Superalloys 718, 625, 706 and Derivatives 2005 *Edited by E.A. Loria*
TMS (The Minerals, Metals & Materials Society), 2005

Development of forgeable Ni-base alloys for USC steam turbine applications by use of microstructure simulation and formability testing

X. Li[1], R. Kopp[1], M. Wolske[2]

[1]Institute of Metal Forming, RWTH Aachen University;
Intzestr. 10, Aachen, D-52056, Germany
[2]Now at Hydro Aluminium Deutschland GmbH;
Aluminiumstr. 1, Grevenbroich, D-41515, Germany

Keywords: Ni-base alloy, FEM simulation, microstructure model, forging, formability, etc

Abstract

For the industrial production of large safety components such as turbine discs and turbine shafts, FEM coupled microstructure modeling offers a possibility to describe the microstructural changes such as recrystallization and grain growth during forming. Therefore, the material performance during the production process can be judged by understanding of the microstructure information.
In this project, the microstructure evolution and the formability during the industrial processes were investigated with the help of FEM simulations. For numerical investigation of a forging process, compression tests, stress relaxation tests and annealing tests were carried out. After the analysis of the experimental results and the metallographic research on the immediately quenched specimens, microstructure models for simulating recrystalization and grain growth on the basis of empirical-phenomenological equations were developed for each alloy. The models were verified and fitted by means of 3-step compression tests. Finally, a sequence of upsetting and hammer forging operations were simulated via FEM coupled microstructure simulation. To determine and compare the formability of the investigated Ni-alloys, compression tests were performed using specimens with flange geometry.
The research was firstly focused on the commercial alloys Inconel 706, Inconel 617 and Waspaloy, to identify the best material candidate for the industrial processing and application of stationary steam turbine components. Based on these results, two novel alloy variants, “DT 706” and “DT 750”, were developed and studied again with the above described approaches.

Introduction

The joint research project “Wrought Ni-Base Superalloys for Steam Turbine Applications beyond 700°C” sponsored by the Deutsche Forschungsgemeinschaft (German Research Foundation) was originally to develop new Ni-base alloys for high-temperature applications in stationary power plants. In the first phase of the project, three commercial alloys Inconel 706, Inconel 617 and Waspaloy were selected, which represent alloys with γ''-hardening, solid solution hardening and γ'-hardening respectively. The manufacturability and mechanical performance (castability, forgeability, long term stability, creep strength, and creep crack growth resistance) of these alloys were investigated with respect to their applications for steam turbines above 700°C. With the knowledge gathered in the first phase, two novel alloys DT706 and DT750 were developed on the basis of Inconel 706 and Waspaloy. The same material properties were studied for both alloys in the second project phase. The chemical compositions of the investigated alloys are summarized in Table 1.

Alloy	Ni	Fe	Cr	Co	Mo	Nb	Al	Ti	C	Zr
Inconel 617	53.70	0.50	22.00	12.90	9.05	-	1.11	0.55	0.060	-
Inconel 706	41.96	36.97	16.02	0.05	-	3.02	0.20	1.55	0.010	-
Waspaloy	57.10	0.57	19.35	14.00	4.52	0.01	1.22	3.13	0.033	0.06

Table 1: Chemical composition in wt.-% of Inconel 617, Inconel 706 and Waspaloy

The forgeability of the alloys was studied at IBF (Institut für Bildsame Formgebung), RWTH Aachen University by means of FEM coupled microstructure simulations, in which the microstructure evolution caused by recrystallization and grain growth were taken into account, in order to predict the material flow and microstructure development under industrial like process conditions. The formability of the alloys was also investigated via compression tests using specimen of flange geometry. Here, the method of acoustic emission analysis was used to predict the point of crack initiation.

Experimental procedure and determination of material data

Material models are necessary for the forming simulations to describe the material behavior under the given process condition. Additionally, microstructure coupled simulation could be used for rating the materials according to their performance during the process.
Uniaxial cylinder compression tests with Rastegaev specimen were carried out to measure the flow curves [1]. Test temperatures covered a range from 900°C to 1100°C for Inconel 706 and Waspaloy, and from 950°C to 1150°C for Inconel 617 in steps of 50°C. The strain rates were set to 0.001/s, 0.01/s, 0.1/s, 1/s, and 10/s for the three alloys. After upsetting, the compressed sample was immediately quenched in water to enable the metallographic investigation on the deformed microstructure. The obtained flow curve data was corrected to eliminate the softening effect caused by dissipation. After the metallographic investigation, in which the initial grain size, the volume fraction of recrystalized microstructure and the grain size after dynamic recrystallization of the compressed samples were determined, the model parameters describing the flow stress and microstructure development were ascertained, under the consideration of both work hardening and softening mechanisms. The results have been previously reported by Kopp and Wolske [2].
Besides dynamic recrystallization, grain growth also has a significant influence on the microstructure development during the industrial manufacturing process. By means of annealing tests, the relationship between final grain size d_{GG}, initial grain size d_0, annealing time t, and annealing temperature T was established according to the following equation recommended earlier by Sellars [5]:

$$d_{GG}{}^{h_4} = d_0{}^{h_4} + h_5 \cdot t \cdot \exp\left(\frac{-Q_{GG}}{R \cdot T}\right) \qquad (1)$$

where Q_{GG} is the activation energy for grain growth, h_4 and h_5 are material constants and R is the universal gas constant. The coefficients of equation 1 for the alloys studied are given in Table 2.

