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ENHANCED FATIGUE ANALYSIS – INCORPORATING DOWNSTREAM MANUFACTURING PROCESSES

IZBOLJŠANA UTRUJENOSTNA ANALIZA – VKLJUČITEV IZDELAVNIH PROCESOV

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Most failures of engineering components can be traced back to cyclic loads which cause fatigue of the material. These cyclic loads can be either constant or variable. This influence has to be taken into account in the fatigue analysis, the aim of which is to assure a minimum required lifetime of a component without breakdown. Simultaneously, a lightweight design is intended by reducing the size of the component. The strength of materials under cyclic loading is essentially lower than those under static loading. However, the cyclic strength is of more importance in practical applications, as more components fail by cyclic loading than by static loads. Regrettably, the strength of cyclic loaded components was discovered relatively late and the first systematic investigations were performed in the 19th century. Cyclic loadings result from mechanic or thermal service loads, which can be superimposed to static loads. When looking at a truck, the chassis is loaded by the dead load of the vehicle. Due to loading and unloading procedures the load is changed into a quasi-static way. Additional cyclic loads emerge during driving operation in addition to the static loads due to braking, acceleration, cornering, or physical conditions just like bumps on the roadway or air drag. Additional loading is also due to resonance vibrations of engine, gearbox, fuel tank, or the spare wheel. These cyclic loads lead to fatigue of material hence overstraining them to a crack. These cracks propagate and finally lead to failure of the component.

Key words: fatigue life, complex structures, simulation, manufacturing processs, finite elements

Izračun trajnostne dobe za geomertično kompleksne strukture zahteva poznanje lokalne utrujenosti materiala. Po navadi raziskava lokalnega utrujenostnega vedenja komponent ni mogoča, ker je treba za študij vplivnih parametrov preveliko časa. Zato je potrebna metoda za izračun trajnostne dobe z upoštevanjem lokalnih vplivov. Lokalna utrujenostna trajnostna doba je odvisna od zarez, vrste obremenitve, temperature, višine in sekvence obremenitve itd., močan je tudi vpliv procesa izdelave. V tem članku so obravnavani procesi izdelave in njihov vpliv na mikrostrukturo in na utrujenostno trajnostno dobo. Posebej so raziskani vplivi litja, oblikovanja, varjenja in površinske obdelave. Različni procesi so bili simulirani, da bi bil dosežen lokalni učinek, kot so čas strjevanja, hitrost deformacije in rezidualne napetosti. Pripravljeni so bili preizkušanci z opredeljenimi procesnimi parametri, njihova utrujenostna trajnostna doba pa je bila določena eksperimentalno. Ti rezultati so bili podlaga za napoved utrujenostne trajnostne dobe geometrično kompleksnih oblik na podlagi rezultatov analize s končnimi elementi, ki je upoštevala lokalne napetosti, gradiente napetosti in proces izdelave. Simulacija procesa izdelave in razumevanje vpliva lokalnih razmer na utrujenostno trajnostno dobo omogoča dobro simulacijo zapiranja verige od procesa izdelave do napovedi te dobe.

Ključne besede: utrujenostna trajnostna doba, kompleksne strukture, simulacija, procesi izdelave, končni elementi

1 FATIGUE ANALYSIS

The science of fatigue analysis deals with the fatigue of components under cyclic loads as in their regular service life. The main goal is to obtain spatial dimensions of the components in a way that they will serve the minimum lifetime required without failure, with the focus also lying on weight reduction by using reduced amount of material. Basically dimensioning of components can be done in two ways.

Dimensioning by testing

In this case the expected loads are applied on prototypes. When the required fatigue life is not achieved, a modified prototype is built and tested again. This development cycle continues until the required specifications are reached. The weak points in components or complete construction could be easily detected as against oversized regions with no visible damage.

Dimensioning by simulation

Based on stresses, knowledge of material behaviour and the loading spectrum, a lifetime calculation is performed. At spots that do not achieve the required lifetime, the geometry or the material is changed or reinforced. Whereas less stressed spots provide scope for a reduction in weight by means of material reduction.

The latter has the advantage that it can be applied very early in the engineering phase and is also less time and cost intensive. However, in contrast to testing, the accuracy of simulation is lesser. Hence, in the initial phase of mass product development, simulations are performed and in the final stages, developed components are tested to evaluate their fatigue resistance.

