

Comparison between microstructure evolution in IN718 and ATI Allvac® 718Plus™ – simulation and trial forgings

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Abstract. Aerospace gas turbine disks operate in an environment of relatively high stresses caused by centrifugal forces and elevated temperatures. Because of the strong mechanical requirements and narrow specifications of such parts not only a correct, defect free final geometry is necessary, but also a defined microstructure. Even though the microstructure evolution during thermo-mechanical processing is well studied and understood for superalloys like IN718, the influences cannot easily be described analytically. Thus simulation tools are used to assure process stability and to optimize design parameters to meet the tough requirements in aerospace industries.

Microstructure simulation of IN718 (and other materials) is well established at Bohler Schmiedetechnik GmbH & Co KG and appreciated by its customers. The advent of the newly developed nickel-base superalloy ATI Allvac® 718Plus™ led to extensive investigations and the development of an adapted microstructure model by Bohler Schmiedetechnik GmbH & Co KG and its research partners.

Aim of this paper is a comparison of the microstructure evolution in IN718 and ATI Allvac® 718Plus™ during the thermo-mechanical treatment of turbine disks. Influences of process temperature, strain and strain rate on the final grain size are discussed by finite element simulations with a coupled grain structure model. Experimental results from trial forgings are compared with the outcome of the microstructure simulations.

Introduction

First applications of IN718 go back to the early 1960s. Over all these years lots of scientific research was done on that alloy. Popularity of IN718 is based on its excellent strength, good malleability, best weldability of all superalloys and especially moderate costs. One of the most important applications of IN718 are turbine disks for aerospace engines and gas turbines. A limitation of IN718 is its maximum longtime operation temperature of 650 °C due to the stability of primary hardening precipitate γ'' Ni₃(Nb, Al, Ti). Long time exposure above 650 °C leads to over aging of meta-stable γ'' to equilibrium δ Ni₃Nb phase. This results in dramatic loss of strength and creep properties.

Typical γ' Ni₃(Al, Ti) precipitation hardening alloys, like Waspaloy or René 41, show significantly higher temperature resistance, though these alloys are harder to forge and to weld and due to higher contents of alloying elements more expensive than IN718. Thus the call for a new nickel base superalloy with the same combination of good mechanical properties and moderate costs and additional higher operation temperature arose. In the course of the *Metals Affordability Initiative CORE Program* ATI Allvac® 718Plus™ was chosen for extensive melting experiments. In 1997 ATI Allvac® made first trials with derivatives of IN718 by changing (Al+Ti) content and (Al/Ti) ratio to rise the volume fraction of γ' and minimize the volume fraction of γ'' and δ phase. Best results in γ' stability were found to be at (Al/Ti) ratio of 4:1 and (Al+Ti) content of 4 at.%. Furthermore 1wt.% W was added and Fe was partially substituted by Co. This newly developed alloy shows an approximately 55 °C improved thermal stability.[1-7]

The chemical composition of IN718 and Allvac® 718Plus™ is listed in Table 1 and Table 2, respectively.

Table 1: Chemical composition of IN718 in wt.% [8]

IN718	C	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al
min	-	bal	17.00	2.80	-	-	18.00	5.00	0.65	0.20
max	0.08	bal	21.00	3.30	-	1.00	19.00	5.50	1.15	0.80

Table 2: Chemical composition of Allvac® 718Plus™ in wt.% [9]

Allvac® 718Plus™	C	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al
min	-	bal	17.00	2.50	0.50	8.00	8.00	4.75	0.50	1.20
max	0.06	bal	21.00	3.10	1.50	10.00	10.00	5.80	1.00	1.80

The addition of Co advances the formation of γ' particles by reducing Al and Ti solubility in the Ni matrix and decreases the stacking fault energy. W as well as Mo are used for solution hardening, increasing the elastic modulus for better creep properties, lowering the diffusion coefficient and elevating the γ' solution temperature. [10, 11]

Precipitation Structures. The advantage in temperature resistance of Allvac® 718Plus™ derives from the change in primary hardening phase. Whereas IN718 is a typical γ'' hardened nickel base superalloy, changed chemical composition of Allvac® 718Plus™ suppresses the precipitation of γ'' and favors the precipitation of γ' as primary hardening phase. In both superalloys δ phase is used to control grain growth [12].