Alloy	h_4	h_5 in µm/s	Q_{GG} in kJ/mole
Inconel 706	4.5	3.5×10^{21}	395
Inconel 617	3.0	9.0×10^{19}	310
Waspaloy	4.5	3.0×10^{17}	375

Table 2: Material constants and activation energy for grain growth model

The FEM coupled microstructure simulation is implemented in the program Strucsim [3]. Using Strucsim, together with the implicit FEM code Larstran, the interdependence of flow stress and strain, strain rate, temperature, and grain size can be reflected in FEM coupled microstructure simulations. The current local forming parameters (strain, strain rate, temperature) are delivered from Larstran to Strucsim in each iteration. Based on these data, the microstructure changes i.e. recrystallized volume fraction and grain size, as well as microstructure dependent flow stress will be calculated by Strucsim. The calculated flow stress will be given back from Strucsim to Larstran. With this flow stress, the forming data for the next step will be calculated by the FEM code Larstran [3].

Three-step compression tests were performed as model validation. Goal of such tests is to verify the determined microstructure models with use of an inhomogenous and nonsteady-state process on laboratory scale, since the model parameters were all determined under homogenous and steady-state conditions (constant temperature, constant strain rate). The principle of this test is given in Fig. 1 and the micrographs of Inconel 706 obtained after each single step are also included.

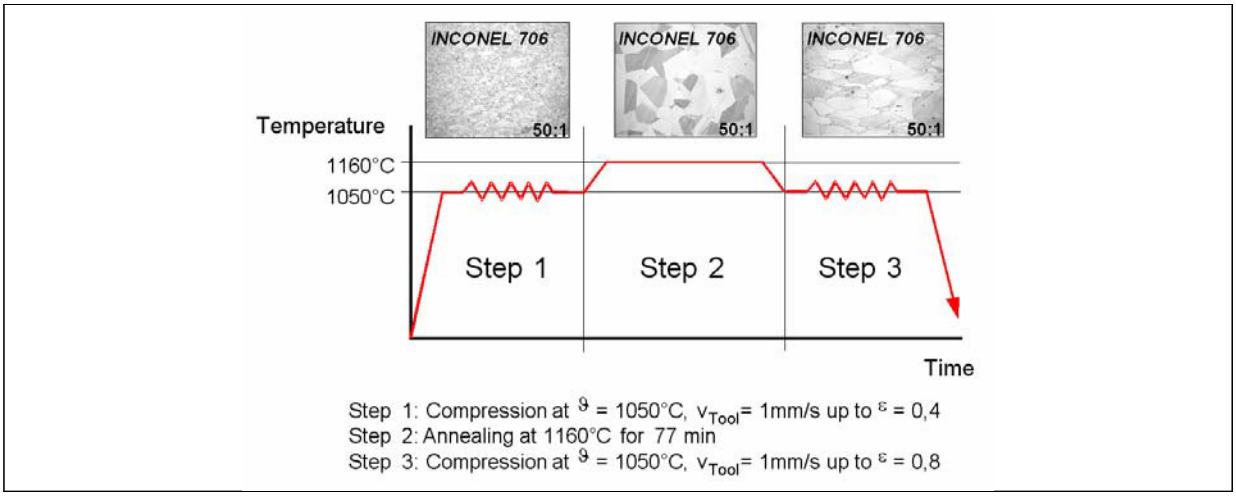

Fig. 1: Principle of a three-step compression test with Inconel 706 for the model validation

The sequence of the experiments was simulated using the established microstructure models. The boundary conditions of the simulations were reported by Rösler et al. [4]. Fig. 2 shows the results (load curve) of the simulations for the three alloys. Good agreement between measured and simulated loading for all the investigated alloys can be seen in Fig. 2.

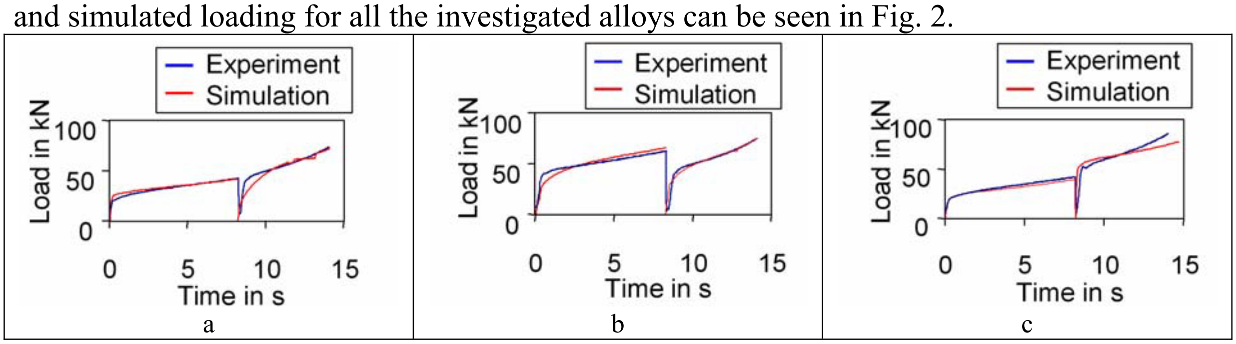

Fig. 2: Comparison of measured and simulated loads for the model validation with three-step compression test for a: Inconel 706, b: Inconel 617, and c: Waspaloy

