



Fatigue 2010

## Lifetime evaluation of hot forged aerospace components by linking microstructural evolution and fatigue behaviour

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Received 26 February 2010; revised 12 March 2010; accepted 15 March 2010

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### Abstract

The present work aims at linking the local distribution of fatigue strength in a forged part to its manufacturing process. To this purpose, a predictive fatigue strength model for Inconel 718, also including the operating temperature, is derived from a reduced set of numerous microstructural parameters. The model is implemented, along with a microstructural evolution model from earlier work [4], into a finite element code in order to predict the local fatigue strength distribution in a component after being subjected to an arbitrary forging process.

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*Keywords:* Fatigue; Hot Forging; Inconel 718; Microstructure

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### 1. Introduction

The nickel-base alloy Inconel 718 has been very successfully used under extreme conditions for many years, mainly because of its resistance against creep and corrosion. One of the most prominent areas of use is in aircraft turbines, where the blades are confronted with corrosive atmosphere, high temperatures and enormous centrifugal forces. With the aim to improve the mechanical properties further, these heavy duty components are often forged. In the aircraft industry, great emphasis is put on lightweight construction as well as on operational reliability and safety, and so a matter of particular interest already in the design stage is an accurate assessment of product lifetime. The present contribution aims at establishing a link between the microstructure resulting from a particular forging process and the component's fatigue lifetime. The static strength properties of a material are often predicted via a Hall- Petch relation using the grain size. However, the estimation of the fatigue strength from the microstructure is

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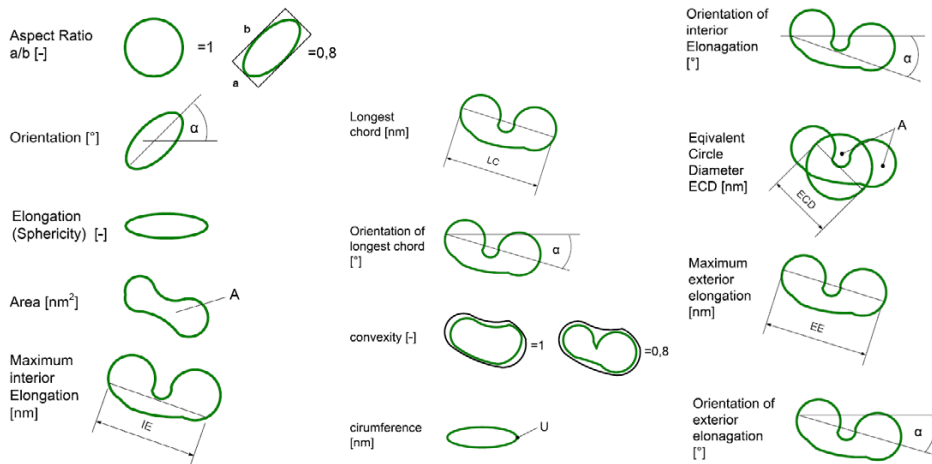


Fig. 1. Microstructural parameters analysed

more difficult. In an earlier work [1], many S/N curves were measured for different material conditions. Various specimens were machined from components with different geometries and forged with different forging aggregates.

Additionally the specimens were tested at various temperatures. During the forging process and the subsequent heat treatment there arise varying temperatures, plastic strains, strain rates and temperature gradients, so that there are huge distinctions in the local microstructure. In order to find a possible correlation between fatigue strength and microstructure, from nearly each specimen 16 micrographs in different coordinate directions were prepared. In a subsequent step all the micrographs were analysed in terms of numerous microstructural parameters using the software package Analysis.

The microstructural parameters analysed are shown Fig. 1. Besides the grain size, shape and orientation many additional parameters are covered. In addition, the microstructural parameters  $e$  and  $b$  from earlier work [1] are considered. Here,  $e$  is an indicator for the resistance against distortion. Fine and globular microstructure leads to a small value for  $e$ . The value  $b$  specifies the sensitivity of  $e$  with respect to the orientation of the loading. In this sense,  $b$  is descriptive of the material's anisotropy. For a more detailed discussion of the underlying model, the reader is referred to [1].

## 2. Results

To make the fatigue strength of the specimens comparable with the respective microstructure, each data point of the fatigue test results is related to a lifetime of 300,000 cycles by translating the point along the S/N curve as shown in Fig. 2.

