ASSESSMENT OF LIFETIME CALCULATION OF FORGED IN718 AEROSPACE COMPONENTS BASED ON A MULTIPARAMETRIC MICROSTRUCTURAL EVALUATION

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Abstract

The goal of linking a fatigue life approach with different forging parameters enforces the consideration of the main process dependent influence factors, e.g. effective strain, effective strain rate, grain size etc. In case of forged parts, the thermo-mechanical process allows a specific adjustment of microstructural features like grain size or fraction of precipitates, etc.

Linking the specimen lifetime results to these microstructural features, a new design parameter for forged parts has been achieved. This forecasting parameter can be used in the preliminary design stage to optimize forgings with regard to lifetime. For this reason it is possible to get minimized weight and maximized lifetime in the final part and therefore optimize the total life cycle costs. The main objective of the research was the

development of a method to predetermine the lifetime of forged alloy 718 aircraft parts.

Introduction

To describe a forging process with the aim of linking a fatigue life approach, relevant influence factors must be considered. The presented methodology shows the generation and use of a microstructural based evaluation method to link the grain-based texture and morphology to fatigue. So, global parameters of the forging process and the coupled heat treatment are no longer needed for the derivation of this simulation model; but the resultant local texture and morphology of the microstructure is used in this context. The developed microstructural damage parameter allows an implementation of the forging process into damage concepts.

Figure 1. Flowchart of a microstructural based fatigue approach.

The microstructural evaluation is not only based on average grain size evaluation, but also a detailed particle-based examination is done. Additionally, the relationships of the particular grains are

included, leading to an adjacency matrix. The connectivity and the particle-based grain parameters allow the implementation of homologous unit-cell models. Due to combining results of grain

morphology and individual grain parameters, a stiffness transfer-function of unit-cells is realized.

Evaluating the transfer function by the use of finite element beam models, microstructural damage parameters to determine the position and shape of the specimen S/N-curves are achieved.

This new developed methodology allows a unified description between microstructure and fatigue life for IN718.

The flowchart in figure 1 shows a guideline of the holistic work. Each mark in figure 1 represents a dominant milestone in the development of a new microstructural based energy approach and is presented further on in detail.

Experimental Procedure

The task of determination the fatigue life dependency to the microstructure starts with experimental procedure, labeled as mark one in figure 1. The fatigue life behavior of three different forging processes was examined. The results are depicted in figure 2. The lifetime varies with the effective plastic strain rate, whereas specimens forged at the equipment with the lowest and the highest plastic strain rate show reduced lifetime compared to the screw press technology.

Figure 2. Comparison of the forging processes – IN718, rotating bending tests, survival probability 50 %.

Moreover the influence of notches and the type of loading was examined in order to build up a simulation model being capable to account the transferability of specimen data to forged aerospace components. Such a general fatigue model allows the calculation of the lifetime based on local stresses and stress gradients, e.g. by the use of the finite element method in every node of the model. To assess this local lifetime, the local strength of the material has to be known. By reason of the fact that mechanical properties vary in a wide range due to forging process dependent influence factors like effective strain, effective strain rate, grain size, grain morphology, etc., it is a comprehensive task to assess the local fatigue strength. Therefore, the manufacturing based knowledge of the local material properties in conjunction with the local fatigue strength build the fundamental of numerical fatigue life calculation using local stress concepts [1, 2].

To visualize the microstructural based influence of the forging process as well as the influence of different rolled pre-material lots, an excerpt of the tested fatigue life data is shown as S/N-curves. Two different suppliers of IN718 were examined using round billets with a diameter of three inches. Both suppliers used the double-melt-process (VIM+VAR) to manufacture the billets.

This two batches are further on called as pre-material lot one and pre-material lot two. The chemical composition of the main contingents of both batches is shown in table I. Evaluating the microstructure of metallographic sections an increased amount of as-large-as grains near the surface layer was found at pre-material lot two; as-large-as grain size of five to six compared to nine of pre-material lot one.