3-D Process Simulation

Forging of remelted ingot to the final shape of a turbine rotor is carried out in several steps. At first, an upsetting operation is performed to break up the large as-cast grain structure. The final shape is usually obtained in succession of several hammer forging and upsetting operations [4]. Two criteria have to be considered for the forgeability assessment. Firstly, the flow stress at forging temperature should be as small as possible since press load capacities are limited. For the material with a lower flow stress, a greater deformation can be reached in each process step.

This means a more reasonable utilization of the available equipment. Secondly, a homogenous and refined grain size at the end of deformation is required.

The operation series were simulated via FEM integrated microstructure simulations for the three Ni-base alloys [4]. The calculated normalized loads and dynamically recrystallized grain size after upsetting simulations are presented in Fig. 3. In Fig. 3b it can be seen, that among the three alloys, Inconel 617 exhibits the maximum force requirement, while Inconel 706 possesses the minimum one. The reason is, as explained by Kopp and Wolske [6], the strengthening phases of Waspaloy and Inconel 706 are dissolved at forging temperature, leaving solid solution strengthening as the remaining hardening mechanism. The grain size evolutions at the examined positions in dependence of the equivalent strain ε_{eq} are included in Fig. 3c and Fig. 3d as well. It is clear, that Waspaloy exhibits the best grain size homogeneity (minimum grain size difference between center and surface), while Inconel 617 displays the maximum grain size gradient.

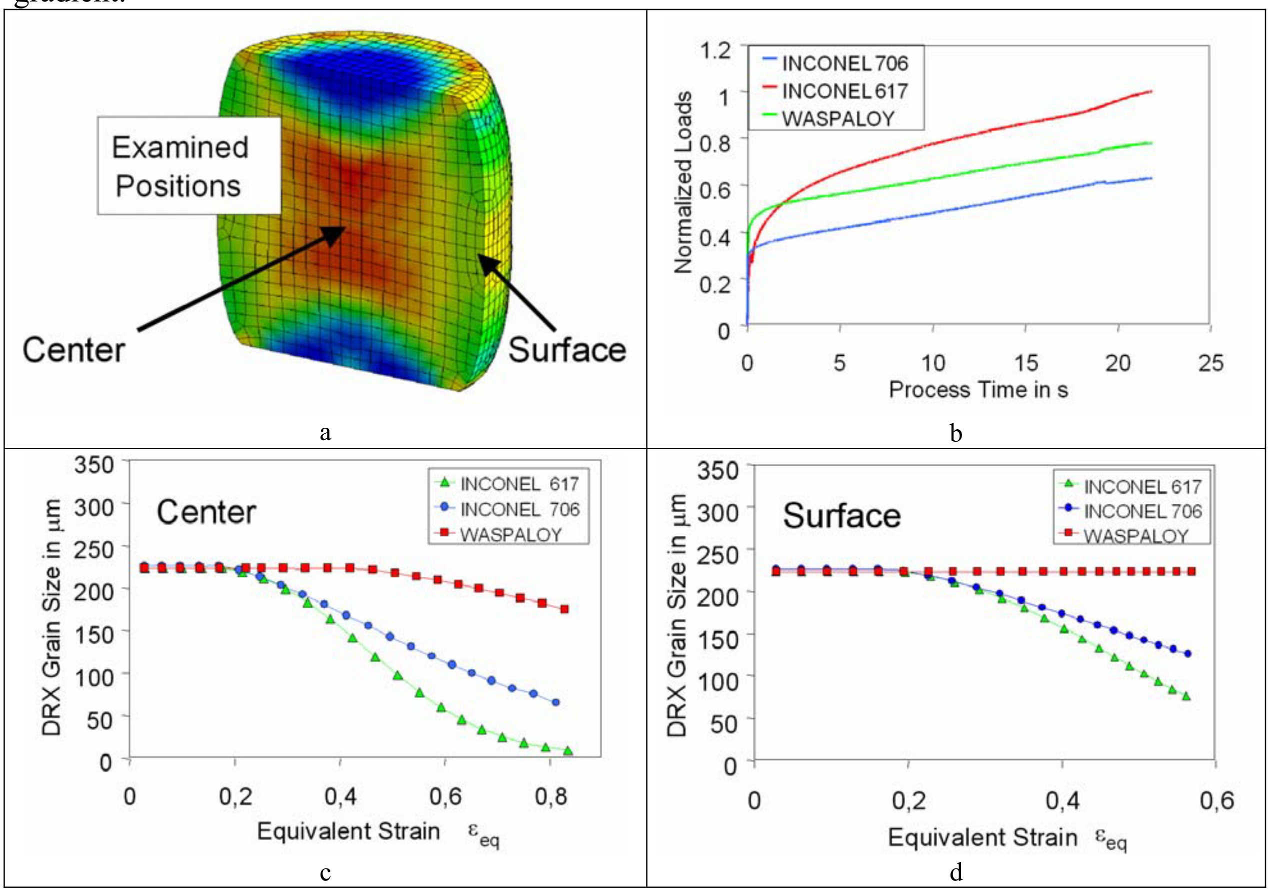

Fig. 3: FEM integrated microstructure simulation for upsetting of a billet with a height reduction of $\varepsilon_h=\Delta h/h_0=0.75$ (initial grain size: 220 µm). a: examined positions on the 3D FEM model. b: comparison of normalized calculated loads for the three alloys. c: calculated DRX grain size development in the center. d: calculated DRX grain size development at the surface.