1.1 Damage accumulation

In real life applications, dynamic loads have variable amplitudes instead of constant amplitudes that too with different frequencies and stochastic sequences. The damage under cyclic load is based on the formation and motion of crystalline defects in the material which has not yet been measured in a quantitative way. Hence, the knowledge of an engineer depends on empirical models. In the last few decades numerous hypothesis have been established. One of the oldest with distinction from others and also most often used is that of Palmgren and Miner. This model, like the other models, concentrates on describing the two following observations:

a) There exists an additional damage D_i due to a number of load cycles n_i with a stress amplitude of σ_i, which is caused by the amplitude itself and the foregoing loadcycles and loads.
b) The accumulation of the single damage leads to a global damage D, at a critical damage parameter D_c failure occurs.

1.1.1 Palmgren Miner Method

The most famous rule to define the damage accumulation was already described by Palmgren in 1924 and Miner in 1945. Thereby, the service life at single constant amplitude is considered as the base for calculating the service life at variable amplitudes. The damage D_1 due to on single load cycle is given by,

$$D_1 = \frac{1}{N_i} \tag{1}$$

where N_i is the number of load cycles to fracture of the S-N curve at a load level σ_{ai}.

When, at the load level σ_{ai}, the load cycles appear with a frequency n_i, the damage D_i at that level is given by:

$$D_1 = \frac{n_i}{N_i} \tag{2}$$

By summing up the damage at each load cycle for a specific load spectrum, one gets the total damage

$$D = \sum_{i=1} \frac{n_i}{N_i} \tag{3}$$

wherein i is the spectrum level, n_i the number of load cycles on the i^{th} level and σ_{ai} the corresponding load amplitude. Experiments show that components fail below or above the damage sum of 1 whereas, components are to fail, as per definition, when the damage sum reaches a critical value of 1:

$$D = 1{,}0 \tag{4}$$

2 EXTENDING THE SIMULATION CHAIN – INTEGRATION OF THE MANUFACTURING PROCESS

For lifetime evaluation of complex geometric components, concepts based on local stresses or strains are required (**Figure 1**). For investigating local stresses, finite element method (FEM) has been well established. For

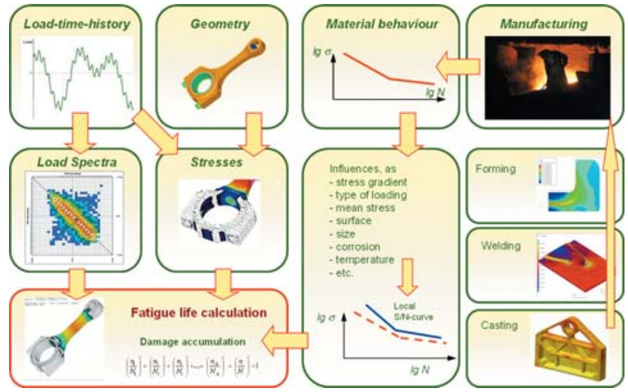


Figure 1: Lifetime prediction based on local stresses and strains
Slika 1: Napoved trajnostne dobe na podlagi lokalnih napetosti in deformacij

lifetime calculation, knowledge of local fatigue strength of material, described by the S-N curves of component and, the service conditions are needed, but these are not identical with the data of fatigue tests performed on idealised specimens. In an ideal case the strength of a component is determined by tests and can be used for lifetime calculation. Since no components exist in the construction phase, S-N curves are obtained by simulation.

These influences can either lead to an increase or decrease in stiffness and when occurring synchronous, these effects may boost or weaken each other. The experimental investigation of these effects on fatigue strength at a full scale is quite time consuming and also cost intensive whereby making it impractical. Hence, these tests are performed very selectively. The fatigue strength characteristics are not uniform all over the component and the S-N curve of the whole component is obtained by encompassing all the local S-N curves. The task is to transfer the S-N curve of the specimen with respect to the influencing factors into an S-N curve of the component.

In the following consideration, a few models for describing the influence of the production process are explained. These models facilitate lifetime calculation based on the results of finite element calculations.

2.1 Notches and load type

Notches, zones of bending stress, or components exposed to irregular force flow show irregular characteristics of the stress level. These irregularities can be derived from the stresses which gives the stress gradient χ or with reference to local stress, the relative stress gradient χ* (**Figure 2**):

$$\chi^* = \frac{1}{\sigma_{max}} \left(\frac{d\sigma}{dx} \right) \tag{5}$$

As the stress gradient can be calculated easily with the help of finite element results, it is obvious to use it for the assessment of stresses and to describe the influences on the S-N curve in the case of notches as well as under tension/compression and bending loading.