Table I. Chemical composition of IN718 pre-material billets as mass fraction percentage

Lot	Ni	Cr	Fe	Nb+Ta	Mo	Ti	Al
One	53.81	17.68	18.62	5.25	2.94	0.96	0.45
Two	52.83	18.10	18.15	5.41	3.00	0.98	0.54

To characterize the fatigue strength of these round billets, specimens were taken out of each lot and tested under rotating bending to achieve the influence caused by varying pre-material microstructure. The ‘fatigue limit’ in the low cycle fatigue region was evaluated with standard methods using the log-normal-distribution [3]. At the high cycle ‘fatigue limit’, the arcsin $\sqrt{p}$ -standard evaluation method was applied, see [4].

Figure 3. S/N-curve pre-material lot one, rotating bending tests.

Comparing both pre-material batches, it is obvious, that the fatigue behavior differs. Evaluating the microstructure of selected samples at three stress levels allows the analysis of the influence of the two pre-material suppliers.

Figure 4. S/N-curve pre-material lot two, rotating bending tests.

Due to the forging process a significant increase in fatigue life could be achieved, comparing figure 5 with figure 3. Screw press

technology was used as forging process in figure 5. While the number of transition cycles and the declination are nearly unaffected, the median stress level increases by one third at the transition region.

Figure 5. S/N-curve of forged pre-material lot one, forged with screw-press technology.

The thermo-mechanical process management has a major influence to fatigue life. To research this, the soaking time before forging of the rolled billets was changed significantly at the forging process of pre-material lot two. The cycle time (heat-up and soaking) was changed from about sixty minutes to one hundred and twenty minutes. The subsequent screw press forging step including the Inconel 718 heat treatment process kept unchanged. This distinct increase of soaking time led to grain growth. Minor variations of cycle-times are caused in industrial manufacturing; this intended increase of soaking time reflects a defined 'worst-case' forging scenario. Applying this 'worst-case' manufacturing forging process to the billets of pre-material lot two, the fatigue behavior as shown in figure 6 is achieved.

Figure 6. S/N-curve of forged pre-material lot two, modified thermo-mechanical heat treatment by extended soaking time.

Comparing the life time behavior of this 'worst-case' forged material, see figure 6, with the pre-material fatigue strength in figure 4, no significant increase is examined. Moreover, the fatigue life results in figure 6 show huge scatter; the median value of the S/N-curve is obviously lower than in figure 5. Examination of the microstructure on multiple metallographic sections shows that the grain distributions of both forged material lots are definitely different.

To allow a direct comparison of the different S/N-curves, all nominal stress levels are scaled in the same manner. Using standard test methods to determine the average grain size [5] like intersection counting or planimetric methods, no general applicable direct link between the tested S/N-curves and the microstructure was identified.

In addition to the presented choice of S/N-curves, other influence parameters on fatigue life like notch influence, mean stress ratio and forging parameters and technologies were examined; refer to [6, 7]. Supplementary, forged components have been tested and the microstructure analyzed. The examined S/N-curves of this extensive experimental work are posted as mark three in the general flowchart, see figure 1.

Metallographic Assessment

Across all tested S/N-curves, several specimens at three specified stress levels were chosen for metallographic investigation. Based on the specimens geometry orthogonal cuttings were applied to get metallographic sections. Hence, a total number of seventeen section points were inspected per specimen. The microstructure was investigated by light optical microscopy at different magnifications to achieve not only information about the shape of the grains, but also the amount of carbides, carbonitrides, twins and δ -phase. The used procedure is shown in figure 7.

From the images taken, grain boundaries were transformed into synthetic binary grain boundaries. In the creation process of these images, carbides and twins were extinguished. A particle based evaluation of the synthetic grain structure was done for each metallographic section. Due to the high amount of sections, the particle based evaluation was done using the special purpose software tool analySIS[®], which is widely used in microstructural evaluation. Additional scripts, written in ImagingC[®], suited the program to the user-specific needs. Moreover, the complete database management was done in analySIS[®]. As described in the section about the microstructural model, user-defined Matlab[®] executables, invoking comprehensive calculations, are called from the main program.