The γ' phase is coherent with the γ matrix. Therefore the nucleation occurs homogeneously, which leads to an even distribution within the matrix. Due to the coherence with the γ matrix the phase boundary enthalpy is very low which improves thermal stability. The γ'' phase in IN718 is semi-coherent with the γ matrix and precipitates plate-like. After long time exposure at temperatures higher than 650 °C the γ'' phase transforms to the stable δ phase. Its coarse plate-like morphology leads to higher notch sensitivity and lower fatigue strength. [10]

Process Simulation. In the past the evaluation of deformation parameters was a long lasting process, often based on experience as well as trial and error. This is in contrast to the demands of modern industry longing for short development times and cost reduction. The implementation and application of simulation of deformation processes changed the design methods. Deformation simulation can be divided into three major parts: global modeling (prediction of forces), local modeling (calculation of thermo-mechanical variables by use of the finite element (FE) analysis) and microstructure modeling. During thermo-mechanical treatment the material goes through a series of microstructural changes, e.g. dynamic/static recovery, recrystallization and grain growth. It is essential to combine microstructure simulation and FE simulation to get a joint model of microstructure evolution during thermo-mechanical treatment [13]. Whereas local and global models are provided by different software suppliers, accurate microstructure models for specific materials have to be implemented by the user. These models are often based on semi-empiric equations published by Sellars and Whiteman [14]. A closer look at these equations for IN718 and Allvac® 718Plus™ can be found elsewhere [15, 16].

Closed Die Forging. Bohler Schmiedetechnik GmbH & Co KG has a long time experience on closed die forging. Currently it holds the world largest and second largest screw press with 355 MN and 315 MN maximum press force, respectively. The main products are turbine blades for steam and gas turbines, structural parts for aerospace industry and turbine disks and engine mounts for aircrafts. Customer requirements for engine disks are high regarding grain size and mechanical properties. Special emphasis has to be put on the process parameters to develop a stable process with appropriate outcome. The usage of high-performance alloys combined with an optimized forging process enables the production of lightweight parts that are mechanically extremely durable.

Material properties

Final microstructure and mechanical properties are tightly linked. Customer requirements concerning mechanical properties and grain size depend on the field of application of the final part. While high low cycle fatigue properties require a finer microstructure, this microstructure would lower the creep properties. The main impacts on the microstructure are forging temperature and local strain distribution. Therefore the manufacturing process has to be tailored to the customers' requirements. The influence of manufacturing process on the fatigue properties of the final part is described in [17].

Microstructure modeling

Because of the interdependence of microstructure and mechanical properties, as well as the demand for "first time right" in modern industry, microstructure modeling is essential. Many physical and semi-empirical approaches to describe microstructure evolution during hot forming have been established throughout the time. The microstructure model implemented in Bohler Schmiedetechnik GmbH & Co KG is a semi-empirical one due to its simulation efficiency. Strains, strain rates, temperatures and times are taken from the process simulation in DEFORMTM. The microstructure evolution is calculated in linked subroutines using the equations describe in [15, 16]. Special emphasis has to be put on the model parameters. These parameters are specific for each material and have to be determined by experiments which have to be tailored to the expected mechanisms for microstructural changes. For nickel-base superalloys about forty material parameters have to be determined to describe the mechanisms of dynamic, meta-dynamic and static recrystallization as well as grain growth. By use of these parameters and a set of semi-empirical equations the change in microstructure from starting grain size in the billet through all hot forming and annealing operations to a final grain size can be calculated. A comparison of recrystallization and grain growth in IN718 and Allvac® 718PlusTM can be found in [18].

Processing

IN718 and Allvac® 718PlusTM raw material were both produced by triple melt (VIM–ESR–VAR) technology and converted to 8" (203.2mm) diameter bar material by several open die forging operations on hydraulic and rotary forging equipment to achieve a homogeneous structure in the cross-section of the billet. For 8" IN718 and Allvac® 718PlusTM bar material ASTM 6 (50µm) and finer is the average grain size throughout the cross-section.

For a comparison a typical engine disk forging process was chosen exemplarily. Two different forging strategies are compared for both materials. The first forging strategy consists of two pre forging operations and a final forging. The second strategy is only one pre forging and final forging. Forging temperatures of 970 °C and 1000 °C were chosen. Both temperatures are below the solution temperature of δ phase in IN718, but close to the solution temperature of δ phase in Allvac® 718PlusTM.

