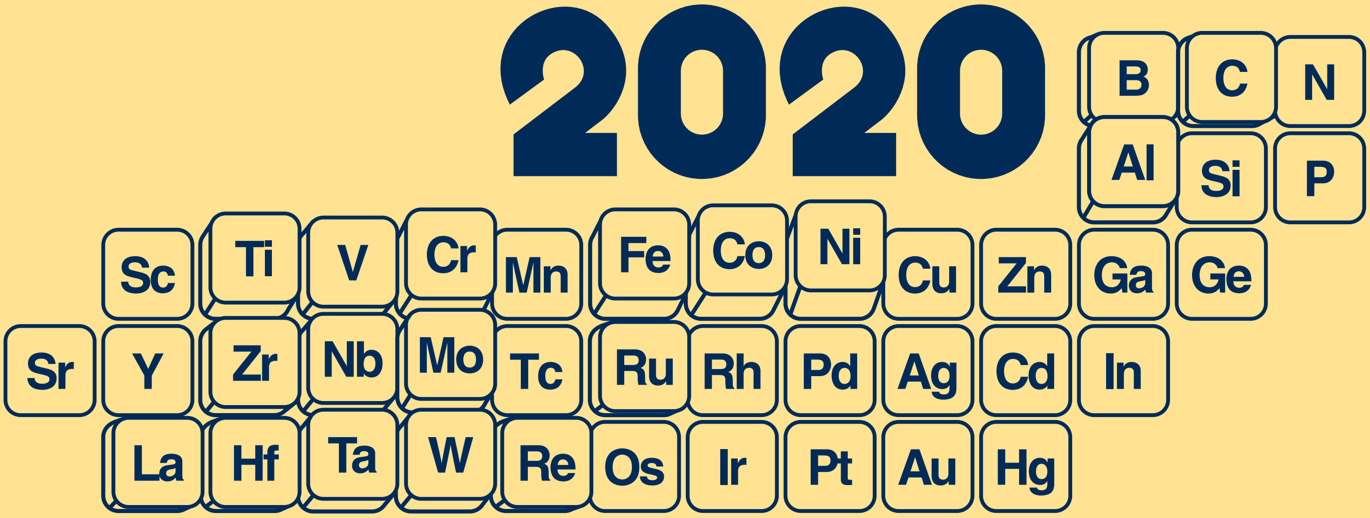
SUPERALLOYS
2020



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The Minerals, Metals & Materials Series

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Editors

Superalloys 2020

Proceedings of the 14th International Symposium on Superalloys

TMS

Springer

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This volume is a collection of papers from the 14th International Symposium on Superalloys, to be held on September 12–16, 2021, at the Seven Springs Mountain Resort, Seven Springs, Pennsylvania, USA. The proceedings is sponsored by the International Seven Springs Symposium Subcommittee of the TMS International Affairs Committee, the TMS Structural Materials Division (SMD), and the TMS High Temperature Alloys Committee, and co-sponsored by the Institute of Materials, Minerals and Mining (IOM3).

Preface

The purpose of the International Symposium on Superalloys, which takes place every four years, is to provide a forum for researchers, producers, and users to exchange recent technical information regarding the high-temperature, high-performance materials that are used in gas turbine engines and related products. The principal goal of the symposium is to highlight new initiatives and future growth opportunities for superalloys, recent advances in the understanding of their behavior, and progress in integrating them into new systems. The first symposium, held in 1968, emphasized phase instabilities in superalloys. Since then, the scope of the symposium has expanded considerably to cover all aspects of research, development, manufacture, and application of these materials. Over the years, the symposium has developed rich traditions, encompassing a high-quality peer-reviewed publication, which is presented before the conference, single-session presentations, and lively discussions during and after formal sessions, which are facilitated by the Seven Springs Mountain Resort. Participation from the international superalloy community in the technical program has always been key to the success and reputation of this symposia, so due to the unprecedented COVID-19 pandemic, the Superalloys 2020 Organizing Committee and TMS have rescheduled the 14th International Symposium on Superalloys to September 12–16, 2021. The collected proceedings is being published and released to the community as scheduled in September 2020 to ensure that that the reported findings are timely and up to date.

This, the Fourteenth Symposium, will be taking place at a time when advances in the superalloy community have been largely driven by the development of property models, computational tools, processing methods, and innovative characterization techniques. For example, 3D mesoscale through atomic-scale characterization, machine learning algorithms, integrated computational materials engineering (ICME), and physics-based property models have all contributed to improve the processing and performance of existing materials, while accelerating the development of new alloys. As highlighted in the collection of proceedings, the development and application of innovative technologies in academia, industry, and government laboratories have been critical for improving the overall life cycle of superalloys.

For the first time, the keynote address of this symposium will be a joint presentation from representatives of an engine OEM and a superalloy supplier. Christian Dumont, Chief of the Materials and Processing Modeling Department at Aubert & Duval, and Arnaud Longuet, an expert in the mechanics of high-temperature materials at Safran Aircraft Engines, will provide a unique overview of how data and information generated from process modeling tools used by the supply chain have been integrated into lifing methodologies used by the engine's original equipment manufacturer (OEM).

Starting with the Second Symposium in 1972, each symposium and its corresponding published proceedings have been dedicated to an individual as a means of honoring his or her contributions to the superalloy industry. The Fourteenth International Symposium is dedicated to Pierre Caron, a true pioneer and innovator in our field. Further details of Pierre's career and contributions can be found on the following pages.

