA project [18] tackled the problem of making large sub-assemblies from parts made by Laser Beam Melting (LBM) and assembled together by FSW.

Thanks to previous generation experience and database analysis, a new titanium engine nozzle has been proposed to equip the B777X aircraft powered by two GE9X engines. The nacelle systems design and the manufacturing processes using metal materials have been optimized together with the development of the assessment methods of the performance of titanium components on the nozzles. The B777X titanium nozzles have the advantages of being lighter with a greater resistance to heat compared to previous designs. In addition, they will incorporate acoustic treatments, also of titanium, to reduce the noise footprint of the engine. In the past, the nacelle systems of the A380 jumbo jet were the first in the world to be equipped with an electrically-actuated thrust reverser, still considered as a technological reference. The airborne evaluations of the GE9X were performed beginning of 2018 on the GE Aviation's 747 flying testbed in the USA, with a test power plant installed on the left-hand wing's inboard engine pylon. After the success of the initial flight test and validation of the GE9X's key operational and functional characteristics, the subsequent qualification steps are currently in progress and expected to be finalised late 2019.

In the domain of *additive manufacturing*, feasibility developments for the manufacture of titanium engine parts or equipments have motivated the acquisition of Electron Beam Melting (EBM) or Selective Laser Melting (SLM) machines. Theseprocesses make parts such as a complex geometry oil tank or a hydraulic block accessible. The new development methods provide an ideal framework for conducting joint studies, so-called "co-innovation", between industrial partners. This is the case for example for the hydraulic block project for the A350 XWB aircraft called AMaLGaM (pour *Additively MAnufactured Landing GeAr single integrated Manifold*) [19]. The entry into service of this hydraulic block could be envisaged starting 2021. The principle of working in co-innovation illustrates the commitment of the major industrial groups to innovate not only at the technological level but also in the methods and organisation of work in the spirit of « Factory of the Future ». This concept is intended to be the framework for a new approach facilitating the introduction of disruptive technologies (virtual and augmented reality, collaborative robotics or « cobotics », additive manufacturing etc.), the revision of design and manufacturing methods with a view to improve competitiveness, greater respect for the environment and better performance.

In addition, developments are being carried out [20] to develop a titanium atomisation process in order to produce a powder for use in techniques by additive manufacturing. In 2017, a first powder production was carried out thanks to an experimental atomization equipment whose objective is to explore the parameters to optimize the production of metallic powders, in particular titanium and its alloys (TiAl, Ti-6Al-4V etc.). Aeronautics, Medical and Energy sectors are more specifically concerned by this means of production. Eventually, the intention is for France to be autonomous in the titanium industry, whereas today most of the raw material comes from abroad.

Intermetallic alloys with titanium aluminide are excellent candidates for aeronautical applications because they compromise mechanical properties/density higher than some commonly used nickel base alloys. This explains their recent introduction on the latest generations of turbo machines (LEAP, *Geared Turbofan or GTF*) for the production of blades for low-pressure turbines. This technological evolution is the result of an improvement in knowledge in this domain and the development of alloy grades dedicated to these applications.

Examples include industrial works [21] carried out with the aim of optimisation of g-titanium aluminide blade manufacturing in the perspective of the increase in the production rate of LEAP engines. History in the domain is old since the first developments date back to 1997 with the research for chemical compositions of alloys favouring ductility during the stages of isothermal forging. The first applications appeared starting in 2002 with the production in small series of a few thousand pieces in γ-TiAl for Formula 1 race cars. In 2006, R&D work resumed to explore more advanced manufacturing techniques of γ-TiAl blades with the aim of identifying compatible processes for mass production at more competitive prices such as the Precision ElectroChemical Machining (PECM). In 2012, process development began for LEAP γ-TiAl blades including the work on the casting, the machining, the grinding, the coating and the Non Destructive Testing of the final parts. The culmination of these years of investment came in 2014 with the beginning of the serial production demonstration of the blades. Depending on the current state of the art of the process used, the blade is drawn from a rod manufactured by a loss wax centrifugal casting process combined with a skull melting or a Plasma Arc Melting (PAM). The shape of the rod has the great advantage of a simple geometry to cast whose dimensions allow the head-spade entanglement of two blades which are then separated by 3D cutting to optimise waste of material and cut off recycling. The machining involves the most advanced equipment, cutting tools and programming. The production line is fully integrated and automated, running 24/7. Thanks to this mastery of the entire production process, the buy-to-fly ratio is very similar to Near Net Shape NNS casting with a significant material cost optimisation with a scrap rate after machining lower than 1%. Thanks to this, the current process is deemed to be the most competitive manufacturing route of g-TiAl blades compared with NNS or EBM additive. Production has gradually increased from 50,000 blades in 2017 to 100,000 in 2018 and is expected to reach 150,000 blades in 2019. The mass production target is 200,000 blades/year.