Process 1. For the first forging process the cut billet was heated up in a rotary furnace to forging temperature and held for homogenization. After that a two blow pre forging operation was done on a 315 MN screw press. After the second blow the blocker was reheated for the second pre forging operation in one blow on the same equipment. After the subsequent reheating process the two blow final forging was performed and the part was water quenched. Finally the forging was solution annealed and aged. This represents the optimized forging process especially for Allvac® 718PlusTM. A schematic process diagram is given in Figure 1.

Process 2. The second forging route started with reheating in a rotary furnace, followed by a three blow pre forging on the 315 MN screw press. After a reheating operation the part was forged in a two blow final pressing and subsequently water quenched. Finally the forging was solution annealed and aged. This represents the standard forging process for the IN718 engine disk. A schematic process diagram is given in Figure 2.

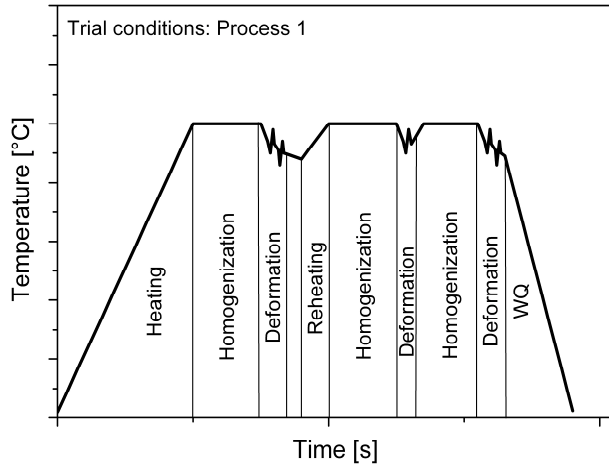


Figure 1: Schematic diagram of forging process 1.

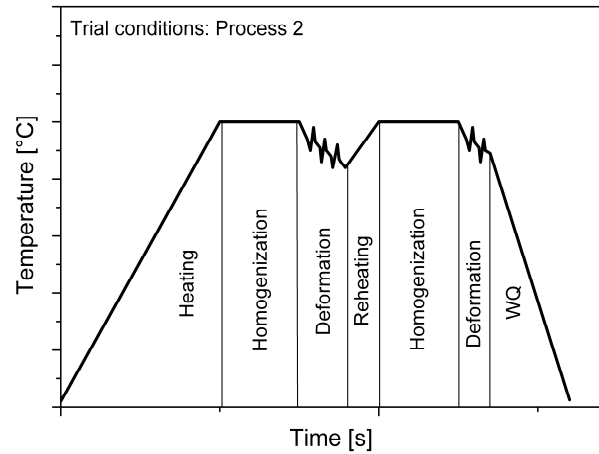


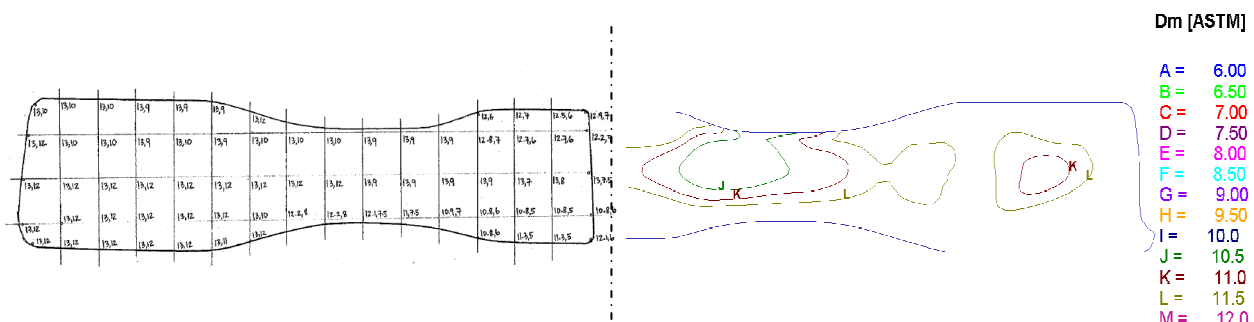
Figure 2: Schematic diagram of forging process 2.

Results. For 8" pre material an average grain size of ASTM 6 ($50\mu\text{m}$) and finer was specified. Therefore an average grain size of ASTM 6 was used as initial grain size for microstructure simulation.