Finally, it should be noted that this symposium would not have been possible without the efforts of the current and past members of the committees that serve the International Symposium on Superalloys. The Program Committee for the Fourteenth Symposium, listed below, was responsible for preparation of the technical program, including critical review of abstracts and manuscripts for originality, technical content, and pertinence to industry. The TMS staff, particularly Trudi Dunlap, Jennifer Booth, Matt Baker, and Doug Shymoniak, devoted considerable effort to organizing all other aspects of the symposium.

Sammy Tin, Chair
Mark Hardy
Justin Clews
Jonathan Cormier
Qiang Feng
John Marcin
Chris O'Brien
Akane Suzuki

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Dedication

The 14th International Symposium on Superalloys is dedicated to Pierre Caron for his substantial contributions to our field. He has been a pioneer and innovator in the development of Ni-based single-crystal superalloys, their processing, property optimization, and compatibility with coatings.

Dr. Pierre Caron was born in Paris, France, in September 1954. He attended Paris XI University from 1971 to 1979, earning a postgraduate degree in special metallurgy in 1976 and a Ph.D. degree in metallurgy in 1979. After a one-year military internship at the French Atomic Energy Commission, he joined ONERA, the French Aerospace Research Center, in November 1980 as a research engineer. As his career progressed, Pierre was successively appointed Head of the Cast Superalloys Group, Head of the High Temperature Materials Research Unity, and finally Special Advisor in the field of superalloys. In 2005, he successfully defended a habilitation thesis to supervise research and advise Ph.D. students and then he received the title of senior researcher at ONERA. Since his retirement in December 2016, he has kept in touch with the world of superalloys as a scientific consultant.

Pierre began at ONERA in the Department of Materials initially under the supervision of Dr. Tasadduq Khan who led the activities on nickel-based superalloys for single-crystalline blades. During his entire career, this topic has been the central theme of his research activities, although he also made important contributions to studies on intermetallic high-temperature alloys and in the field of wrought powder metallurgy superalloys (alloys NR3, NR6, and N19). He contributed to the design and the development of new single-crystal superalloy chemistries (AM1, AM3, MC2, MC-NG alloys) for applications in aircraft and helicopter engines to fulfill the requirements of the French gas turbine engine manufacturers of the Safran Group. AM1 is currently used as high-pressure turbine blade and vane material in the M88-2 engine powering the Rafale fighter, in the TP400-D6 European engine for the Airbus A400M military transport airplane, and in the SaM146 engine produced by PowerJet, a joint venture between Safran and NPO Saturn, for powering of the Sukhoi Superjet 100 regional aircraft. AM3 and MC2 alloys were introduced in various versions of the Arriel 2 and Arrius 2 Safran helicopter engines. Pierre also participated in the development of the SC16 superalloy that was optimized for large single-crystal blades in industrial gas turbines (IGTs). His interest in this area extended to the coordination of European research BRITE-EURAM program SC2, which led to the development of the SCA425 and SCB444 single-crystal superalloys for IGT. Pierre contributed also to the development of the THYMONEL 2 and THYMONEL 8 superalloys specifically designed for single-crystalline blades of a hydrogen turbo-pump in rocket engines. Very recently, he made a significant contribution to the design of the AGAT single-crystal superalloy that was developed to meet the demanding requirements of advanced Safran Aircraft Engines. The other research activities performed by Pierre covered various topics including: the application of transmission electron microscopy to analyze deformation mechanisms, effects of solidification parameters, heat treatments, anisotropy, microstructure and microstructural instabilities on the mechanical behavior, effects of minor alloying elements on oxidation resistance, interactions with protective coatings, optimization of the single-crystal superalloy/thermal barrier system, strengthening γ'-Ni_3Al-based and β-NiAl-based intermetallic alloys, and contributions to the development of Co-based and Cr-based alloys. Several of these studies were performed in collaboration with a number of French academic research laboratories, giving Pierre the opportunity to explore fundamental aspects of the physics and the chemistry of various high-temperature alloys.

Pierre is Author/Co-author of about 160 research papers in journals and conference proceedings and, as Co-inventor, made applications for 15 patents. From 1988 to 2014, he was Teacher and then Educational Leader at the National Conservatory of Arts and Crafts, Paris, France, in presenting the training course “Properties and Applications of Superalloys.” He was Co-organizer of Superalloy Symposiums at the EUROMAT 1999 and THERMEC 2003 Conferences, Member of the Program Committee of the 11th International Symposium on Superalloys, and Member of the Organizing Committee of the Euro Superalloys 2010 and Euro Superalloys 2014 Conferences. He received in 1988 in Hanover, Germany, the Dr. Ernst Zimmerman Memorial Award for its contribution to the promotion of propulsion technology in the field of aeronautics. As Co-author, he received the Best Paper Award of the International Symposium on Superalloys in 1988 and 2012. In 2017, he was named Knight in the Order of Academic Palms, delivered by the French Ministry of National Education, Higher Education and Research.

Last but not least, Pierre has always been a source of knowledge and inspiration for younger generations from both academia and industry, sharing in a very kind way all the experience he has gained from his professional activities.