In addition, the question arises whether the average values of the microstructural parameters are descriptive of the fatigue resistance, or whether fatigue failure follows rather the weakest link principle so that the extremal values of the microstructural parameters are more relevant.

Hence the mean values as well as the standard deviations of the microstructural parameters are considered. If a certain structural parameter such as the grain size exhibits, for two different specimens, identical mean values but different standard deviations, the specimen with the larger standard deviation contains a larger fraction of coarse grains (and is therefore assumed to be more susceptible to fatigue failure initiation). So, the standard deviation of the grain size is well suited for assessing the probability of coarse grains above a certain size; however, it gives no

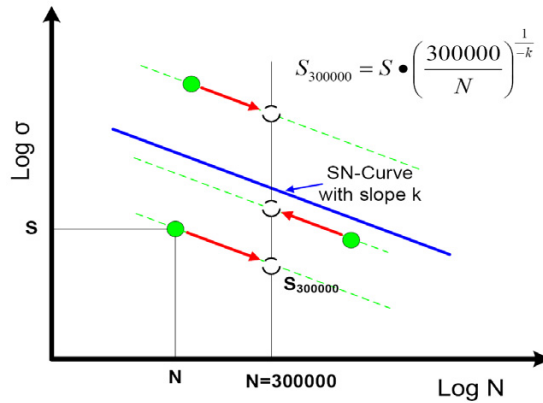


Fig. 2. Translation of test results along the S/N curve to the reference cycle number N=300000

information whether these coarse grains are homogeneously distributed or rather tend to agglomerate into clusters, which is also expected to influence the fatigue behaviour. To this purpose, an inhomogeneity parameter as proposed in [2] is also determined.

All micrographs were evaluated with respect to the mean value and standard deviation of the aforementioned microstructural parameters. The correlation of all of the parameters  $X$  with the fatigue strength  $Y$ , computed as

$$Corr(X, Y) = \frac{Cov(X, Y)}{\sqrt{Var(X) \cdot Var(Y)}} \tag{1}$$

with

$$Cov(X, Y) = E[(x - E(X)) \cdot (y - E(Y))] \tag{2}$$

is summarized in Table 1. A correlation of 1 means that there is a linear dependence between  $X$  and  $Y$ ; a correlation of -1 means that  $Y$  is an inverse multiple of  $X$ . A correlation of 0 implies complete independency of the two parameters  $X$  and  $Y$ .

In Table 1 all parameters having a correlation of at least 70% with the fatigue strength are marked by an X. Interestingly, all of these parameters, besides  $e$  and  $b$ , are a measure of the grain size, whereas grain shape, grain orientation and inhomogeneity do not have any influence on the fatigue strength.<sup>1</sup>

<sup>1</sup> In addition, the evaluation was performed not only on the complete micrographs, but also on subsets of the  $n$  biggest grains in a micrograph, with  $n$  taking values of 10, 30, 50, and 100. It turned out that the smallest variance between microstructural parameters and fatigue strength was reached if the complete grain ensemble was evaluated, which provides strong evidence against the weakest link hypothesis.

In order to determine the smallest possible set of microstructural parameters being able to give a reliable fatigue strength estimate, a factor analysis was performed on this data set [3]. Fig. 3 shows the result of the factor analysis, where the effect of all parameters is reduced to three fictitious influence factors. These three factors could be interpreted as a grain size factor, a grain shape factor, and a grain orientation factor. It is easily seen that the fatigue strength vector is almost collinear with the parameters related to the grain size. The length of an individual vector in the figure is a degree for the reproduction accuracy of the parameter by the three factors. A length of 1 means a reproduction accuracy of 100%.

84% of the total variation of all microstructural parameters can be reproduced by this three-factor model. Furthermore, the nearly absolute independency of the fatigue strength from the orientation and the grain shape is seen, because the vector components of the fatigue strength in these directions are almost zero (for clarity, only mean values are displayed in Fig. 2, and standard deviations are omitted).