Figure 7. Metallographic section configuration and particle-based grain property evaluation.

An extensive table with particle based properties was achieved as a result of this step. The analyzed properties included planimetric measures like area, equivalent circle diameter as well as geometric properties like form factor, elongation, convexity, exterior diameter, interior extend and cord length. In addition, as parameters to describe morphology, both the center of gravity and its corresponding principal axes vector were determined.

Figure 8. Analysis of the crack surface (light optical and scanning electronic microscopy images including EDX-results).

To achieve a manageable number of influence factors, the examined fatigue tests for model evaluation were performed at room temperature. Verification work, presented later on, includes high temperature test results, too. In general the crack initiation started from the surface layer. To determine the influence of carbides and carbonitrides, each crack surface was investigated by the use of scanning electronic microscopy and energy dispersive X-ray mapping (EDX); see color-coded maps in figure 8 and circle-marked carbides in figure 9. Each fracture surface was electronically scanned near the crack initiation area. A three color coded EDX-mapping was done for each crack surface, involving specimen and part tests. In the first frame, labeled as one in figure 8, calcium, silicon and sulfur were grouped to red color to detect inclusions. Carbon was mapped green, blue characterizes the remaining oxygen. As shown in the first color coded frame in figure 8, no occurrence of inclusions was detected. Blue color appeared because of the remaining oxygen in the low level pressurized vacuum chamber. In the second frame, the map of nickel was colored red, niobium green and molybdenum blue. A heterogeneous appearance of δ -phase ($NiNb_3$) could not be detected. At least, aluminum and titanium were mapped with red color, to indicate the appearance of carbides. Chromium, mapped in green color, and ferrous, blue colored, completed the analyzed spectra.

Figure 9. Crack surface inspection of the forged part using light optical (LOM), laser scanning (LXT) and scanning electronic microscopy (SEM) including EDX-analysis.

A major fatigue-related influence of carbides near the surface layer couldn't be verified, neither on examined specimens nor on forged mount-link reference parts.

Summarized, the metallographic inspection of the cracked surfaces show that dominant 'as-large-as' grains play a major role in the crack resistance exposed to alternating load. This fracture behavior was found both at specimen and part fracture surface analysis, as shown in figure 9. Based on striation counting, these grains showed a dominant transgranular cracking behavior. Beside this, homogenous trans- and intergranular cracking was chiefly observed at the thermo-mechanical treated material. Therefore, the shape and adjacency of individual grains was founded to be the major point of interest further on.

The extensive failure analysis was done as an accompanying work to fatigue life tests. The analysis of the fracture surface including trans- and intergranular striation rating and carbide detection is drawn as mark two in the flow diagram in figure 1.

Microstructural Model

With the aim of correlating the fatigue lifetime with the morphology and texture of the thermo-mechanical treatment dependent microstructure, a short crack-growth analogy was used. The fatigue life chiefly depends on the mode and occurrence of crack growth channels on slip bands. The fast single slip crack growth or the slower double slip crack growth occur alternating interior the grain, dependent on the crystallographic orientation and dislocation appearance, as discussed in [9]. Once the crack tip reaches a boundary, a comparatively high energy input is needed to conquer this barrier. Because of this fracture mechanical based crack growth theory, a general description of the shape of the individual grains is used as the basis for the comparison of different microstructures to each other.

First, the shape based properties of each grain were calculated. A particle based tabular evaluation of the grain shape properties was done. Area, equivalent circle diameter, elongation, convexity, interior and exterior stretch and cord length were examined. The build-up of this extensive database is marked as point four in figure 1. Standard methods for evaluation of the mean grain size are well known in literature; see the standards in [5, 10-12]. For unimodal microstructure evaluation methods according to [5] were executed. For duplex microstructure, additional distinctions, as explained in [10], were considered. Due to this, standard values for the mean grain size of the metallographic sections were achieved.