Past Dedicatees

1972—Clarence Bieber
1976—Falih Damara
1980—Rudy Thielman
1984—Gunther Mohling
1988—Herb Eiselstein
1992—Carl Lund
1996—John Radavich
2000—Wilfred "Red" Couts
2004—Fred Pettit
2008—Raymond Decker
2012—Anthony Giamei
2016—Louis W. Lherbier

Best Paper Award

The following paper was selected by the Awards Committee of the International Symposium on Superalloys as the winner of the Best Paper Award for the 14th symposium:

"Enhancing the Creep Strength of Next Generation Disk Superalloys via Local Phase Transformation Strengthening"

by

T. M. Smith[1], T. P. Gabb[1], K. N. Wertz[2], J. Stuckner[1], L. J. Evans[1], A. J. Egan[3], M. J. Mills[3];

[1]NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, USA;
[2]Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433, USA;
[3]Center for Electron Microscopy and Analysis and the Department of Materials Science and Engineering, The Ohio State University, Columbus, OH, USA

The selection was based on the following criteria: originality, technical content, pertinence to the superalloys and gas turbine industries and academic community, and clarity and style.

Committee Members (14th International Symposium on Superalloys)

Program Chair

Sammy Tin

Program Committee

Justin Clews
Jonathan Cormier
Qiang Feng
Mark Hardy
John Marcin
Chris O’Brien
Akane Suzuki

Awards Committee

Eric Huron
Gern Maurer
Tresa Pollock
Roger Reed

Part I

Keynote

Advanced Modeling Tools for Processing and Lifing of Aeroengine Components

Arnaud Longuet, Christian Dumont, and Eric Georges

Abstract

Lifing is one of the main challenges for aeroengine manufacturers. For fatigue prediction, attention has been focused on the crack initiation mode depending on stress level and initial microstructure. Microstructure prediction during the component manufacturing, especially for final heat treatments and final forging operations, is required if it is to be included in fatigue analysis. Reliable tools are now available for basic nickel-based alloys such as Inconel 718. For other alloys, notably γ/γ' alloys, research is still being performed in close partnership with academia. Globally, two main trends are emerging; first, one of our main interests is to develop the modeling capability for the entire manufacturing process, including ingot conversion and billet forging. Second, new approaches are still under development by introducing more physical considerations through full-field models, which are very useful for a better understanding of specific issues such as heterogeneous grain growth. From a component lifing point of view, the initial state of stress is also a key parameter to be considered. One method for the control of residual stresses is application of a pre-spinning process. Finally, a standard lifing methodology is explained and improvements are proposed; in particular, size effect is used to model notch specimen life considering surface or internal initiation.

Keywords

Inconel 718 • γ/γ' alloys • Modeling • Recrystallization • Lifing • Residual stresses • Manufacturing process

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Introduction

Aeroengine turbine disks are among the most challenging components to design. Material choice and microstructure evolution are crucial to the performance and durability of a part design, which is dependent on the application, required fatigue/creep life and temperatures reached. The design process for such a component is iterative. To select a material for a particular application, specifications need to be given by the pre-design and the design department. Highly representative material properties are necessary for models to accurately predict the life and integrity of a part.

Disk qualification packages are submitted for certification to airworthiness authorities (e.g., FAA and EASA). The two most critical risks to avoid are disk burst in case of over-speed and disk failure due to fatigue. Material properties and their response to processing are of the utmost importance to meet certification requirements.

Often times, the material performance for the selected application is too low with respect to the design requirements and a new superalloy is desired. However, multiple approaches can be used in an aim to meet the design requirements: Improve the material by a change in the chemical composition, improve the manufacturing process (i.e., conversion, forging, heat treatment, machining) to have better material properties, or improve the material's constitutive modeling approaches to better understand any conservatism in the predictive methodology. For decades, many research programs have been devoted to microstructure prediction, from ingot casting to final closed die forging of parts. For the forging process, models are based on post-processing of thermomechanical histories during part manufacturing, deduced from finite element modeling, Inconel 718 being the material of choice [1–3]. This presentation will be oriented toward improving the modeling tools that can help with improving forge process and lifing methodologies of forged rotating components. For microstructure prediction, we propose to address more specifically the three following points:

- The reliability of the thermomechanical description of processes as a requirement for realistic microstructure prediction
- The relevance of new full-field models for microstructure prediction
- The specificity of γ/γ' alloys versus Inconel 718.

Several examples presented in this article are from Aubert & Duval and Safran Aircraft Engines in house research activities, as well as from French Industry–University research programs, through joint PhD students or large-scale programs like the OPALE, DIGIµ, and TOPAZE chairs [4–6] supported by the ANR (French National Agency for Scientific Research), Safran, and/or Aubert & Duval.

It should be noted that research activities on high-temperature materials can be performed on very applied (industrial) topics in French academic laboratories due to a well-established intellectual property (IP) system. The IP is shared in most cases between the university and the industrial partner to existing agreements. Governmental initiatives encouraging joint industry–university research are further strengthened by providing funding, e.g., half of Ph.D. student grants if hired by industry or half of the financial support for large-scale research programs (like the above-mentioned ones) for more fundamental research activities.

Effect of Microstructure on Inconel 718 Life

Inconel 718 (IN718) is the most widely used superalloy for disk applications. It is low cost compared to γ/γ' superalloys and relatively easy to process and has good mechanical properties up to 650 °C. The forging process produces different microstructures, mainly in terms of grain size. The understanding of crack initiation mode on the durability of IN718 is critical to be able to estimate the scatter linked to each crack initiation mechanism [7]. Figure 1a shows that the surface crack initiation (example in Fig. 1b) mode has a lower scatter than the internal crack initiation mode. It is of the utmost importance at the stress level where the two crack initiation modes are competing to be able to draw the minimal master curve used for the component design, and to understand the possible origins of scatter.