In an attempt at further model simplification, only the parameters having at least a correlation of 70% to the fatigue strength are considered, cf. Fig. 3. In this case, the factor analysis yields only two factors. However, all parameters are along almost identical directions. This means that the fatigue strength can be described with about 70% accuracy by any one of the grain size parameters,  $e$  or  $b$ , all of them being almost linearly dependent from each other; in other words, almost no improvement over a single-factor model is to be expected

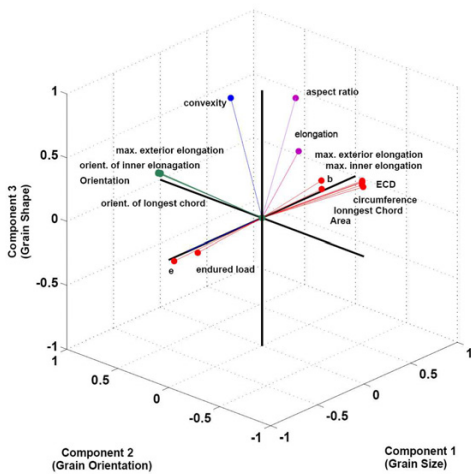


Fig. 2. Result of factor analysis (3 factors)

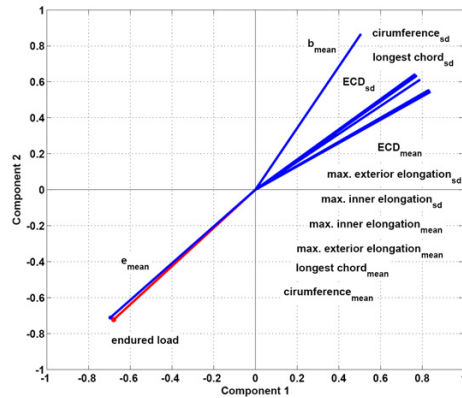


Fig. 3. Result of factor analysis (2 factors)

Table 1. Correlation of the various microstructural parameters with the fatigue strength

Microstructural parameter (m = mean value sd = standard deviation)	Correlation between microstructural parameter and fatigue strength	correlation higher than 70%
(fatigue strength)	(1,00)	
<i>e</i>	0,75	X
<i>b</i>	-0,70	X
aspect ratio m	-0,48	
aspect ratio sd	-0,20	
orientation m	0,10	
orientation sd	-0,02	
elongation m	-0,45	
elongation sd	-0,57	
area m	-0,69	
area sd	-0,67	
max. inner elongation m	-0,72	X
max. inner elongation sd	-0,74	X
orient. of interior elongation m	0,08	
orient. of interior elongation sd	-0,02	
ECD M m	-0,72	X
ECD M sd	-0,74	X
max. exterior elongation m	-0,72	X
max. exterior elongation sd	-0,74	X
orient. of exterior elongation m	0,10	
orient. of exterior elongation sd	-0,02	
longest chord m	-0,72	X
longest chord sd	-0,74	X
orient. of longest chord m	0,06	
orient. of longest chord sd	-0,02	
convexity m	-0,58	
convexity sd	0,17	
circumference m	-0,72	X
circumference sd	-0,74	X
inhomogeneity	-0,03	

On the basis of this evidence, a single-parameter approach was chosen for modelling the microstructural influence on the fatigue strength. For the particular case an exponential approach was chosen which uses the mean value of the parameter ECD (equivalent circle diameter). The fatigue strength  $S$  is then given by

$$S = 6.55 * e^{(-1.78 * \frac{ECD}{2718})} + 5.87 * e^{(-0.017 * \frac{ECD}{2718})} \quad (3)$$

In addition, the influence of the operating temperature on the fatigue strength must be accounted for. The behaviour of Inconel 718 at different temperatures can be seen from Fig. 4. From a polynomial fit, the temperature factor is determined as

$$\begin{aligned} r_{TEMP} = & -1.729 \times 10^{-11} * T^4 + 2.81 \times 10^{-8} * T^3 \dots \\ & -5.397 \times 10^{-6} * T^2 + 8.622 \times 10^{-4} * T + 1.504, \end{aligned} \quad (4)$$

giving a calculated, temperature dependent, normalised fatigue strength of

$$S_{real} = S * r_{TEMP} \quad (4)$$

Fig. 5 shows the comparison of the calculated fatigue strength values with the tested ones, all related to the reference cycle number of 300,000 load cycles. As can be seen, the predictive capability of the model is, despite its simplicity, quite satisfactory. The predictive accuracy of the resulting single-parameter microstructural model is about 75% , leading to a relatively big scatter band (Fig. 5). However, as stated above, no marked improvement is obtained by a two- or three-parameter model.

### 3. Conclusion

The present work shows that the multitude of microstructural parameters investigated can be reduced to a set of just 3 factors corresponding to grain size, shape, and orientation. From these 3 factors, only the grain size shows a significant correlation with the fatigue strength, leading to a single-parameter predictive microstructural model for the fatigue strength.