Second, the relations between adjacent grains were assessed using the delaunay triangulation and connected by voronoi-polygons [13]. The calculation of these contiguity relations was implemented in Matlab[®] codes, which have been compiled and linked to analysiS[®]. By reason of the triangulation method is settled up in the center of gravity per grain, the tendencies in morphology can be clearly seen by visual inspection; compare to the voronoi-plots in figure 10. Mark five in figure 1 labels this milestone. For illustration, the metallographic evaluation in one point of one section is shown in figure 10 as an example of the whole investigated metallographic sections. The nominal stress levels S_a investigated were about 0.9 to 1.25. The accompanying number of load cycles to failure N varies from one to three millions.

Due to voronoi tessellation an auxiliary convex hull is build up. This convex hull is unrequested, because no grain specific properties exist for the hull. A user-defined function was implemented in Matlab[®] to remove the convex hull in a proper manner without affecting the remaining triangulation border.

Figure 10. Microstructural images; color coded with area and form factor information; voronoi-diagrams;
col. one: pre-material, see figure 3, $S_a \sim 0.92$, $N \sim 10^6$;
col. two: forging lot one, see figure 5, $S_a \sim 1.24$, $N \sim 7 \cdot 10^5$;
col. three: forging lot two, see figure 6, $S_a \sim 1.03$, $N \sim 2 \cdot 10^6$.

The particle-based grain properties were color-coded in the same manner, meaning that equivalent colored grains possessed the same specific property. Evaluated the ASTM grain size G with standard test methods for the two investigated pre-material lots, show that planimetric methods lead to a larger mean value $\bar{G}$ of the grain size than interception methods. These results are shown in [8]. Additionally, the number of as-large-as (ALA) grains N_{Gj} was counted, regarding to the definitions in [11]. Exemplary results are shown in table II.

Due to the spread of the ASTM G number in planimetric measurement, the interception method according to Abrams was used as reference further on. The number of as-large-as grains varies in a wide range; the new microstructural evaluation method has to combine and benchmark the mean grain size, the scatter and the amount of as-large-as-grains in a combined unique manner.

Table II. Excerpt of planimetric and interception measurement and number of ALA grains

Planimetric measures in three points of one section	Interception method	As-large-as grains
$\bar{G} = 9$ $7.5 < G < 10$	$\bar{G} = 8$	$N_{G5} = 1$
$\bar{G} = 8$ $7 < G < 11$	$\bar{G} = 7.5$	$N_{G6} = 45$
$\bar{G} = 9$ $7 < G < 10$	$\bar{G} = 7.5$	$N_{G5} = 8$

The microstructural link between adjacent grains is generally defined as equation (1) using an ellipsis as constitutive geometry.

$$EPROP \sim \frac{l_n^2}{2(l_h + \sqrt{l_h^2 - l_n^2 \cos(\alpha_{hCOG})})} A^{f^1 k f^2 e f^3} \quad (1)$$

The main idea of interconnecting two adjacent grains aims in finding an adequate universal substitution for the shaped grain boundary, which is not regular in most cases. After some iteration work, it was found out that synthetic ellipsis matches the grain

properties with minimized loss of accuracy. The axes of the ellipsis are signed as major radius l_h and minor radius l_n . Additional influence factors like convexity k and elongation e are integrated. The use of exponential factors f_j ensures an adequate transformation of the microstructural properties.

As an example, considering the link of grain number one and two in figure 11, the angle of the specific link, e.g. β_{III} , and the orientation vector of the major ellipsis radii, e.g. δ_{III} , are used to define the connecting element property.

Following these rules, homologous models were built up, for each grain according to the number of its independent links. This milestone is shown as mark six in figure 1.

Figure 11. Homologous model of interacting grains.