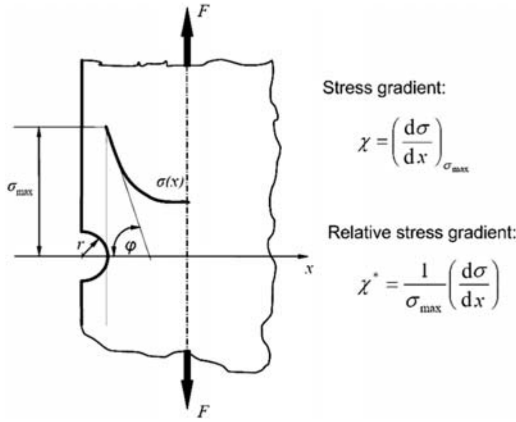


Figure 2: Stress gradient in notch root
Slika 2: Gradient napetosti na dnu zareze

2.1.1 Relative Stress Gradient Concept (RSG)

Notches are characterized by an increase in stress and formation of stress gradient within the component. Further, beams subjected to bending loading show a stress gradient. In both cases the material exhibits a locally higher fatigue stress limit than those under pure tensile loading on un-notched specimens which is a result of the support effect (**Figure 3**).

Two different fatigue limit parameters form the base for describing the influence of the stress gradient on the fatigue limit of any component:

– The fatigue limit σ_{zdw} of an un-notched specimen exposed to tension-compression load with the relative stress gradient $\chi^* = 0$ and
– The fatigue limit σ_{bw} of a bending specimen with thickness b and a relative stress gradient $\chi^* = 2/b$.

To describe the fatigue limit of components with arbitrary stress gradients one has to interpolate or extrapolate these values. Experience shows that the relationship between fatigue limit and stress gradient is not linearly proportional, with increasing stress gradient the growth of the fatigue limit is reduced (**Figure 4**).

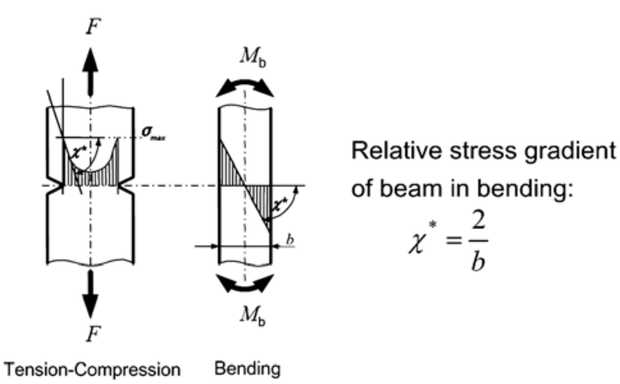
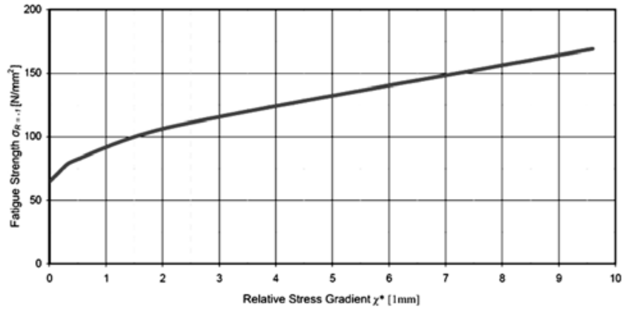


Figure 3: Stress gradient in notch for tension-compression and bending
Slika 3: Gradient napetosti za razteg-tlak in upogib



Figire 4: Fatigue limit at 10^7 load cycles depending on stress gradient
Slika 4: Meja utrujenosti pri 10^7 obremenilnih ciklih v odvisnosti od gradienta napetosti

To describe this relationship, an exponential curve is chosen, which is characterised by the exponent K_D:

$$\sigma_D = \sigma_{zdw^*}\left(1+\left(\frac{\sigma_{bw}}{\sigma_{zdw}}-1\right)\cdot\left(\frac{\chi^*}{2/b}\right)^{K_D}\right) \tag{6}$$

$$\sigma_D = \sigma_{zdw}\cdot n_\chi \tag{7}$$

For the fatigue life calculation with the help of S-N-curve according to (8) two additional parameters are necessary; the number of cycles at the fatigue limit N_D and the slope k of the S-N-curve.

$$N = N_D \cdot \left(\frac{\sigma_a}{\sigma_D}\right) \text{for } \sigma_a \geq \sigma_D \tag{8}$$

Generally speaking, with an increase in the sharpness of a notch the slope k gets steeper, while the number of cycles at the fatigue limit N_D decreases. To describe the trend of N_D and k of the S-N-curves, the corresponding minimum and maximum values at low and high gradient (χ^*) from test results are defined.