The model is currently being implemented, along with a microstructural evolution model from earlier work [4], into a finite element code in order to predict the local fatigue strength distribution in a component after being subjected to an arbitrary forging process.

Another interesting feature of Inconel 718 is its ability to be hardened by its precipitations  $\gamma'$  and the metastable  $\gamma''$ . The  $\gamma'$  phase stabilizes as the  $\delta$  phase, leading to massive losses in fatigue strength [5], [6], [7], [8]. During the forging process, disadvantageous temperatures can lead to increased amounts of  $\delta$ . It may be hypothesized that including the  $\delta$  content, or the fraction of carbides as an additional factor will improve the predictive capabilities of the current single-parameter model; related work is currently underway.

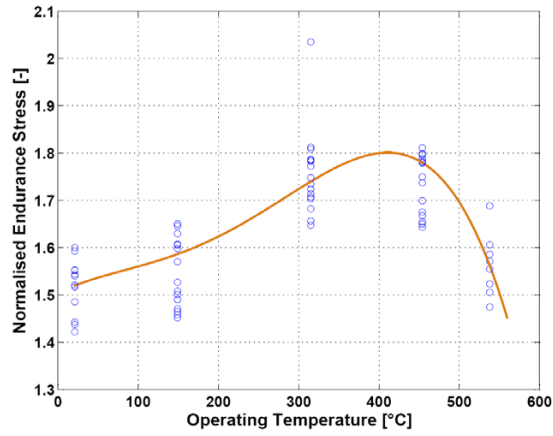


Fig. 4. Dependence of the fatigue strength on the operating temperature

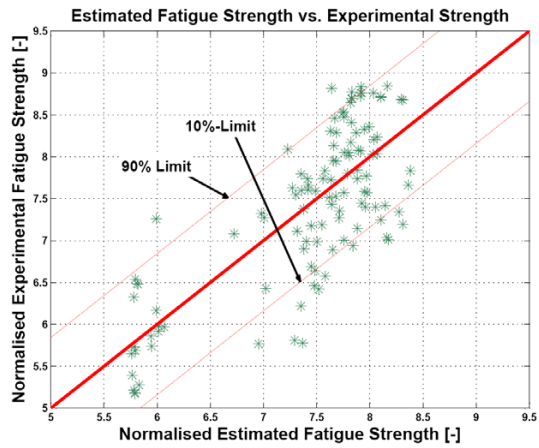


Fig. 5. Comparison of the calculated fatigue strength with the experimental results from fatigue test

### Acknowledgements

Financial support by the Austrian Federal Government and the Styrian Provincial Government, represented by Österreichische Forschungsförderungsgesellschaft mbH and Steirische Wirtschaftsförderungsgesellschaft mbH, within the research activities of the K2 Competence Centre on “Integrated Research in Materials, Processing and Product Engineering”, operated by the Materials Center Leoben Forschung GmbH under the frame of the Austrian COMET Competence Centre Programme, is gratefully acknowledged.

### References

- [1] Stoschka, M., Assessment of lifetime calculation of forged IN718 aerospace components based on a multi-parametric microstructural evaluation, in: *Proc. Superalloy* 2008
- [2] Maderbacher, H. Entwicklung eines Inhomogenitätsparameters für die Gefügeauswertung, *AMB Bericht Nr. AMB10B13*, Leoben 2010
- [3] Leyer, Multivariate Statistik in der Ökologie, *Eine Einführung*, Springer-Verlag Berlin Heidelberg 2007
- [4] Stockinger, M., Mikrostrukturelle Simulation des Gesenkschmiedens von Nickelbasis-Legierungen (Microstructural Simulation of Die Forging of Nickel Base Alloys; in German), Ph.D. Thesis, Technical University of Graz 2003
- [5] Changzheng, W., Effect of double aging treatment on structure in Inconel 718 alloy, *Journal of Materials Science* **39** (2004) 2593-2595
- [6] Antonsson, T., The Effect of Cooling Rate on the Solidification of INCONEL 718, *Metallurgical and Materials Transactions B*, Volume 36B, February 2005-85
- [7] Huang, Y., The evolution of delta-phase in a superplastic Inconel 718 alloy, *J Mater Sci* (2007) **42**:421-427
- [8] Investigation of Microstructural Changes in INCONEL 706 at High Temperatures by In-Situ Small-Angle Neutron Scattering, *Metallurgical and Materials Transactions A*, Volume 34A, December 2003-2781