In detail, the calculation of the major radius of the synthetic ellipsis is based on the unbiased average of interior extent, exterior diameter and cord length. The minor radius is build up as sum of two parts; one the one hand based on area equivalency and on maximum interior extent on the other. The summarizing equation is multiplicative weighted by convexity and elongation. For linking the properties of the two adjacent grains, the proposed equation (2) was implemented in the program. Using this relationship, both small-small and large-large combinations can be described in an adequate manner.

$$EPROP(r_j, r_m, f, k) = \frac{r_j (f + k)}{\left[1 - \left(\frac{r_m - r_j}{r_m} \right) \right] f k 2} \quad (2)$$

The values r flags the synthetic ellipsis radii at the connecting link angle β of the adjacent grains. Subscriptions j and m identify the connected grains, e.g. $j = I$ and $m = II$ as shown for the link in figure 11. Form factor f and convexity k are considered in equation (2). So, resulting from the voronoi triangulation each grain was linked to others in a unique manner. Each link was modeled as a two element beam with a unique material property card, depending on the shape of the connected grains. Using this procedure for the whole triangulated matrix, a synthetic microstructure with adequate stiffness was build up. In the next step, the synthetic microstructure was loaded by a unified displacement vector.

The elastic strain energy as a characteristic answer function is bonded to the stiffness of the underlying microstructure. In the

implemented code, a linear Nastran[®] solver, type 101, was used to solve the nodal displacements. This subprogram is also part of the user-defined Matlab[®] code, called as executable from the analySIS[®] shell. Each synthetic microstructure was loaded at several angles, leading to an innovative description of the microstructure as stiffness transfer function, compare to mark seven in figure 1.

Auxiliary, the result of the nodal elastic strain energies is analyzed. Major sized grains show a characteristic dependency of the elastic strain energy consumption influencing the connecting beam elements. To visualize this relation, one synthetic microstructure grid is shown in deformed scale in figure 12. The microstructural energetic transfer function is additionally sketched over the varying load angle, acting as a nodal displacement vector at the exterior synthetic boundaries.

Figure 12: Angle dependent microstructural energetic transfer function and deformed synthetic grain shapes.

Interpreting the local inflection points of the elastic strain energy distribution in figure 12, a conclusion to the morphology of the microstructure is possible. This new developed microstructural evaluation model, which is based on interpretation of the energy transfer function, supports an alternative characterization method of the microstructure, including morphological information in a combined and unique manner.

Microstructural Damage Parameter

To assess a link between fatigue life and microstructure, the angle dependent distribution of the energetic transfer function has been evaluated further on. Due to statistical operations two new parameters were derived from the energetic transfer function; the median microstructural energy parameter e and the factor of heterogeneity b , indicating the degree of bimodality. The response of the microstructural energetic transfer function is shown exemplarily for three specimens in table III.

The evaluation of the microstructural energy parameter e and the factor of heterogeneity b are done in sequential order for all metallographic investigated points per specimen. For reference of the metallographic section points see figure 10. As an excerpt, the shown microstructural parameters in table III are achieved from the evaluation of three single specimens. Comparing these results,

the mean microstructural energy value e is quite low in row one of table III, whereas row two and three ought to be similar at the first point of view.

Table III. Microstructural parameters e and b
col. one: pre-material, see figure 3, $S_a \sim 0.92$, $N \sim 10^6$;
col. two: forging lot one, see figure 5, $S_a \sim 1.24$, $N \sim 7 \cdot 10^5$;
col. three: forging lot two, see figure 6, $S_a \sim 1.03$, $N \sim 2 \cdot 10^6$

Microstructural energy parameter e		Factor of heterogeneity b	
$\bar{e} = 3.5$	$\sigma_e = 1.0$	$\bar{b} = 51.8$	$\sigma_b = 5.1$
$\bar{e} = 59.8$	$\sigma_e = 12.9$	$\bar{b} = 62.4$	$\sigma_b = 6.1$
$\bar{e} = 45.7$	$\sigma_e = 18.5$	$\bar{b} = 67.8$	$\sigma_b = 7.1$

The similar values in row two and three of the mean microstructural energy parameter might be in contrast to the significant decrease of fatigue life; comparing the corresponding S/N-curve results shown in figure 6 and figure 5. Including the scatter of the microstructural energy σ_e in the comparison, the minima of the e values are different. The minimum of the microstructural energy parameter in the third row is significant lower than in the second row of table III.