After upsetting, the compressed ingot should be processed by several steps of hammer forging until an extension ratio of 1.345 is reached. The longitudinal length of the ingot will be covered by forging in three strokes within one pass. Then the dies are turned 90° in simulation for the next pass and move backwards. After such a cycle the cross section of the billet will turn from round to square. To study the grain size homogeneity, two auxiliary lines along the longitudinal axis were imported in the center and at the surface of the ingot respectively, as shown in Fig. 4. The calculated grain size of each node located on the auxiliary lines was recorded. Fig. 4 illustrates the grain size distribution along the longitudinal axis at the end of two pass simulations. Again, Inconel 617 displays the least homogeneity of grain size both in the center and at the surface of the ingot, while Waspaloy showed the most favorable homogeneity among the alloys investigated. The comparison of the forging forces also proved, the calculated stress in Inconel 617 exceeds that in Inconel 706 by a factor of 2 [6].

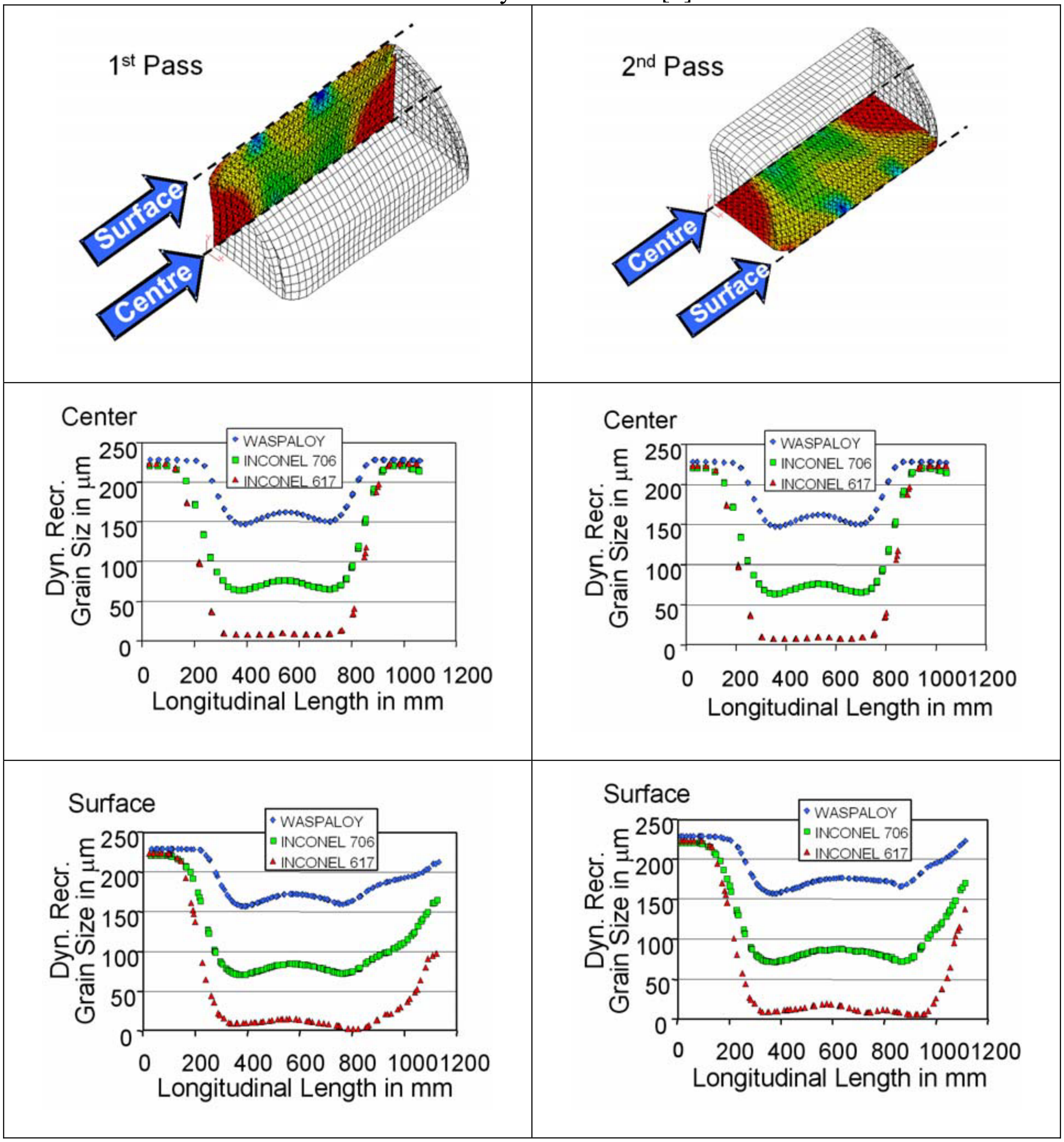

Fig. 4: Grain size distribution after simulation of hammer forging from round to square cross section

