Fatigue life of high strength aerospace materials: influence of residual stresses and work-hardening induced by surface treatments

PhD at University of Technology of Troyes, supervised by Prof. Manuel FRANCOIS and Dr. Pascale KANOUTE

1. Aim of the PhD work

The safety and life expectancy of aircrafts or spacecrafts relies on very advanced knowledge of the effect of manufacturing processes on the microstructural and mechanical state of materials. Among the critical factors that are identified, residual stresses and work-hardening play a major role. Unfortunately, to the present date, no systematic procedure exists to take them into account in the design process of highly loaded components. During the past decade, UTT has performed intensive research in this field through academic work or industrial cooperation with automotive, aerospace or nuclear industries.

The aim of the proposed research work is to define a consistent initial state for fatigue life assessments based on process characterization by e.g. X-ray diffraction or instrumented nano-indentation. The goal is to bridge the gap between experiments and numerical modelling through the construction of a model that takes into account all the physical phenomena affecting the fatigue life. This implies mechanisms occurring in both the manufacturing and the cycling service loadings and at different scales (nanoscale, microscale and macroscopic scale). To ensure relevant assessment the evolution of the mechanical state of the material during the fatigue loading needs to be also investigated. This work will include both experimental and modelling work from the PhD student.

2. Scientific, technological and economic context

The ability to estimate the lifetime to crack initiation of mechanically loaded components is a recurrent problem for high technology industry (automotive, aerospace, electronics, power production…). It is necessary not only to guarantee fail safe operation for the customer but also to optimize design and life cycle of the component or of the system in which it is embedded. One of the most commonly used processes to increase the life of a part is shot-peening because it induces a compressive stress state (prestress) at the surface and slows down the development of micro-defects leading to crack initiation. If the process itself is well known, significant research work still has to be done to obtain quantitative predictions and above all, the relation with life duration remains largely empirical and requires long and costly characterization and test campaigns. Because of this and of the lack of design tools,

the shot-peening process is seldom taken into account during the design of mechanical system and remains a simple mean to increase qualitatively safety margins.

Shot-peening is a costly process and the lack of design tools that enable to relate process parameters to fatigue behavior hinders its diffusion towards new industrial applications. One of the goals of LASMIS team of Charles Delaunay Institute is to develop an integrated procedure to include fatigue requirements during the design process, taking into account the material, the manufacturing process, the geometry of the component, the loading conditions and fatigue calculations. The PhD work proposed will enable significant progress in this direction in particular by questioning in depth the procedure as a whole. Scientific and technological gaps will be highlighted and answers can be proposed.

3. Detailed description of the research project

The initial state introduced at the surface of the material by the shot-peening process involves 3 aspects:

- Residual stresses
- Work-hardening
- Microgeometry (roughness)

The latter will be characterized but not specific development will be made during the PhD. The two first constitute the core of the encountered scientific problem. The residual stress state can be obtained by a variety of methods such as X-ray diffraction or the hole drilling method, however the quantitative estimation of work-hardening is still an open problem. At LASMIS team, diffraction peak width and instrumented nano-indentation have already been used successfully for specific cases but these techniques still lack the desired degree of generality and their physical interpretation is not completely clear. Furthermore, instrumented indentation is sensitive to both residual stresses and work-hardening and it is still difficult to separate both contributions for practical use.

The shot-peening treatment introduces an initial mechanical state that will then evolve during the fatigue loading and influence the mechanical stress-strain response of the material. The influence of residual stresses is well documented in the literature but the role of work-hardening and the coupling of the two phenomena are still not completely understood. The corresponding modelling tools to consider future optimization of the shot-peening process on specific industrial parts has also to be developed.

The PhD work will thus be divided in two objectives:

- Improve and test the instrumented indentation technique to characterize prestressed surfaces.
- Understand and model the coupled role of residual stresses and work-hardening on the cyclic behavior of the material for different initial mechanical states.

These two objectives will be reached through the use of indentation tests, X-ray diffraction measurements, constitutive behavior modelling and finite elements modelling. Although the

methodologies developed in the PhD must be generic and apply to many metallic alloys, aerospace titanium alloys such as two phases Ti-18 alloy and Ti6Al4V alloy will be used in the experiments.

4. Work environment

The University of Technology of Troyes (UTT):

UTT is a French institution of higher education established in 1994. It is today one of the largest engineering schools in France. Over 2,700 students are registered at the University, enrolled on undergraduate, postgraduate and doctoral study programs. In the renowned yearly ranking of French magazines UTT takes enviable positions. More detailed information is available on http://www.utt.fr/en/about-utt.html.