Aero-structures

The ANR DUSTI project (2014 – 2017) [22] looked at the extension of the field of use of titanium alloys such as Ti-17, Ti-6Al-4V and Ti 6-2-4-2 in structural parts of the aircraft subjected to temperatures impacted by the proximity of the engines.

Because the requirements on performance are continuously growing, the new generation engines are showing higher by-pass ratios. This impacts the pylon directly because, as a consequence, with the increase of the external diameter of the nacelle, the space between the engine and the wing is getting smaller and the pylon is exposed potentially to higher in service temperature. Also, the design of pylons thus evolve to a greater compactness and thus, by combination, it is expected to better investigate the behavior of the titanium alloys (in this case Ti-6Al-4V) with regard to oxidation, ageing and mechanical properties in temperature. On the other hand, the objective of mass reduction for the future pylons pushes the designers to replace the nickel alloy used today by a titanium alloy. First, the gain in density is about 50% and second, the titanium is presenting good mechanical properties at ambient and elevated temperature. The same challenges of mass reduction and rise of the operating temperatures are encountered by the air systems that is transforming the air taken at compressing stages of the engines to a fresh air to the passengers. Thus the use of light materials offering of high temperature resistance becomes essential. Titanium alloys are expected to be the best candidates for these applications by their low density and their heat resistance. The DUSTI project was aiming to have a better understanding of metallurgical phenomena which act in the studied titanium alloys related to the environment and in service solicitation: 1°) oxidation and link with fatigue properties, 2°) metallurgical mechanisms of ageing in titanium alloys and induced amendments of the oxidation kinetic and mechanical properties, 3°) damage mechanisms in titanium alloys in temperature, 4°) fatigue crack propagation behavior of titanium alloys at high temperature, in link with the environment.

The theme of the ANR SATISFLAIRE [23] project, which ended in 2016, was the development of linear friction-welded (LFW) titanium parts in aeronautical applications such as seat track. The project qualified the process after having completed all the steps leading up to the full-scale demonstrators. Combinations of technologies and assemblies are also validated such as linear friction welds on more or less complex extruded geometry parts to form brackets from L profiles, or T-clips. At the end of the process, the parts undergo a final machining. This work has resulted in the industrialisation of parts in aircraft with significant cost savings compared to conventional methods of production and finishing less efficient in terms of buy-to-fly.