Turbine disks always show variation in grain size due to the forging process. Among all the microstructural features critical for component lifing, grain size is the most important for IN718, while this is not always true for other γ/γ' alloys [8–12]. Figure 2 shows the effect of grain size on IN718 fatigue life. In the same way, the fatigue life variability is dependent on the crack initiation mechanism and hence on the grain size. For a surface crack initiation mode, carbides/nitrides for 10 ASTM (~10 µm) material or twin boundaries for 7 ASTM (~30 µm) material can be crack starters [8, 10–13]. But the fatigue life remains identical between these two modes. For the internal crack initiation mode, as 10 ASTM IN718 material already initiates on grains/at twin boundaries, the initiation mode does not change. However, the fatigue life is reduced with larger grain size.

A more detailed review of the data is presented in Figs. 3 and 4. LCF strain-controlled fatigue tests were performed on two different IN718 materials (different forging routes) with nearly the same grain size at an intermediate strain level where crack initiation could occur at the surface with a low life or internally with higher lives [8]. According to Fig. 3, it is clear that material 1 has a lower life compared to material 2. In an unexpected way, material 1 initiates mainly on grains/twin boundaries near the surface and material 2 internally on nonmetallic inclusions, nitrides especially. Better fatigue life is expected with internal crack initiation compared to (sub)surface initiation, but usually grain initiation gives better lives than inclusion initiation.

The explanation for this result can be found in Fig. 4. The two materials have a very similar average grain size, but the

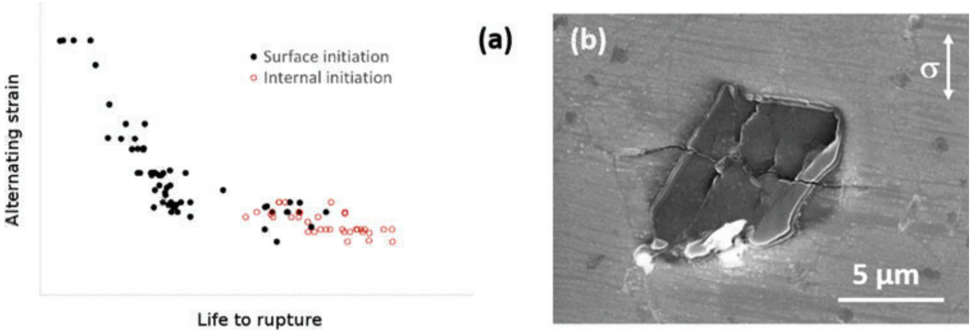

Fig. 1 Nature of crack initiation mode of IN718 in a *S–N* diagram at low and intermediate temperature (i.e., $T < 500$ °C) (**a**) and typical LCF surface crack initiation from a nonmetallic inclusion (a nitride in this case) at intermediate temperature—adapted from [10] (**b**)

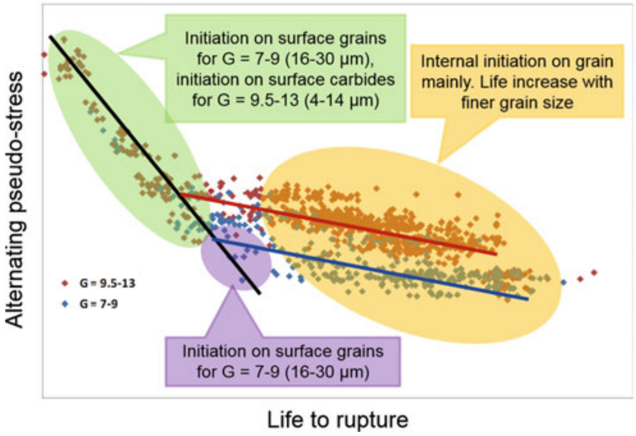

Fig. 2 Effect of grain size on fatigue life of Inconel 718 (G—ASTM grain size)

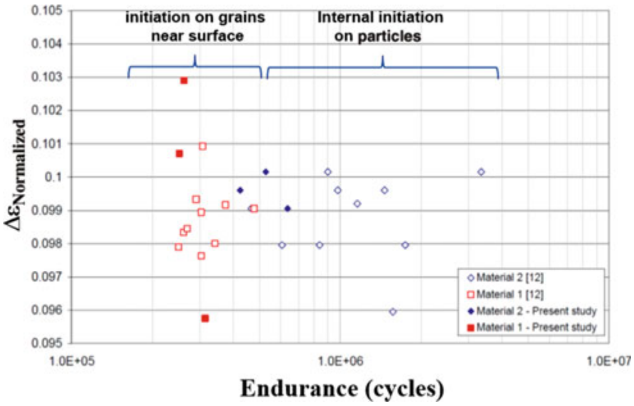

Fig. 3 Comparison between LCF lives of different IN718 forgings at an intermediate strain level and low temperature (i.e., $T < 500$ °C)—adapted from [8]