The LASMIS research team:

The LASMIS research team (about 60 researchers) is part of Charles Delaunay Institute which is associated to CNRS (the French National Center for Scientific Research, equivalent to the Chinese Academy of Science).

The LASMIS team has a significant experience in the field of shot-peening, of residual stresses modelling, of residual stresses measurements, of nano-indentation and of advanced modeling of the cyclic behavior of materials. During the last 10 years, it is one of the teams that publish the highest number of scientific papers in the field of shot-peening world wide and possesses a recognized know-how in the field of residual stresses (see figure 1). Our team cooperates with industrial partners such as Renault, Peugeot SA, Cisson-Lehman (Wheelabrator), Allevard-Rejna, Ultra-RS, SNECMA or Turbomeca (Safran Group) and academic partners such as University Paris 6, Shanghai JiaoTong University, Dortmund Technical University or AGH University of Krakow (Poland).

As can be seen in Table 1, the University of Technology of Troyes (LASMIS group) is one of the world leading groups in the field of shot-peening.

The international recognition of UTT in the field of shot-peening and residual stresses is shown through the organization by UTT of the 9th European Conference on Residual Stresses in 2014 (Chairman Prof. Manuel François) with 268 participants from all over the world (http://ecrs9.utt.fr/).

Field: Organizations-Enhanced	Record Count	% of 1866	Bar Chart
UNITED STATES DEPARTMENT OF DEFENSE	64	3.430 %	
SHANGHAI JIAO TONG UNIVERSITY	62	3.323 %	
UNITED STATES AIR FORCE	54	2.894 %	
POLYTECHNIC UNIVERSITY OF MILAN	51	2.733 %	
US AIR FORCE RESEARCH LABORATORY	47	2.519 %	
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	46	2.465 %	
UNIVERSITY OF TECHNOLOGY OF TROYES	44	2.358 %	
CHINESE ACADEMY OF SCIENCES	40	2.144 %	
BEIJING INSTITUTE OF AERONAUTICAL MATERIAL	30	1.608 %	

Table 1: number of papers published between 2000 and 2016 according to ISI Web of Science with the keyword "shot-peening". UTT ranks at #7 with 44 papers among other prestigious institutions. The total number of published papers in this period and indexed in ISI Web of Science is 1866. It should be noted that CNRS (rank 6) and the Chinese Academy of Sciences (rank 8) are not really laboratories but groups of laboratories.

Available equipment:

- 4 circles X-ray diffractometer for residual stresses analysis
- Instrumented nano-indentation system
- Shot peening equipment (ultrasonic or air jet).
- Finite Element codes (ABAQUS, Z-Set).
- Every PhD student shares an office with other PhD students. A personal desk is proposed to each PhD student along with a personal computer and full personal access to the internet and bibliographic data bases.

PhD supervisors

The PhD work will be supervised jointly by Professor Manuel François and Dr Pascale Kanouté. They have co-supervised two PhD works together: Dr Yugang Li (defense in 2015), sponsored by a CSC grant and Dr Amélie Morançais (defense in 2016), sponsored by Safran Company.

Prof. Manuel François, 55, obtained a Master of Engineering from Arts et Métiers ParisTech in 1985, a Master of Science in Metallurgy from University Paris 6 in 1987. He defended his PhD in Arts et Métiers ParisTech in June 1991. After being Associate Professor in University of Nantes from 1993 to 2000, he became full Professor in UTT in 2000 (promoted exceptional class in 2011).He lived one year in China to teach French language. He has supervised 18 PhD students and has been involved in 11 others PhD theses. He has published about 235 papers among which 80 in rank A international journals. He has been Dean of the Mechanical Engineering Department of UTT,

Development Manager of UTT, member of the Executive Board of UTT and director of the LASMIS research laboratory (51 people, including 21 faculty)

Dr. Pascale Kanouté, 45, obtained a Master of Science in Solid Mechanics from University Paris 6 in 1995. She obtained a PhD of University Paris 6 at CERN (Switzerland) in 1999. Just after, she has joined ONERA where she has been working since in the Metallic Materials and Structures Department. Her main research topics are non-linear and multiscale modeling, fatigue-creep interaction and lifetime assessment. Since 2010, she is also a part-time associate professor at the Université de Technologie de Troyes. In 2013, she has become the head of the Behavior and Damage Mechanics research unit at ONERA (11 people and around 5 PhD students).