On a related theme, the OPTIMUM project [24] (2014 – 2018) aimed at the experimental and numerical study of metal assemblies made by LFW by linking the development process, the consequences on microstructural developments and use properties, in particular with regard to the prediction of the lifespan of the assemblies. The material choice was on the new grades of metal alloys and on the assembly of bi-materials. Innovative and multi-scale characterisation techniques were used to analyse the effects of process parameters on the evolution of microstructures in the welding area (i.e. ability to interpret the mechanisms at the origin of the different observed zones of the microstructure). A numerical simulation tool by finished elements of the linear friction welding process taking into account the different phases involved in the realisation of the assembly and validated by extensive confrontations with data experimental results from process instrumentation, was developed to examine variations in thermal, kinematic and stress fields during welding. The numerical modelling of the process has contributed to the interpretation of the physical phenomena involved at the origin of the microstructural evolutions (e.g. temperature level reached and microstructural transformation, stress fields and microstructure refining mechanisms). In the first part of the study, assemblies with different pairs of titanium- or nickel-based materials were made. Tests were then carried out for various process parameters (pressure, frequency and amplitude of oscillations) for the following configurations: square butt, lap joint and multiple lap joints. The joints were subjected to physico-chemical and microstructural analysis in the welding zone supplemented by residual stress measurements and nano-hardeness instrumented measurements. Subsequently, the study focused on the development of a thermomechanical simulation tool of the LFW process in combination with the Forge® code. Experimental and numerical data confrontations such as thermal gradient space, welded joint geometry (e.g. size and geometry of the burrs), the material consumption (i.e. reduction of the size of the material plots after assembly) made it possible to judge the quality of the digital tool developed. This tool was subsequently used to assist in the interpretation of the observed experimental microstructural evolutions (local mechanical fields, cooling time, etc.). The last part of the study was dedicated to the durability of the welded joints through the use of non-destructive experimental methods such as the tomography, laminography for analysis of possible defects induced by the process (e.g. porosity). In situ damage evolution and crack propagation tests using sequential or in situ mechanical tests under synchrotron beam were carried out.

In the domain of the production of high temperature titanium parts, work has been carried out to combine the hot forming (HF) with the superplastic forming (SPF) in order to finalise the areas of great deformation on parts with strong deflection [25]. This has enabled the development of forming matrices and metal processes to produce complex parts more quickly at a more competitive cost. For example, the titanium sheets used are thinner and the HF/SPF hybrid process is more repeatable. Two significant advances have also resulted from the reduction of material. Firstly, an improvement in the final quality of the parts, the thickness of the plates is more homogeneous and has a better surface condition. Secondly, the production cycle time is reduced. Finally, the development of this new process made it possible to work with a reduced forming temperature, which has a direct impact on energy consumption. The project allowed us to develop a part on scale 1 and a complementary capability study was carried out on about 30 parts. The good results of the project have led to two other projects allowing further development on this type of process: SITCOM (which focuses on the development of a numerical simulation tool to predict thermomechanical damage to high temperature forming tools) and LIPSKIN (development of innovative processes for the hot and cold metal forming of an aluminium alloy for the realisation of a leading edge section of an engine air inlet).

Also worth noting is the further development of an SPF formatting method using ultra-fast infrared (IR) heating of titanium sheets in the RAPID FASTE and FASTE 2 projects [26]. The main advantages of the process are to extend the complexity of the shapes of the parts made by a superplastic forming approach, to reduce the cost of manufacturing the parts and to drastically improve the manufacturing efficiency. The main innovations are in the process and design of the SPF press: innovative design of heating moulds based on refractory concrete (with silicon carbide), self-heating moulds and IR heating. This innovative approach leads to forming of parts in mass by IR method with greater dimensions to the m² and advanced geometries. In addition, work has been carried out on a fairly complex range of industrialisation leading to the forming of a sheet with previously rolled stiffeners. A scale 1 prototype has been developed for an application in the spatial domain.

Technological focus on the cryogenic machining

The Dry to Fly project [27] is a research & development project for structural competitiveness (PSPC - Projet de Recherche & Développement structurant pour la compétitivité) initiated in 2015 and funded under the Future Investments Programme (PIA – Programme Investissements d'Avenir). This industrial project has had the objective of reducing the production costs of large parts by more than 30%, mainly in the sectors of aeronautics, space, energy (nuclear, wind, oil...) and transport (railway, maritime-naval...). To this end, it explores three ways: a preparation of the material by an innovative 3D cutting system, new machining strategies with a suppression of Computer-Aided Manufacturing (CAM), replaced by algorithms layer-by-layer manufacturing (solid/solid additive manufacturing process) combined with an adaptive steering and cryogenic machining support. And it is in this area that the project has advanced the most, with the realisation of three cryogenic-assisted milling demonstrators. Cryogenic assistance consists of avoiding overheating by cooling the part and the tool as close as possible to the cutting zone with liquid nitrogen at -196°C. This technique targets materials with high mechanical characteristics, generally used for parts that are often complex and subject to heavy loads, and that are known to be difficult to manufacture.