Formability of the analyzed alloys

After the investigation of the forgeability during manufacturing of large turbine components, the global formability of each alloy is analyzed and compared. As described in previous work [6], the compression tests with sample geometry 'flange' were carried out at temperatures of 800°C and 950°C with a constant strain rate of 0.05/s. For detection of the crack initiation, acoustic emission analysis was used. The temperature 800°C is regarded as the lower boundary during forging, which could be reached in the contact area between the hammer and the work piece. The cracks will normally be initiated at the flange of the sample, where the highest tangential tensile stresses are present. Here a specific height reduction up to crack initiation is introduced to quantify the level of formability (Equation 2) [6].

$$\varepsilon_{h,c} = \left| \frac{h_1 - h_0}{h_0} \right| \qquad (2)$$

As shown in Fig. 5, no appearance of crack was found for Inconel 706 at 950°C, while Inconel 617 and Waspaloy show an average value of 0.66 and 0.69 respectively. The formability at the test temperature of 800°C shows a significant loss of ductility for all alloys. In this case, Inconel 706 proved to be the most ductile alloy among those investigated due to its highest average value of specific height reduction up to crack initiation ($\varepsilon_{h,c} = 0.71$). With the decreased temperature the formability of Inconel 617 and Waspaloy drops dramatically, as observed in Fig. 5. This can be explained by the increased solid solution (Inconel 617) and the inhibition of dynamic recrystallization (Waspaloy) [6]. Waspaloy turns out to be the most unfavorable alloy at 800°C.

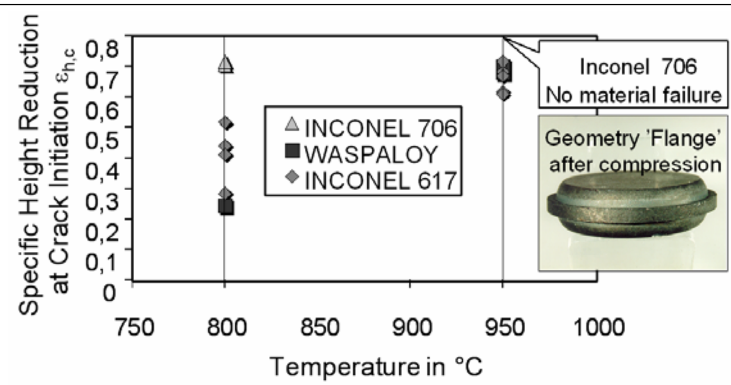

Fig. 5: Temperature dependency of formability for the investigated Ni-base alloys. As example, the final shape of sample of Inconel 706 is shown, after compression at 950°C

Investigation of the new alloys

Considering both the forgeability and the formability studies, it could be concluded, that Inconel 617 appeared to be the least suitable candidate for the application in USC steam turbines mainly due to its high flow stress at forging temperature. Inconel 706 was found to be a good choice because of its combination of low forging forces, grain refinement behavior and the good formability. Combined with other mechanical performance studied by further project partners, two new alloys, “DT706” and “DT750”, were developed on the basis of Inconel 706 and Waspaloy respectively within the framework of this project. Their chemical compositions are listed in Table 3.

Alloy	Ni	Fe	Cr	Co	Mo	Nb	Al	Ti	C	Zr
DT750	Bal.	**-**	19.3	13.84	4.5	**1.53**	1.32	**1.52**	0.027	0.042
DT706	Bal.	**22.17**	17.65	-	-	3.03	0.55	**1.93**	0.007	-

Table 3: Chemical composition in wt.-% of DT750 and DT706

Microstructure models to describe dynamic recrystallization and grain growth were established with uniaxial compression tests and annealing tests for the new alloys as described before. The softening effect caused by static recrystallization is also considered for the new alloys, in order to simulate the grain size evolution during holding time. The models for the static recrystallization were determined by stress relaxation tests.

At the stress relaxation test, the die is stopped after a pre-defined deformation and is kept to a constant distance for a certain time (Fig. 6). The sample experiences no more plastic deformation, but maintains its elastic deformation at the beginning of the relaxation time. At this moment the sample is loaded by a stress which is just slightly below the flow stress.

Because of the static softening mechanisms under the hot deformation conditions during the relaxation time, such as static recovery and static recrystallization, the flow stress of the material will drop under the presented stress and plastic flow takes place. The presented stress will be reduced in this way until it lies under the current flow stress again. In this way the elastic deformation of the sample will be successively relieved by the plastic deformation [8].