Figure 3 shows the calculated and measured grain size distribution in the Process 1 forging at 970°C for Allvac® 718Plus™. It can be seen, that both measured and calculated grain size show good correlation. Figure 4 presents the results of an IN718 forging of Process 2 at 1000°C . It can be seen, that these processes result in optimum microstructure.

However, a Process 2 forging of Allvac® 718Plus™ at 1000°C leads to coarser grains in low strain areas, as depicted in Figure 5. Higher temperatures and worse strain distribution during the forging operation lead to higher grain growth and less recrystallization.

Therefore the whole manufacturing process has to be reconsidered when changing from IN718 to Allvac® 718Plus™. The lower solution temperature of the δ phase in Allvac® 718Plus™ has an influence on every heating operation. Whereas the regular forging temperature of IN718 is about 1000°C , which is about 30°C lower than the solution temperature of the δ phase in IN718 [12], this temperature is about 25°C above the solution temperature of the δ phase in Allvac® 718Plus™ [19]. This instance leads to massive coarsening during heating when keeping the process parameters of IN718 forgings. For instance a two hours heating and homogenization cycle at 1000°C of ASTM 6 pre materials would lead to ASTM 3 in Allvac® 718Plus™ billets compared to ASTM 6 in IN718 billets. This difference in grain size affects subsequent forging operations and microstructure evolution.

Figure 3: Measured and calculated grain size distribution in the Process 1 forging at 970°C for Allvac® 718Plus™.

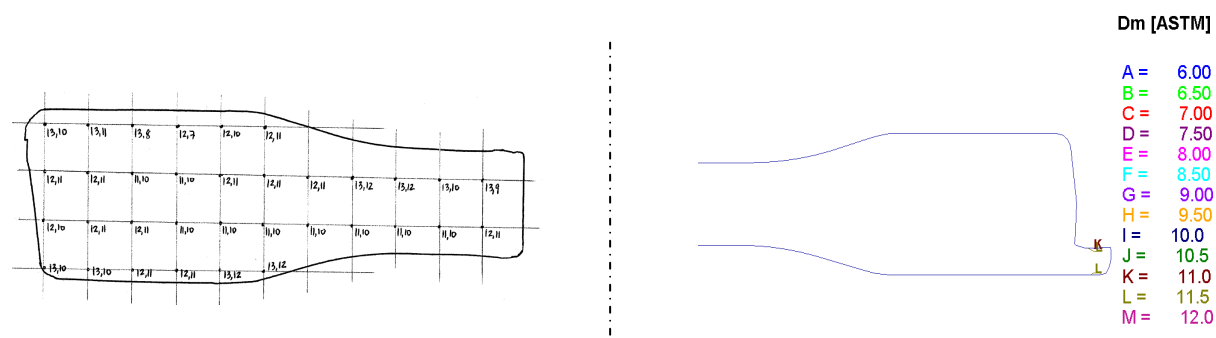


Figure 4: Measured and calculated grain size distribution in the Process 2 forging at 1000 °C for IN718. Please note that the grain size map is flipped.

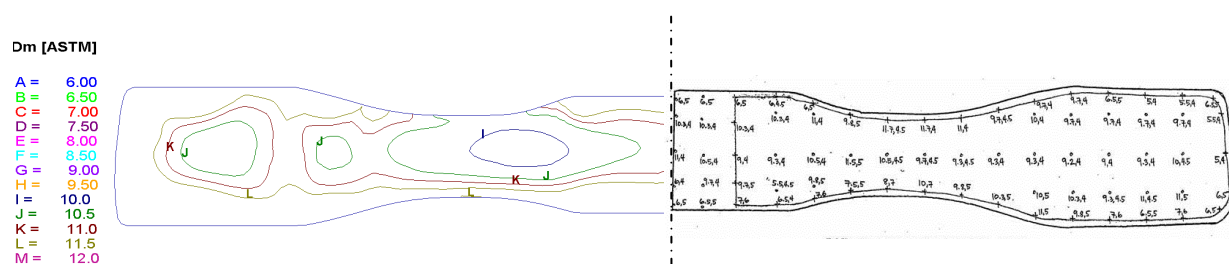


Figure 5: Calculated and measured grain size distribution in the Process 2 forging at 1000 °C for Allvac® 718Plus™.

Conclusion

A comparison between microstructure evolution in IN718 and Allvac® 718Plus™ by use of microstructure simulation was presented in this work. Differences in solution temperature of δ phase and their influence on the forging process were discussed. Two different forging routes and temperatures were compared in terms of final microstructure.

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