The low thermal conductivity and high specific cutting coefficient make Ti-6Al-4 an excellent application case. The technological development was particularly challenging in the case of milling where the nitrogen must circulate in the cutting tool, and thus inside the spindle, and arrive in a liquid state at the end of the tool. As soon as liquid nitrogen comes into contact with the tool, it vaporizes instantly, with perfect reliability, allowing to capture the calories generated by the cut. The work achieved very interesting results with almost doubling the cutting speed and flow rate compared to conventional machining. Moreover, the integrity of the surface of the part is respected and the tolerances are compliant with the expected requirements. At the beginning of 2019, the Cryogenic machining of the Ti-6Al-4V is, as a result, switched to standard production on a part of the LEAP engine and the project partners mobilized to organize a «French cryo cut network» bringing together actors in the field whose vocation is to promote technology and develop its employment.

Medical

Developments in the medical field have resulted from work carried out on nano-structured advanced materials. In particular, two nano-structures titanium powders enriched with 1% nano zirconia were developed to meet the specific needs of prosthetic alloys shaped by additive manufacturing [28]. For instance, the ZTi-Powder® is claimed to be an enhanced Ti-6Al-4V power, especially developed for additive powder bed Selective Laser Melting (SLM) and being up to 50% harder and more resistant. Its main characteristics is an ultimate compressive strength of 1482 MPa, a compressive yield strength of 1100 MPa, an ultimate tensile strength of 1035 MPa and micro hardness of 441 HV. The other form of product, the ZTi-Med®, is made up of nano-structured titanium and zirconia that has been developed specifically for implant applications. It has been designed with the objective to solve the stress shielding effect in medical implants, having an elastic modulus of 35 GPa. It has an ultimate compressive strength of 1030 MPa, a compressive yield strength of 630 MPa and an ultimate tensile strength of 950 MPa. It can be applied as a coating on orthopaedic implants and provide non-toxic protection.

Industrial applications

In the industrial sector, France is the market leader for welded tubes for heat exchangers. In nuclear power plants, the welded tubes are used in condensers, high-pressure and low-pressure feedwater heaters and moisture separator reheaters. The criticality of the applications requires perfect mastery of the technical requirements and permanent quality control over the entire production line.

Developments have been made to significantly increase heat exchange in titanium tubes in order to improve condenser performance. A new design of tube (named Helix® [29]) was proposed after intensive research developments and trials with the objective to maximize heat transfer performance during condensation in steam surface condenser and minimize the pressure drop generated by the turbulences. The Helix design concept is involving a helical pattern along the tube which is obtained thanks to a longitudinal cold deformation. This pattern generates turbulences within the fluid, reduces boundary layer thermal resistance and therefore increases the overall heat transfer performance of the tube. At the end, the heat transfer performance is claimed to reach up to +40% versus the conventional smooth tube design. Other research is underway such as the thesis on the study of the impact of hydrogen on the behaviour of titanium alloys welded tubes [30]. Due to its very small atomic size, hydrogen can easily find its way into the interstitial sites in the crystal lattice of titanium. When the hydrogen content dissolved inside the crystalline lattice is sufficient, it can be combined with the metal to form hydrides. It generates a weakening of the titanium matrix and leads to embrittlement of the tube and by consequence the component integrity. The thesis is aiming to identify, for each step of the manufacturing process, the sources of hydrogen absorption and propose modification of the manufacturing processes in order to reduce its content in the material.