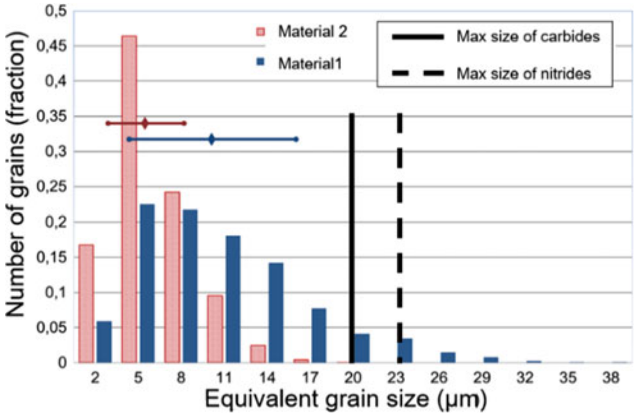

Fig. 4 Grain size histograms and maximum carbide and nitride sizes for Fig. 2 materials—adapted from [8]

grain size distribution of material 1 has a longer tail, with sizes even larger than maximum nitride size. Crack initiation occurring on the largest microstructural feature between nonmetallic inclusions and twins, the results of Fig. 3 are confirmed. A similar trend is also observed in AD730$^{\mathrm{TM}}$ γ/γ' alloy in LCF at 450 °C [9], despite a reduced variability in LCF life compared to IN718. Moreover, it has been clearly shown by Texier et al. that at fixed grain sizes and by considering only nonmetallic inclusion crack initiation, the precipitation state is critical in terms of fatigue life variability. In addition, an alloy with a higher content of γ'' (i.e., lower δ content) leads to greater fatigue life variability for IN718 [10].

All these considerations show that both the microstructure and initial state of stress/strain should be controlled carefully throughout the component manufacturing process. Modeling tools are now used regularly in order to improve both the forging and heat treatment routes. The main goal is to predict the microstructures and residual stress levels. Thus, a review is proposed in the next subsections on the developments and capability of "metallurgical and mechanical post-processing modules" implemented in commercial process simulation software packages.

Microstructure Modeling

Closed Die Forging

Commercial software packages such as FORGE or DEFORM based on Johnson–Mehl–Avrami–Kolmogorov (JMAK) formulations [14] are used to model closed die forging of IN718. They are very useful for testing different forging routes for each new application (geometry of the blank, lubrication, die temperature, etc.). Moreover, correlation between modeling and experimental results is a good way to validate process control and the prediction of thermomechanical history at different locations in the forged part. However, this basic approach may become unsatisfactory for more complex situations such as:

- Multistep forming processes (rolling or ring rolling, open die forging, etc.)
- Adiabatic heating over the δ-solvus, leading to a faster dissolution of δ phase and consequently to unexpected grain growth.

In such cases, modeling equations must be improved, leading to specific experiments to assess new parameters. By considering again the same two examples:

- Recovery effects between each deformation step must be introduced for unrecrystallized grains in the description of the residual strain coming from the previous deformation pass [15].
- In contrast to a simple thermal treatment, deformation significantly increases the precipitate dissolution rate [16].

All these improvements lead to more reliable and complex models, which come progressively close to physical and mean-field approaches. Residual strain accumulated between each pass during an incremental process can thus be considered as describing dislocation density. However, JMAK models are still largely used since the sensitivity analysis and parameter identification are easier, with their main parameters being directly connected to thermomechanical data (strain, temperature, etc.). Moreover, physical models are more difficult to implement in computation codes, because we have to manage larger numbers of parameters, increasing with the level of detail for microstructure description: kinetics of misorientation of sub-grains, twins [17]. Ultimately, it becomes impossible to get a complete map of microstructure parameter distribution (grain size, recrystallized fraction etc.) through metallurgical post-processing. Each thermomechanical operation, extracted from the initial finite element model, needs to be treated separately.

In this sense, full-field models are much more suitable to account for microstructure evolution. A large research program is currently in progress in France which aims at developing the DIGIμ™ software package, based on the state-of-the-art numerical methods and metallurgical models, but optimized to enable their industrial use [18–21]. The collaboration between industrial and academic partners runs in a specific framework with interactive governance and shared IP principles that have been set up. Similar to what has been done in the past for other software developments, such as FORGE, the interaction between industry and academics proceeds through the following steps:

- New numerical developments are proposed by the academia with agreed-upon needs expressed by the industrial partners, in terms of metallurgical phenomena, materials, and processes.
- The new software implementation and their tutorials are delivered by the research laboratory (CEMEF—MINES ParisTech, Sophia Antipolis) to the industrial partners through a software editor company (Transvalor).
- Industrial partners provide a feedback on the software usage and parameter identification for their materials of interest. The latter issue is also subjected to common work performed between several industrial companies of the funding consortium.
- Important feedback is provided for new proposals and requests for further software development that lead to new academic research programs.

Founded and co-funded by industrial partners and the French government (through the French National Agency for Scientific Research, ANR), this process leads to a strong partnership that is highly efficient, flexible, and agile. Even if they are not IP free at the beginning, these numerical tools are ultimately intended to be disseminated on the market by the software company. However, this process offers numerous benefits for the initial funders like exclusive use period, discount for maintenance, and definition of future development plans.

Based on a level-set description of polycrystals, the DIGIμ framework has been developed in order to model the evolution of an actual grain size distribution during static, dynamic, and post-dynamic recrystallization. In this case, the main goal is not to simulate an actual forging process, but it can be very useful for optimization of model parameters. One of the main interests of this approach consists also in carrying out numerical experiments in order to study specific phenomena occurring during subsequent solution heat treatments. One typical example deals with heterogeneous grain growth [22], which can be uncontrolled and lead to large grain sizes, with a deleterious impact on mechanical properties [23]. For this specific concern, three main parameters governing grain boundary motion have to be taken into account:

- Capillarity driving force directly connected to grain size distribution
- Distribution of second-phase particles, such as δ phase in IN718 (volume fraction and size)
- Difference of stored energy between neighboring grains.