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The applicant should send his/her detailed CV, a motivation letter, a list of references, a copy of grades sheets and two recommendation letters. Before the final decision, some of the applicants will be interviewed through Skype (or equivalent system).

5. Publications in the last 10 years

Our publications restricted to the field of shot-peening, residual stresses, titanium alloys, fatigue, constitutive behavior and instrumented indentation

5.1. Prof. Manuel François

1. Fréour S., Gloaguen D., **François M.,** Guillén R., Application of inverse models and XRD analysis to the determination of Ti17 β-phase coefficients of thermal expansion, Scripta Materialia 54 (2006) 1475-1478.
2. Ould C., Rouhaud E., **François M.,** Chaboche J.L., A kinematic hardening finite elements model to evaluate residual stresses in shot-peened parts, local measurements by X-ray diffraction, Materials Science Forum, vol 524-525 (2006) 161-166
3. Micoulaut M., Mechkov S., Retraint D., Viot P., **François M.,** Granular Gases in mechanical engineering : on the origin of heterogeneous ultrasonic shot-peening, Granular Matter, 9(2007) 25-33
4. Guelorget B., **François M.,** Lu J., Microindentation as a local damage measurement technique, Materials Letter, 61 (2007) 34-36
5. Guelorget B., **François M.,** Liu C., Lu J., Extracting the plastic properties of metal materials from microindentation tests: experimental comparison of recently published methods, J. Mater. Res., vol 22, n°6, 2007, 1512-1519.
6. Ferreira C., **François M.,** Guillén R., Round robin test for X-ray stress analysis standards: Optimisation for discrepancy reduction, Journal of Strain Analysis for Engineering Design, 43, 1, 2008, 67-74
7. Rouquette S., Rouhaud E., **François M.,** Roos A., Chaboche J.L., Coupled thermomechanical simulations of the shot peening process, effects of temperature on the residual stress field, J. of Materials Processing Technology, 209, 8, 2009, 3879-3886
8. Baczmanski A., Hfaiedh N., **François M.,** Wierzbanowski K., Plastic incompatibility stresses and stored elastic energy in plastically deformed copper, Materials Science and Engineering A501 (2009) 153-165
9. Palma J., Rivero R., Lira I., **François M.,** Measurement of the residual stress tensor on the surface of a specimen by layer removal and interferometry, Measurement Science and Technology, 20, 2009, 1-10
10. Van Wijk S., **François M.,** Sura E., retained austenite and residual stress evolution in carbonitrided

shot-peened steel, Materials Science Forum, vol 681 (2011)374-380
11. Cellard C., Retraint D., **Francois M.,** Rouhaud E., Le Saunier D., Laser shock peening of Ti17 titanium alloy: Influence of process parameters, Materials Science and Engineering A 532 (2012) 362– 372
12. Celentano D., Guelorget B., **François M.,** Saanouni K., Cruchaga M.A., Numerical simulation and experimental validation of the microindentation test applied to bulk elastoplastic materials, Modelling Simul. Mater. Sci. Eng., 20 (2012) 1-32.
13. Raceanu L., Optasanu V., Montesin T., Montay G., **François M.,** Shot-Peening of Pre-Oxidized Plates of Zirconium: Influence of Residual Stress on Oxidation, Oxidation of Metals, 79 (1-2), 2013, 135-145
14. Badreddine J., Micoulaut M., Rouhaud E., Remy S., Retraint D., **François M.,** Effect of the confinement on the properties of ultrasonic vibrated granular gases, Granular Matter 15 (2013) 367-373
15. Morancais A., Fevre, M., **Kanouté, P.,** Kruch S., **Francois M.**, Impact of residual stresses on the fatigue behavior of a Nickel-based superalloy, Materials Science Forum, 2014.
16. Morançais A., Fèvre M., **Kanouté P., François M.,** Longuet A., Impact of shot-peening on a single crystal nickel-based superalloy, Advanced Materials Research Vol. 996 (2014) 70-75
17. Li Y., **Kanouté P., François M.,** Characterization of residual stresses and accumulated plastic strain induced by shot peening through simulation of instrumented indentation, Advanced Materials Research Vol. 996 (2014) 367-372
18. Lefebvre F., Wasniewski E., **Francois M**., Cacot J., Le-bec P., Baumhauer E., Bouscaud D., Bergey T., Blaize D., Gloaguen D., Cosson A., Jegou S., Cheynet Y., Leray S., Meheux M., Monvoisin J.C., Allain P., Vidal J.C., Sprauel J.M., Goudeau P., Charles C., Daflon L., Fischer C., Desmas L., Ouakka A., Moya M.J., Bordiec Y., Hamdi H., External reference samples for residual stress analysis by X-ray diffraction, Advanced Materials Research Vol. 996 (2014) 221-227.
19. Li Y., **Kanouté P., François M.,** Disturbance induced by surface preparation on instrumented indentation test, Materials Science and Engineering A, 642 (2015) 381-390
20. Morançais A., Fèvre M., **François M., Kanouté P**., Kruch S., Longuet A., Residual stress determination in a shot-peened nickel-based single crystal superalloy using X-ray diffraction, J. Appl. Cryst. (2015). 48, 1761–1776
21. Menan F., Adragna P-A., **François M.,** The Stress-Strength Interference Method Applied to Fatigue Design: the Independence of the Random Variables, Procedia Engineering 133 (2015) 746 – 757