Naval

In the naval field, research and development work has been carried out with the aim of identifying ways of improving the tribological behaviour of titanium. This work has been cited previously in the section dedicated to the Thesis Prize 2017 of the titanium association [9]. For the naval industry, this work has led to an improvement in the tribological behaviour of titanium alloys treated by Micro-Arc Oxydation (MAO). In particular, there was a significant reduction in the coefficient of friction of approximately 2 after treatment on a Ti-6Al-4V alloy. In addition, this improvement in contact conditions, in both linear and circular friction conditions, is accompanied by an extension of tribological behaviour by a factor of 5. The validation of the gain in performance could be various experiments carried out on friction test setup to simulate the behaviour of crank link systems immersed in a boat transmission shaft. The seizure of the parts in bearing – axis contact, classically observed on untreated titanium, was thus avoided due to the treatment.

Also, additive manufacturing techniques are used in the naval field to produce parts of complex geometry and occupying an optimized volume. This need for compactness is proven not only for applications in ships but also for equipment used in Marine Renewable Energies, in particular, the Ocean Thermal Conversion. Other studies are carried out to replace conventional techniques like foundry for the manufacturing of parts such as hydraulic distributors or heat exchangers. In all cases it is the Ti-6Al-4V alloy that is used and power additive manufacturing techniques such as Selective Laser Melting® (SLM).

Titanium subjects in the naval field also concern the replacement of Stainless steel 304L and 316L with Ti-6Al-4V or CP titanium for nuclear boilers in warships. In particular, the ANR TESANI project deals with the study of the effects of irradiation on microstructure and the consequences on mechanical performance. Titanium and its alloys are particularly interesting in irradiated environments (primary and secondary circuits) because they do not activate very much, which facilitates dismantling and maintenance. In addition, their low density is an advantage vis-à-vis seismic behaviour (lower inertia). The phenomenon of titanium embrittlement by delayed hydride cracking is in particular studied for titanium steam generators.

.

Titanium is used in many parts refrigerant/seawater exchanger, secondary circuits, flat tubes, tubes, seawater pumps and filters. The trend is to replace forging parts and machined parts by casting parts and, as presented before, by additive manufacturing methods. Recently, proof of concept of propeller blades made by superplastic forming and diffusion bonding have been produced at a reduced scale (one metre in span). These tests are promising; they open up new perspectives for the use of titanium in naval applications.

4. Conclusion

Titanium is a material of choice, in some cases, indispensable to the industry. The research, study and development topics discussed in this paper reveal only a small part of the considerable efforts made by our researchers, engineers and technicians to promote the use of this material in our everyday life. I would like to take this opportunity to apologize to those whom I was unable to quote in my presentation.

The French titanium community is endowed with an association that does excellent work in the animation and cohesion of the industrial and academic networks. I encourage all stakeholders, especially the industries, to join in order to support its action and finance its initiatives. Like any association, the main wealth is that of the contribution of its members, so you are very welcome!

The French titanium industry is characterized by a strong predominance of application-based industrial activities supported by a large multidisciplinary academic community. The means of production are relatively limited compared to large producing countries such as the USA, Japan, Russia, China… In recent years, industrial initiatives, supported by the government, have enabled alternative production lines to emerge in France, which are not only profitable for the European Community but also beneficial for the diversity of the worldwide supply. The development of new technologies for additive manufacturing is, of course, opening up new avenues for the use of titanium, but traditional industries are still essential for most of our needs. France intends to be the driving force behind a coordination of European interests in the field. A recent example of this is the opening in September 2017 of EcoTitanium®[31], the first European plant for the development of aeronautical grade titanium alloys by recycling. This plant is already beginning to produce titanium ingots from scrap collected from major aircraft manufacturers and their subcontractors.

References

[1] P.-F. Louvigné, *Etude de veille sur le marché du titane 2015-2017*, Market Survey Report, MTES/DGALN, 2017, 149p. (http://www.mineralinfo.fr/sites/default/files/upload/documents/louvigne_titane_rapport_2015-2017_edition_publique.pdf)

[2] http://www.mineralinfo.fr/page/comite-metaux-strategiques

[3] D. Depriester, *Caractérisation et modélisation du procédé de fluotournage inverse à froid du TA6V*, Ecole Nationale Supérieure des Mines de Paris, in French, 2014, 209 p. (https://pastel.archives-ouvertes.fr/tel-01132501).