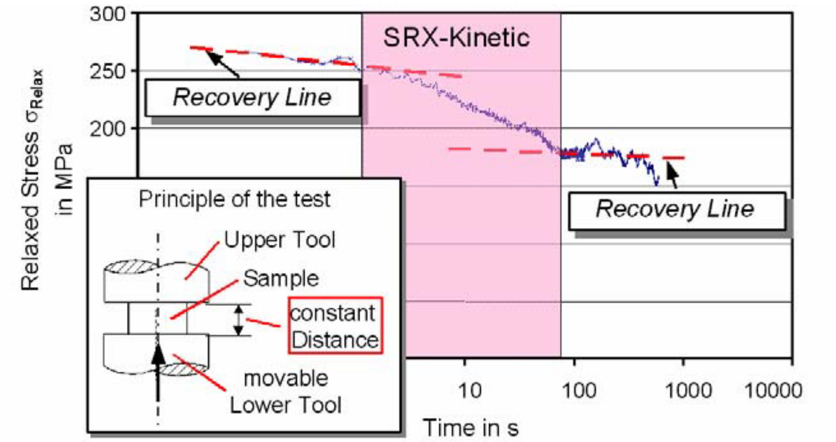

Fig. 6: Principle of the stress relaxation test and the result analysis

According to Karjalainen [7], the kinetic of the static recrystallization can be derived from the progress of relaxed stress (Fig. 6). It is characterized by the time of 50% static recrystallization $t_{0.5}$, and can be described by the following equation [9]:

$$X_{SRX} = 1 - \exp\left((-\ln 2) \cdot \left(\frac{t}{t_{0.5}} \right)^{g_1} \right) \qquad (3)$$

where X_{SRX} is the statically recrystallized volume fraction, t is the process time and g_1 is the Avrami exponent, which can be determined for each test.
After the regression according to equation 3 the $t_{0.5}$ of each test can be ascertained. The further determination of the activation energy for SRX Q_{SRX} was described by Sellars et al. [9]. The description of the grain size after SRX d_{SRX} was also recommended by Sellars et al. [9]:

$$d_{SRX} = c_1 \cdot d_0^{\,c_2} \cdot \varepsilon^{c_3} \cdot Z^{c_4} \qquad (4)$$

where c_1-c_4 are material related constants, d_0 is the initial grain size, ε is the strain in the pre-deformation and Z is the Zener-Hollomon parameter.
After the establishment of the microstructure model for static recrystallization, the developed models (DRX+SRX+GG) are verified simultaneously with the help of three-step compression tests. The results are shown in Fig. 7.

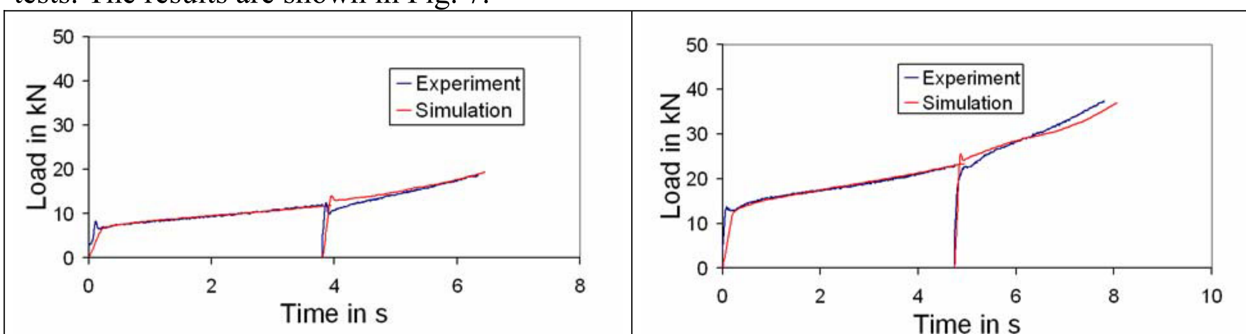

Fig. 7: Comparison of measured and simulated loads for the model validation with 3-step compression test for a: DT706 and b: DT750

The upsetting and hammer forging operations were again simulated with FEM integrated microstructure models. Comparing the calculated upsetting forces of the alloys (Fig. 8a) one can see, that the developed alloys generally possess much lower upsetting force levels than the original alloys do. In terms of force reduction to favor the manufacturing process, the alloys development was successful, since a lower flow stress level is reached. However, the grain size gradients of the new alloys are less favorable than the original ones, as shown in Fig. 8b.