An example is shown in Fig. 5 adapted from [22]. Pattern (a) represents an initial microstructure on IN718 (100 × 100 μm) with a volume fraction of 4% of round δ particles 0.8 μm in diameter. The blue grain is free of stored energy, while the surrounding grains are characterized by a stored energy equal to 200 kJ/m^3. Subsequent heat treatment at 985 °C is then calculated with DIGIμ™. This difference in stored energy leads to the faster growth of the blue grain after 600 s (b), 1800 s (c), and 3600 s (d). Similar phenomena have also been reported in γ/γ' alloys and attributed to static recrystallization under critical stored energy conditions [24].

Obviously, this approach does not pretend to be representative of a real microstructure and process. However, it can give useful guidelines for understanding unexpected microstructure evolution occurring during heat treatments,

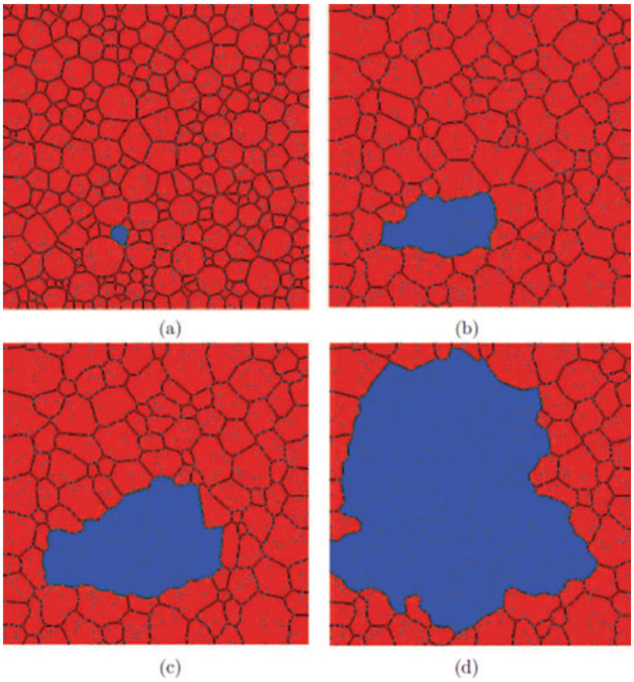

Fig. 5 Modeling of grain growth with DIGIμ™ on a theoretical microstructure on IN718 (extracted from [22])

on a rather wide range of materials (IN718, γ/γ' alloys, etc.) and different processes (ring rolling, bar cogging, etc.). For a given initial microstructure in terms of grain size and secondary phase particles, it is then possible to assess the distribution of stored energy which can trigger heterogeneous grain growth. This phenomenon is more sensitive when grain size decreases due to the higher capillarity effect (typically from grain size finer than 10 μm). However, the link between thermomechanical history and a specific distribution of stored energy between neighboring grains leading to heterogeneous growth is not always so easy to establish.

Upstream Process: Ingot Conversion

Another challenge consists of microstructure prediction during ingot conversion and billet manufacturing [25]. In order to meet the final part requirements, microstructure needs to be controlled at the earlier stages of the product and typically on billets. For γ/γ' alloys such as Rene 65 or AD730™, it is well known that fine and homogeneous grain size must be obtained directly at this step since recrystallization of large and elongated unrecrystallized grains cannot be completed during closed die forging [26, 27]. Thus, the trend is toward modeling of the full process, from ingot to the final part, as shown in Fig. 6.

From a purely computational point of view, we have to address three main challenges:

- As open die forging consists of a large number of various operations (upsetting, bar forging, furnace reheating, etc.), we need to gather a lot of process parameters for accurate modeling of hundreds of press strokes. Improvement of data recording and more continuous communication between the press and computational codes is an important way to move forward [28].
- Regarding microstructure prediction models, specific adaptations have to be implemented in order to take into account all the phenomena occurring simultaneously at different locations of the bars (dynamic, metadynamic, or static recrystallization). Moreover, as these models are usually built from equiaxed initial microstructure, specific attention has to be paid to the evolution of as-cast microstructure during the early stages of the process conversion.
- Lastly, ingot conversion involves several reheating steps in furnaces. In several cases, we do not necessarily look after a full recovery of a homogeneous temperature distribution within the bars. During some processes, we can have some beneficial effect of a progressive temperature decrease at the core of the bar during the whole forging process, leading to microstructure refinement. As shown in Fig. 7 in the case of IN718, heating rate should be in some areas fast enough in order to avoid massive and detrimental precipitation. For all these reasons, an accurate prediction of thermal history in furnaces is also a key point to have an excellent microstructure control. Special attention has to be paid to this part of the process through specific modeling tools, dedicated to furnace behavior.

Taking into account all these considerations, a rather accurate prediction of microstructure evolution during ingot conversion can be obtained. For example, forging route optimization on IN718 for larger diameter bars up to 356 mm has been proposed.