This suits the expectations regarding the life time dependency. For the purpose of clarity only one specimen is shown in table III. As seen later on, the microstructural evaluation method was carried for the whole fatigue data. Supplementary, standard mean grain size evaluation was carried out.

Exemplarily, a mean grain size of $G = 8 \pm 0.5$ for the specimen of lot one is calculated. The corresponding microstructural energy results are shown in row one of table III. The forged material of lot one shows a value of $G = 12 \pm 0.5$. The forged material of lot two achieves a value of $G = 11.5 \pm 0.5$, compare to the analogous microstructural parameters in row two and three of table III. Therefore, no significant difference between the two forged material lots was found by using the standard interception test methods.

Using the evaluation method based on the microstructural transfer function, an additional parameter is responded, the factor of heterogeneity b . The lower the factor of heterogeneity, the more unimodality is examined in morphology. Values of more than eighty correspond to extremely bimodal microstructures, whereas values lower than thirty distinguish grains of nearly equal size and shape. Using both microstructural parameters e and b , a capacious improvement of linking experimental based fatigue life and microstructure as a result of thermo-mechanical processing is achieved.

To visualize the distribution of the microstructural energy value e and the factor of heterogeneity b in a most meaningful manner, each variable is additionally classed. These derived values are in direct context to the original ones. The classed layout of the microstructural energy is shown in figure 13, again evaluated for the three selected specimens in table III.

Figure 13. Microstructural energy parameter e , evaluated for three specimens.

Analyzing the microstructural energy parameter e , it can be seen that the forging process influences the parameter in peak value and distribution. A lifetime increase directly corresponds with increasing microstructural energy parameter class number. Analyzing the microstructural energy parameter distribution, for the specimen of forging lot two, label see legend in figure 13, the descending characteristic of the classed factor of heterogeneity deduces a reduced lifetime.

Figure 14. Microstructural factor of heterogeneity b , evaluated for one specimen of pre-material and two forging specimens.

The bar plot in figure 14 shows that the factor of heterogeneity is quite high for the three investigated specimen microstructures. This indicates the occurrence of some larger grains in the evaluated metallographic sections.

As shown in figure 13 and figure 14, a straightforward evaluation of the mean value in combination with the scatter bands of the microstructural energy based parameter b and accompanying factor of heterogeneity e may not be totally satisfying due to the wide range of possible microstructures inflicted by manifold process parameters. To determine the major lifetime influencing numerical parameters, a self-organizing-map as unbiased neural network was used. Input data for this map was the whole until now examined microstructure data based on the energetic transfer function approach; whereat statistical methods were used to group and classify both the microstructural energetic parameter e and the factor of heterogeneity b for each analyzed specimen. The self-

organizing-map toolbox, for terms of use see [14], solved the data mining process as auxiliary Matlab® tool.

Figure 15. Component planes of the self-organizing-map arranging the microstructural energy and lifetime values.

To achieve adequate input parameters for the self-organizing-map, additional statistic derivatives from the microstructural energy parameters and factor of heterogeneity were generated. Although a total number of fifteen energy parameters were used as input data for the self-organizing-map, only six parameters remained as linear independent ones. The other microstructural based parameters are dependent linear combinations; such a case would be illustrated by the same color scheme in the subfigures illustrated in figure 15. Due to the fact that the color gradient is quite homogenous; a good quality of the self-organizing-map is stated. The position of an ascertained point is identical over all subfigures. This allows an easy comparison of the microstructural properties.

For example, examine the region in the lower left corner in a subfigure of figure 15, a maxima of the microstructural energy parameter e is found, see upper left subfigure. The sustainable stress value in the lower left subfigure has its maxima in the same region. Figure 15 shows the six linear independent microstructural parameters, all statistical derivatives of e and b , and the fatigue life parameters as well the distance matrix as characteristic qualifier of the self-organizing-map. Adding a principle component analysis to the post-processing, the smooth distribution of the underlying neurons is observed. Clustering allows the definition of homogenous areas. In these regions, a direct link between microstructural energy parameters and fatigue life is calculable with minimized errors.