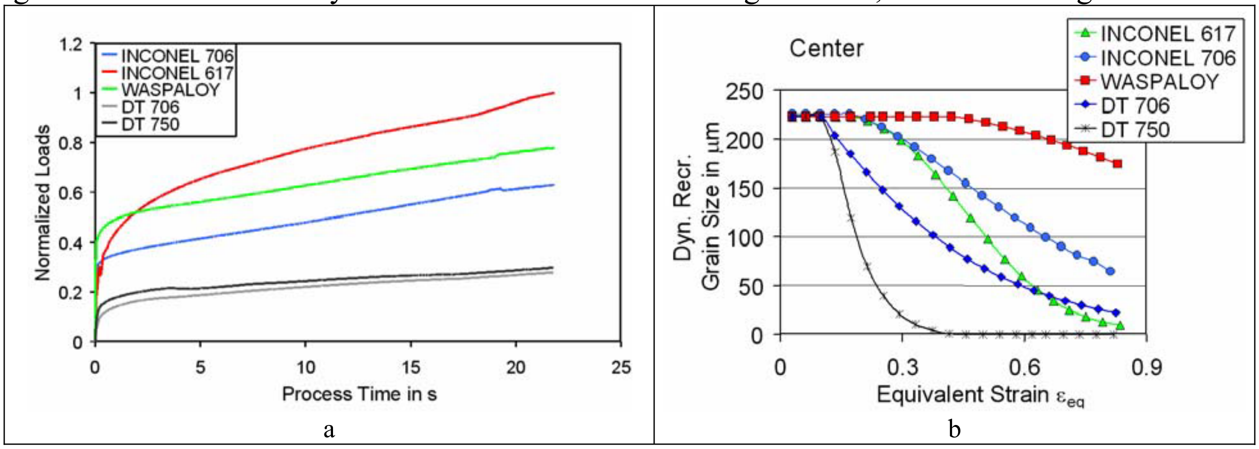

Fig. 8: Comparison of the results after the upsetting simulations of the investigated alloys. a: Upsetting forces. b: Grain size distribution in the center of the billet during the upsetting.

The results after two-pass hammer forging simulations in Fig. 9 show that the grain size distribution for the alloy DT750 turns out to be worse compared to that of Waspaloy. At the cross section, the minimum grain size at the surface reaches 97 µm, while in the center the grain size still remains over 200 µm, so that a great grain size gradient is formed across the cross section. In the contrary, the alloy DT706 displays better microstructure homogeneity in comparison with its original alloy Inconel 706 (Fig. 9b).

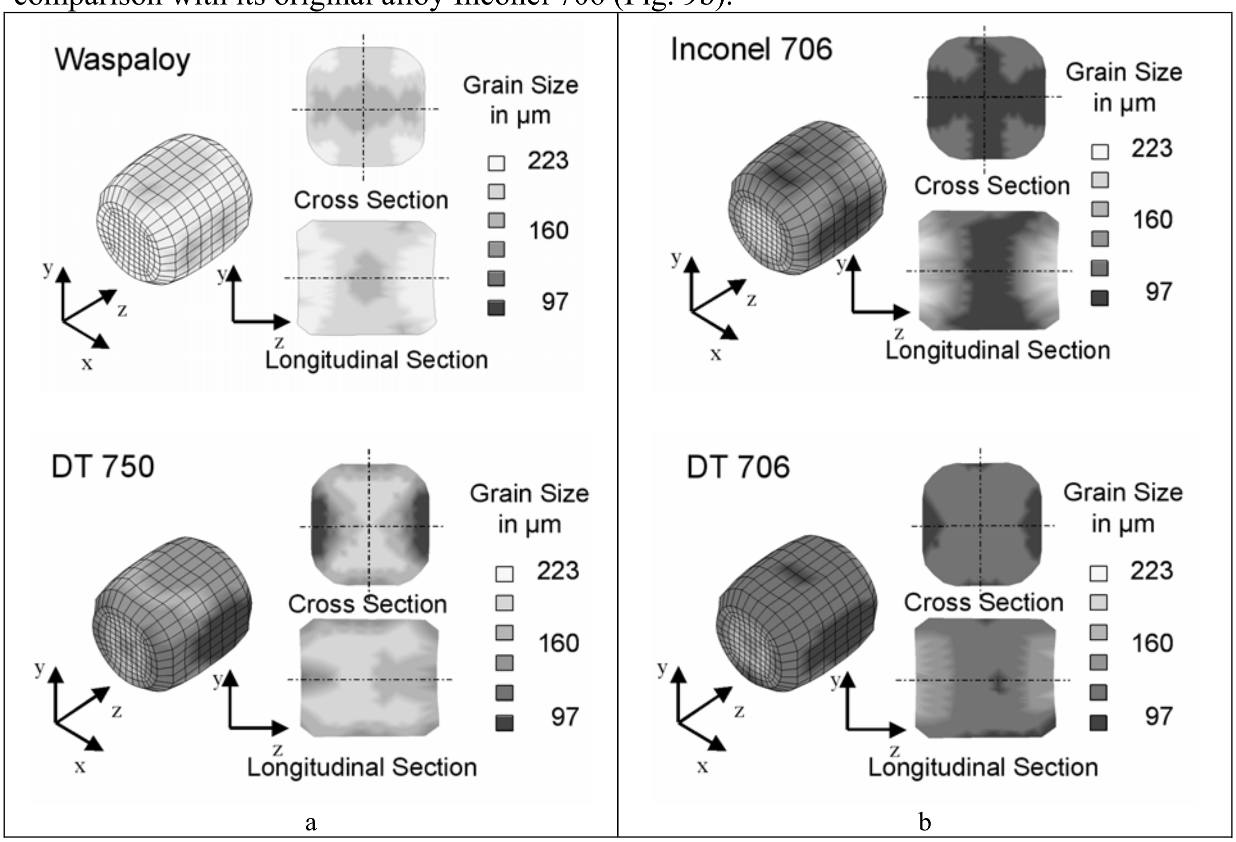

Fig. 9: Comparison of the grain size distribution of the basis alloys and the novel alloys after the 2-pass hammer forging simulations. A: Waspaloy vs. DT750, b: Inconel 706 vs. DT706

The results of the formability study for the new alloys are shown in Fig. 10. Alloy DT750 displays a better performance in the formability test in comparison with its original alloy Waspaloy. In the contrary, the formability deteriorates after the development from original alloy Inconel 706 to DT706. However, the formability of DT706 still remains about 23% greater than it of DT750.