Modeling Capability Versus Alloys

Finally, for processes, from ingot to forged parts, modeling including microstructure prediction can be achieved on IN718. However, additional development needs to be carried out for ring rolling for two main reasons. First, the reliability of thermomechanical prediction must be improved for this complex process: pronounced spatial strain gradient, true displacement rate of the press ram, etc. An exemplary result obtained is shown in Fig. 8. When the press reached its

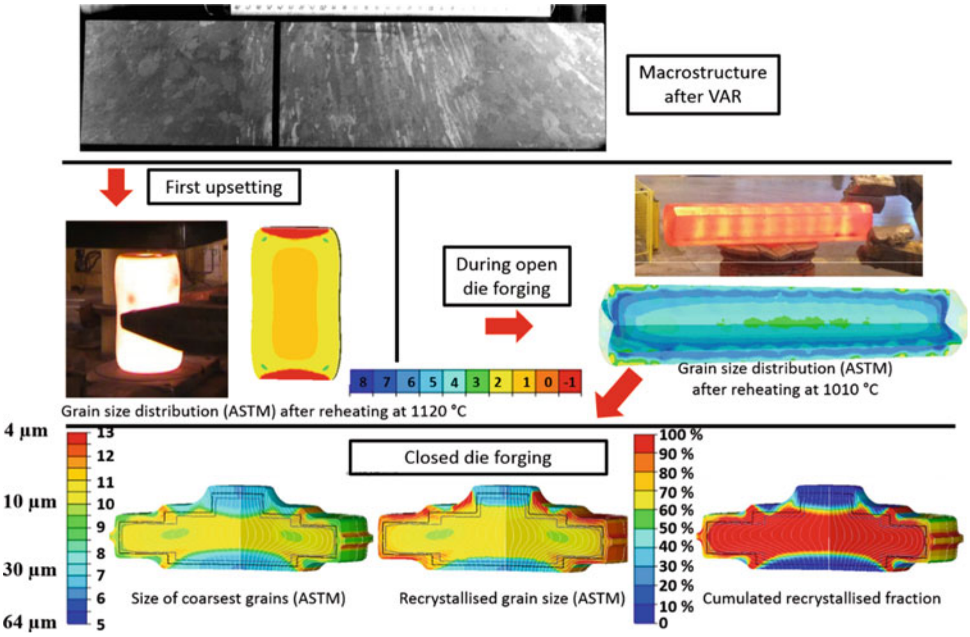

Fig. 6 Flowchart for microstructure modeling from ingot to closed die forging on IN718

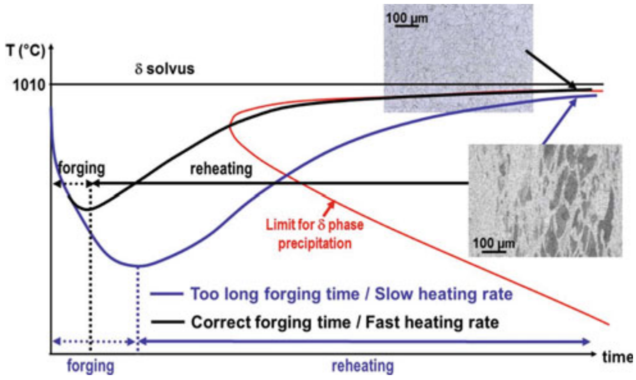

Fig. 7 Temperature evolution close to a bar surface during cogging and reheating—consequences on microstructures for IN718 alloy

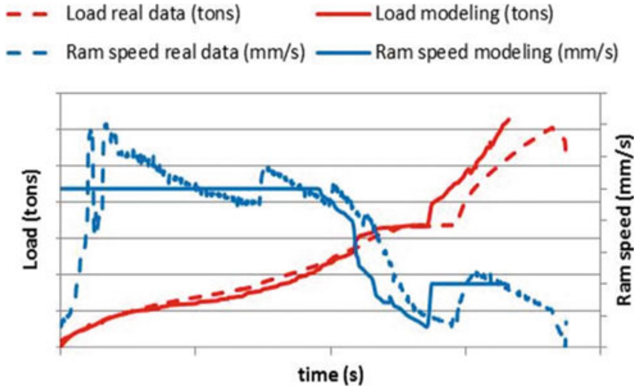

Fig. 8 Comparison between real (dashed line) and predicted (solid line) load (red) and ram speed (blue) during closed die forging of a turbine gas disk in Inconel 706

power limit, this last parameter can significantly decrease due to the pressure loss in the hydraulic circuits. Thus, if the actual behavior of the press is not correctly taken into account, forging time will be in that case largely underestimated, leading to a cascade of incorrect predictions (temperature distribution, load, and microstructures). Moreover, some specific conditions make identification of parameters for microstructure prediction more challenging, including high strain rates (up to 30 s^{-1}) and low strain for each pass (lower than 0.1).

Of course, these models must take into account precipitation which is involved in controlling grain growth by Smith–Zener pinning effects after primary recrystallization: δ phase for IN718, primary γ' particles for Rene 65, Udimet 720Li, or AD730^{TM} alloys. However, rather slight interactions have been observed between δ phase and recrystallization for IN718:

- Accelerated dissolution during hot deformation above the solvus temperature as mentioned above
- Local segregation of niobium, leading to local variation of δ solvus, and consequently local variation in grain size
- Increase of nucleation rate during dynamic recrystallization
- Large amounts of δ phase can slow down metadynamic recrystallization [17].