Because the main target is linking the specimen dependent S/N-curves to their evaluated microstructure, the knowledge of the microstructural energy parameter e and the factor of heterogeneity b are necessary for all specimens. By reason of time and cost 'only' the specimens of three stress levels per S/N-curve were metallographic analyzed. Anyway, due to the extensive experimental setup thousands metallographic section have been evaluated. To achieve the missing microstructural energy parameters of the specimen's not metallographic inspected, neural networks were built up.

For each supplemental parameter an individual neural network was created, leading to a total number of six neural networks. The neural networks were trained with input data of the self-organizing-map. To backpropagate the values, a layout of seven inputs feeding a multiple layer structure was used. Five neurons with biased log-sigmoid transfer functions at level one and a pure

linear transfer function at level two were implemented. The neural network has one output, which responds the missing microstructural value dependent on its known seven inputs.

Figure 16. Neural network layout used in backpropagation of microstructural parameters.

The network was built-up, initialized and solved using the Neural-Network-Toolbox®, which is an add-on to Matlab®. Different training functions were tested. The solution was done iteratively. To backpropagate the microstructural energy e both quasi-Newton method and Levenberg-Marquardt algorithm are applicable. The neural network to predict the factor of heterogeneity b was trained using a one step secant method. Figure 17 shows the quality of the response.

Figure 17. Prediction accuracy of microstructural parameters using neural networks.

The quality of the backpropagated microstructural energy e and factor of heterogeneity b was sufficient, see figure 17. By means of evaluating additional metallographic sections, the prediction accurateness of the neural networks could be further improved. The neural nets supplied each specimen with the complete list of microstructural properties. This permitted the calculation of the microstructural energy parameters for all points of the S/N-curves. This fulfills the target for a life time assessment of forging processes by use of empirical methods; see mark nine in figure 1.

Verification Of The Model

The new developed microstructural energy approach has to meet the standard test methods for determining average grain size. This requirement results from the relationship between fatigue life and grain size of unimodal microstructures. Therefore, the microstructural energy transfer function has to correlate with the average grain size, determined by interception counting.

First, the correlation of the energy transfer function to the ASTM grain size was examined for specimens of pre-material lot one. A correlation occurred, whereat a correlation coefficient of $R \sim 0.85$ confirmed the linear relation. In addition, the non-regularity factor, which characterizes the overall energetic scatter, ranges from three to forty four. Both the correlation between energetic transfer function and grain size and the value of regularity fed the assumption, that the grain structure is chiefly unimodal distributed. This was confirmed by metallographic inspection of the evaluated sections.

If a bimodal or heterogonous microstructure appears; the direct link between energetic transfer function and grain size is not valid. Such a case is shown in figure 18. Therefore, the new

developed microstructural damage parameter e and factor of heterogeneity b must be used instead.

Figure 18. Nonlinear correlation between energetic transfer function and grain size; screw press (forged material lot two).

Such a nonlinear correlation between microstructural energetic transfer function and ASTM grain size is shown in figure 18, which represents the microstructural behavior of all specimens shown in the S/N-curve of figure 6.

Figure 19. 3D-view of the link between fatigue lifetime and microstructural energy parameter.

The integrated S/N-curve in figure 19 displays the fatigue life behavior of forged material, lot two, which is originally shown in figure 6. Analyzing the microstructural energy parameter in figure 19, two main levels of the microstructural energy parameter can be assigned: a lower level at $e_l \sim 40$ and a higher level at $e_h \sim 65$.