[4] F. Grange, *Experimental and numerical investigations of mass finishing processes on titanium Ti17*, Ecole national d'ingénieurs de Saint Etienne, in French, 2014. (https://pastel.archives-ouvertes.fr/tel-01127403/document)

[5] D. Prat, *Development and modelling of finish milling strategies in 5 axis - Application in the machining of closed veins*, 2014, 213p. (https://pastel.archives-ouvertes.fr/tel-01127403/document)

[6] C. T. Sultan, *Abrasive waterjet milling of hard metals*, INSA de Toulouse, 2015, 174 p. (https://tel.archives-ouvertes.fr/tel-01244408)

[7] E. Lebrun, *Microstructures et transformations de phases dans l'alliage quasi-beta T18 pour applications aéronautique*, Ecole nationale supérieure des mines de Paris, 2015.

[8] M. Salib, *Kinetics and crystallographic study of the a phase precipitation at β/β grains boundaries in a titanium alloy*, Université de Lorraine, 2015, 205p. (http://docnum.univ-lorraine.fr/public/DDOC_T_2015_0042_SALIB.pdf)

[9] A. Mathis, *Anodizing of titanium by micro-arc oxidation (MAO)*, Université de Lorraine, 2016.

[10] V. Duquesnes, *De l'hydruration du titane et ses alliages : impact des paramètres de mise en forme du matériau et conséquences sur sa durabilité en milieu corrosif*, Université de Bourgogne Franche-Comté , 2016, 185p. (https://nuxeo.u-bourgogne.fr/nuxeo/site/esupversions/778bf86d-368f-47ca-b7e8-1800cc1974ae)

[11] I. Freiherr Von Thugen, *Cold Dwell-Effect : Relationship Between Microstructure, Microtexture and Mechanical Properties of Titanium Alloy Ti6242*, Ecole nationale supérieure de mécanique et d'aérotechnique, 2016, 312p. (https://tel.archives-ouvertes.fr/tel-01486574)

[12] Cédrik Brobek, *Development and conception of new titanium alloys with high ductility and strong work hardening*, Ecole nationale supérieure de chimie de Paris, 2017, 243 p. (https://tel.archives-ouvertes.fr/tel-01786115)

[13] Héloïse Vigié, *Microstructural evolution and mechanical behaviour of titane beta21S Alloy after Aging*, Toulouse INTP, 2017.

[14] Marie Fischer, *In situ titanium Alloy and Lattice structures processing by additive manufacturing: application to implantable medical devices*, Université de Lorraine, 2017, 191p. (http://docnum.univ-lorraine.fr/public/DDOC_T_2017_0257_FISCHER.pdf)

[15] Safran Aero Boosters

[16] Rapid DISTIR, TRA-C Industrie, 2014.

[17] Rapid IMPAACT, AVANTIS Concept, 2016.

[18] Rapid JOSEFA, TRA-C Industrie, 2017.

[19] Additively MAnufactured Landing GeAr single integrated Manifold, an Airbus/Safran Landing Systems co-innovation project

[20] Metafensch

[21] Mecachrome

[22] ANR DUSTI, partners: Airbus, Liehbeer, Aubert &Duval, Institut Jean Lamour, CIRIMAT and P' Institute, 2014 – 2017.

[23] ANR SATISFLAIRE, partners: IRT Jules Vernes, Airbus and ACB 2012 – 2016.

[24] ANR OPTIMUM, partners: Armines, Airbus, ACB

[25] Project IRT Jules Vernes in partnership with ACB and Airbus, 2018.

[26] Rapid FASTE and FASTE 2, leader: Aurock

[27] PSPC Dry to fly, BPI funding, partners: Mecachrome (leader) with Cetim, Evatec Tools, Inori, Missler Software and MPM (Groupe Meyer France, 2015 – 2019.

[28] Z3DLab

[29] Neotiss

[30] La Chance Lepemangoye, *Impact of hydrogen on the behavior of titanium alloys welded tubes*, Université de Bourgogne, thesis in progress.

[31] UKAD, a joint-venture between Aubert&Duval and UKTMP.