Even if these interactions can lead to some changes in microstructure, both mechanisms (primary recrystallization and δ precipitation) can be studied separately in a first approach for IN718. For γ/γ' alloys, the situation is more challenging, especially during cogging, but more specifically during the first deformation steps below the γ' solvus. For example, a fine and coherent primary precipitation can be

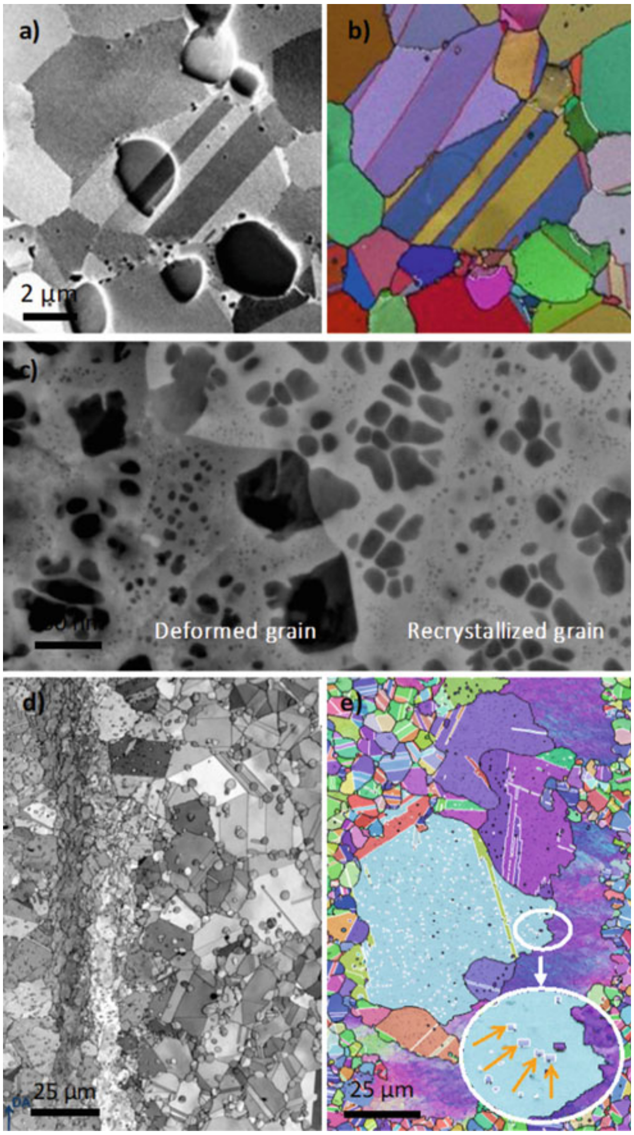

Fig. 9 Back-scattered electron (BSE) image (**a**) and orientation color-coded electron back-scattered diffraction (EBSD) map (**b**) with grain boundaries (>15°) plotted black of a hetero-epitaxially recrystallized grain in the Rene 65 alloy. BSE image at a recrystallization front in the AD730^{TM} alloy (**c**). BSE image in the longitudinal section of an AD730^{TM} alloy billet (**d**). Orientation color-coded EBSD map (**e**) with grain boundaries (>15°) plotted black and twin boundaries plotted white of an overgrown grain with twin-related γ' precipitates (arrowed in the zoomed insert) in the AD730^{TM} alloy

observed in coarse, elongated, and unrecrystallized grains [27]. They can be considered as hard grains during hot deformation, surrounded by soft material, corresponding to fine recrystallized grains (an example of such a microstructure can be seen in Fig. 9d). Therefore, the large grains cannot accumulate enough strain hardening and stored energy in order to advance the recrystallization process. Examinations at different steps of billet conversion show that these large grains are inherited from the early stages without any significant evolution. Therefore, significant increase of deformation is less efficient in order to improve recrystallization fraction [26]. The best solution is then to act on precipitation.

Figure 9 shows other examples of recently reported mechanisms which are specific to γ/γ' alloys. Hetero-epitaxial recrystallization (HEREX—Fig. 9a and b) is a mechanism by which a recrystallized grain arises from inverse precipitation of γ phase at the rim of a γ' precipitate and subsequent growth driven by stored energy consumption [29–31]. The striking feature of HEREX grains is that they have the same crystallographic orientation as the precipitate they originate from, which led to the terminology of hetero-epitaxial recrystallization. Figure 9c shows the complex mechanism at play when a recrystallization front migrates at sub-solvus temperatures, thus in a microstructure with γ' precipitates [32]. The proposed mechanism proceeds by dissolution of the deformed grain precipitates at the recrystallization front, followed by re-precipitation on the other side in the recrystallized grain, the whole process keeping the precipitates coherent with the matrix grains on both sides. The classical Smith–Zener pinning mechanism and model usually considered in recrystallization and grain growth simulations are far from being sufficient in such a mechanism. The last example concerns overgrown grains (Fig. 9e) which develop specifically in elongated recovered grains which can be found in forged billets when the billet conversion route was not optimized enough to fully recrystallize the microstructure [26, 27]. Such an elongated recovered grain can be seen on the left side of Fig. 9d, and the γ' precipitate size is much finer in those areas than it is in the recrystallized equiaxed grains. The mechanism by which those overgrown grains can develop is also driven by stored energy consumption like that of Fig. 5, but it goes along with a dissolution and re-precipitation mechanism at the recrystallization front which leads to γ' precipitates with particular shape and orientation (notably twin relationship with the overgrown grain, as highlighted in the zoomed insert of Fig. 9e). This only occurs if the recrystallizing grain satisfies the condition of being misoriented about a $\langle 111\rangle$-axis with the recovered grain it grows into [33, 34].

Reliable microstructure prediction for γ/γ' alloy forgings will definitely require at least the implementation of the coupling between recrystallization and phase transformation phenomena into the metallurgical models, and likely also the consideration of the local crystallographic texture and orientation relationships. Due to the strong interaction between precipitation and recrystallization, modeling microstructure evolution during forging is by far more complex for these alloys than for IN718 and no suitable tool is available up to now. Knowledge improvement in γ' precipitation