The dashed red line in figure 19 corresponds to the lower microstructural energy level; the point-dashed blue line corresponds to the higher level of microstructural energy. Considering the factor of heterogeneity, it is stated that the points near the red-colored, dashed S/N-curve show a factor of heterogeneity which is one class higher than the others. This implies an increased number of as-large-as grains in this region. Additionally, inspecting the degree of scatter for the factor of heterogeneity b ; a significant increase at the lower stress level bound is observed, see figure 20. This represents an increased occurrence of as-large-as grains and furthermore a more bimodal microstructure at the red-dashed S/N-curve.

Figure 20. Link between fatigue lifetime and spread of factor of heterogeneity (forged material lot two).

Using the novel microstructural energy approach to characterize the metallographic sections, an improved accuracy in linking lifetime results with microstructure is observed.

Using finite element methods in conjunction with microstructure modeling tools [15, 16] to predict the microstructure at design stage, the new developed energy approach closes the simulation chain. Using this, both geometrical features and the fatigue life behavior of forged parts can be optimized by finite element modeling [17].

Until now, fatigue tests on specimens out of forged pan-cakes and the reference mount-link itself as whole part have been analyzed regarding the link of microstructure with fatigue.

To examine applicability of the developed model for complex forgings, four characteristic IN718-forgings have been analyzed exemplarily. The main difference lies in the fact, that not the whole forging part is tested, but specimens taken out of these forgings. Comparing the lifetime behavior of four different parts regarding to the evaluated microstructure, the maximum sustainable stress is reached by the specimen S/N-curve of part C, see figure 21. This S/N-curve was tested at room temperature. Comparing the microstructural damage parameters e and b across the four forged parts, the mean value of $e_C = 83$ and $b_C = 74$ reports the most unimodal and fine grained microstructure. Subscripts of e and b are assigned to the part label.

Figure 21. Lifetime-dependency of forged IN718 parts, microstructure evaluation by use of e and b .

Evaluating the microstructure of part D, an increase of microstructural bimodality was detected, which results in a reduced fatigue life behavior.

The microstructural parameters of specimen taken from part A showed a huge statistical spread. The same characteristic was found on the distribution of sustainable load cycles.

Additionally, it has to be taken in account that the specimens truncated from the parts were tested at different temperatures in order to get an applicability value for high temperatures.

The amount of large grains increases the life-time behavior at thermo-mechanical fatigue due to higher creep resistance. The microstructural evaluation model will be fine-tuned to respond the life-time behavior of IN718 at high temperatures more accurate.

Moreover, the existence, amount and shape of precipitations like δ -phase will be integrated in the model as final step.

Conclusion

The new developed microstructural based energy transfer function approach allows an alternative description of the microstructure. First, the microstructural energy parameter e correlates to the ASTM grain size. Second, morphological information can be achieved by evaluation of the load-angle dependency of the energetic transfer function. Third, the factor of heterogeneity b characterizes the persistence and amount of both bimodal microstructure and as-large-as grains in a unique manner without additional work.

The presented methodology is based on experimental data. The microstructural based energy approach was tested on thousands of metallographic sections to ensure the stability of the implemented program. The program is built up on scripts in ImagingC[®] using shell calls to extensive user-defined Matlab[®] subroutines. The developed program also supports a graphical user interface to access the data management and several user-defined modules.

Integrating the assessed microstructural results into the fatigue life time evaluation, not only a reduction of the fatigue scatter band is observed by specimen outlier recognition; moreover, the microstructural energy approach using the microstructural energy parameter e and the factor of heterogeneity b offers a new universal method to describe the microstructure and texture in a parametric way.

This approach of working out an experimental based methodology from specimen tests, extensive metallographic inspection, linking them with forging parameters, implement the supported damage parameters to FEM lifetime codes, simulate the specimen lifetime and calculate the component lifetime closes the simulation chain for IN718. The investigations show that based on this knowledge a tailored interdisciplinary lifetime optimization and a useful definition of the demanded specifications can be worked out together with the aerospace part designers in order to deliver economic and safe parts.

In future work, the developed microstructural energy approach has to be extended to support a meaningful lifetime description of metallographic sections for $(\alpha+\beta)$ titanium alloy Ti-6-4.

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