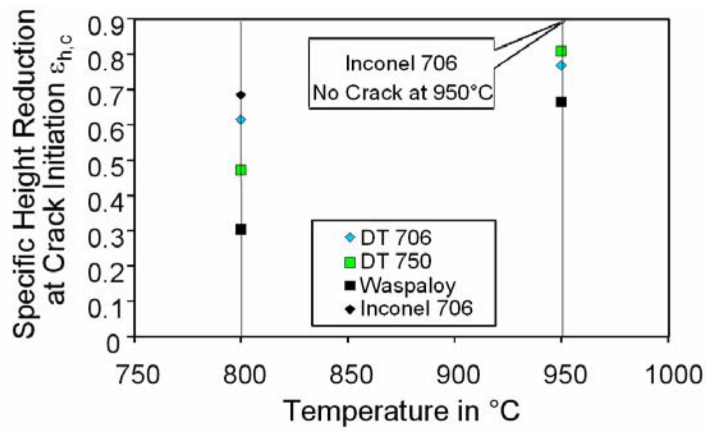

Fig. 10: Comparison of the formability between the basis alloys and novel alloys

Conclusions

Ni-base alloys, Inconel 706, Inconel 617 and Waspaloy, were first investigated under industrial like forging conditions. Three criteria are applied to judge their appropriateness for applications in steam turbines above 700°C: i) grain size gradient; ii) forging force requirement; iii) formability. The forgeability (grain size gradient and force requirement) of the alloys are studied and compared by means of FEM coupled microstructure simulations. The formability of the alloys is determined by using hot compression test with the sample geometry ‘flange’. Two novel alloys DT706 and DT750 were developed on the basis of Inconel 706 and Waspaloy respectively. They were studied with the same approach. The performance of the five alloys can be classified as Table 4. according to the criteria given above.

Criterion	1	2	3	4	5
Grain size gradient	Waspaloy	DT706	DT750	Inconel 706	Inconel 617
Force requirement	DT706	DT750	Inconel 706	Waspaloy	Inconel 617
Formability	DT706	Inconel 706	DT750	Waspaloy	Inconel 617

Table 4: Classification with grade 1 (most appropriate) and grade 5 (most inappropriate) for the investigated Ni-base alloys

The alloy DT706 can be regarded as the most appropriate candidate for the forging process, which possesses the best formability and lowest force requirement during forging. The grain size gradient of DT706 due to recrystallization and grain growth proved to be the second favorable. Because of the low formability, the high force requirement and the formation of great grain size gradient, Inconel 617 is classified as most inappropriate for the production of large turbine components.

Acknowledgements

The authors gratefully acknowledge the financial support of the Deutsche Forschungsgemeinschaft within the joint research project DT5. Material supply by ABB Alstom Power Ltd., Baden (Switzerland) and Saarschmiede GmbH, Freiformschmieden, Völklingen (Germany) is also greatly appreciated.

References

[1] R. Kopp, R. Luce, B. Leisten, M. Wolske, M. Tschirnich, T. Rehrmann, R.Volles, “Flow stress measuring by use of cylindrical compression test and special application to metal forming processes”, steel research 72, 2001, p.394-401

[2] R. Kopp, M. Wolske, “Microstructure Simulation of Ni Based Alloys”, Proc.,IV Conf. Int. De Forjamento/Brasil (XX SENAFOR), Porto Alegre, Brasile, 2000, p.42-53

[3] K. Karhausen, “Integrierte Prozeß- und Gefügesimulation bei der Warmumformung”, PhD Thesis, Institute of Metal Forming, RWTH Aachen University, Germany, 1994

[4] J. Rösler, M. Götting, D. del Genovese, B. Böttger, R. Kopp, M. Wolske, F. Schubert, H.J. Penkalla, T. Seliga, A. Thoma, A. Scholz, C. Berger, “Wrought Ni-Base Superalloys for Stream Turbine Applications beyond 700°C”, Advanced Engineering Materials, Vol.5, No.7, 2003, p.469-483

[5] C.M. Sellars, “The Physical Metallurgy of Hot Working”, Hot Working and Forming Processes (Eds: C.M. Sellars, G.J. Davies), TMS, London, 1979, p.3-15

[6] R. Kopp, M. Wolske, “Alloy Design for Ultra High Temperature Steam Turbine Applications: Simulation of Microstructure during Forging”, The 4th Liège Conference: Materials for Advanced Power Engineering 2002, Liège, Belgium, Vol.21, Part 1, p.325-334

[7] L.P. Karjalainen, “Stress relaxation method for investigation of softening kinetics in hot deformed steels”, Materials Science and Technology, 11, 1995, p.557-565

[8] R. Luce, “Integration metallphysikalischer Werkstoffmodelle in die FEM zur Simulation von Umformprozessen”, PhD Thesis, Institute of Metal Forming, RWTH Aachen University, Germany, 2002

[9] C.M. Sellars, A.M. Irrisari, E.S. Puchi, “Recrystallization characteristics of aluminium-1% magnesium under hot working conditions”, Symp. On Microstructural control in Aluminium Alloys, Met. Soc. AIME Meeting 1985, p.179-196