21.1. Dr Pascale Kanouté

1. Kaminski M., **Kanoute P.**, Kruch S., Busso E., Chaboche J.L., A high temperature fatigue damage model for single crystal superalloys, A high temperature fatigue damage model for single crystal superalloys, Materials at high temperature, vol 33, Issue 4-5: High temperature materials for aerospace materials, 2016.
2. Morancais A., Fèvre M., **Francois M.**, Guel N., Kruch S., **Kanoute P.**, Longuet A, Residual stress determination in a shot-peened nickel-based single-crystal superalloy using X-ray diffraction, Journal of Applied Crystallography, 48, 2015, 1761-1776.
3. Li Y., Kanoute P., Francois M., Disturbance induced by surface preparation on instrumented indentation test, Materials Science & Engineering A, Vol 642, 26, 2015, 381-390.
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5. Morancais A., Fèvre M., **Kanoute P.**, Kruch S., François M., Longuet A., Impact of shot-peening on a single crystal nickel-based superalloy, Advanced Materials Research, Vol. 996, 2014, 70-75.
6. Li YG., **Kanouté P., Francois M.,** Characterization of residual stresses and accumulated plastic strain induced by shot peening through simulation of instrumented indentation, Advanced Materials Research, 2014
7. Sun, Z., Chemkhi, M., **Kanouté, P.** Retraint D., Fatigue properties of a biomedical 316L steel processed by surface mechanical attrition, IOP Conference Series-Materials Science and Engineering, 2014
8. Morancais A., Fevre, M., **Kanouté, P.,** Kruch S., **Francois M.**, Impact of residual stresses on the fatigue behavior of a Nickel-based superalloy, Materials Science Forum, 2014
9. Chaboche J.-L., Gaubert A., **Kanouté P**., Longuet A., Azzouz F., Mazière M., Viscoplastic constitutive equations of combustion chamber materials including cyclic hardening and dynamic strain aging, International Journal of Plasticity, 46, 2013, 1-22.
10. Chaboche J.-L., **Kanouté P.,** Azzouz F., Cyclic Inelastic constitutive equations and their impact on the fatigue life predictions, International Journal of Plasticity, vol 35, 2012, 44-66.

11. Boittin G., Locq D., Raffray A., Caron P., **Kanouté P.,** Gallerneau F., Cailletaud G., Influence of □' precipitate size and distribution on LCF behavior of a PM disk superalloy, Superalloys 2012, Pennsylvania, 2012.
12. Bonnand V., Chaboche J.-L., Gomez P., **Kanouté P**., Pacou D., Investigation of multiaxial fatigue in the context of turbine disc applications, International Journal of Fatigue, vol 33, Issue 8, 2011, 1006-1016.
13. Chaboche JL., **Kanouté P.,** Azzouz F., A Robust Cyclic Elastoplastic Constitutive Framework for Fatigue Life Analysis, Advances in heterogeneous materials 2011
14. **Kanouté P.,** Leroy F.H., Passilly B., Mechanical Characterization of thermal barrier coatings using a micro-indentation instrumented technique, Key engineering materials, 2007
15. Passilly B., **Kanouté P**., Leroy F.H., Mevrel R., High temperature instrumented micro indentation: applications to thermal barrier coating constituent materials, Philosophical Magazine A, 2006, 86 (33), 5739-5752.