For the description of these values between these limits, exponential functions are chosen:

The values lg ($N_{D\min}$) and lg ($N_{D\max}$) describe the lowest and highest number of cycles at fatigue limit, while k_{min} and k_{max} refer to the minimum and maximum slope of the S-N-curve versus the stress gradient. The dependence of N_D and k as a function of n_χ is described by the exponents K_n and K_k, respectively.

$$\lg(N_D) = \lg(N_{D\min}) + \frac{\lg(N_{D\max}) - \lg(N_{D\min})}{n_\chi^{K_n}} \tag{9}$$

$$k = K_{\min} + \frac{K_{\max} - K_{\min}}{n_\chi^{K_n}} \tag{10}$$

The equations (6) to (10) define the S-N curve for a component with notches and irregular stress distribution and can further be used for lifetime calculation of complex geometric components. This allows for an efficient analysis of S-N curves and an estimation of lifetime of finite element structures with more than a hundred thousand degrees of freedom in every node of the structure.

2.2 Statistical size effect

The statistical size effect supposes that the flaws in a component of large volume are more than those in a smaller component owing to to statistical reasons. Hence, bigger components show a higher probability for the occurance of critical local stress due to a flaw. This could probably lead to a crack which would grow and eventually lead to the failure of the component. For evaluation of the statistical size effect the stress integral for the high loaded volume (11) or the high loaded area (12) was proposed:

$$V_\sigma = \int_V \left(\frac{\sigma}{\sigma_{\max}} \right)^m \mathrm{d}V \tag{11}$$

$$A_\sigma = \int_A \left(\frac{\sigma}{\sigma_{\max}} \right)^m \mathrm{d}A \tag{12}$$

$\sigma_{\max}$ represents the notch root stress, σ is the stress of a volume or area element, m represents the Weibull exponent which characterizes the homogeneity of the material. For easier numerical calculation of highest loaded volume it is proposed in [3] that the volume $V_{90\ \%}$ which is loaded by at least 90 % of the maximum stress should be taken into account for evaluation. For calculation of a correction factor for fatigue strength the ratio between highest loaded volume of a reference specimen V_{ref} to the highest loaded volume V of the component is built.

$$n_{\mathrm{st}} = \left(\frac{V_{\mathrm{ref}}}{V} \right)^{\frac{1}{m}} \tag{13}$$

$$n_{\mathrm{st}} = \left(\frac{A_{\mathrm{ref}}}{A} \right)^{\frac{1}{m}} \tag{14}$$

2.3 Technological influences on forged components

Forging at different tool speeds primarily influences the microstructural properties of the material. In addition, a change in mechanical properties of the component like fatigue strength behaviour is also noticed, which is caused by a difference in grain size or grain size distribution.

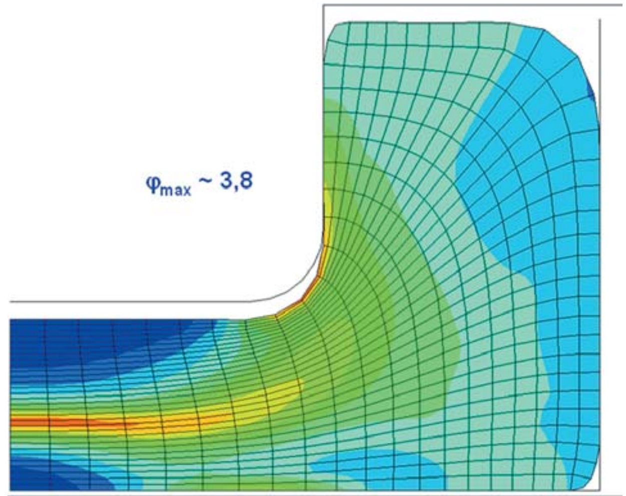


Figure 6: Simulation of degree of deformation
Slika 6: Simulacija stopnje deformacije

The influences on the fatigue limit are not uniform over the complete structure but dependent on local parameters like:

- Local degree of deformation
- Local deformation rate
- Forging temperature
- Grain Size (mean value, variation)
- Inclusions in the microstructure
- Segregation direction

In **Figure 5** the basic principle of a forging process is shown, while **Figure 6** depicts the distribution of degree of deformation of a component calculated by simulation. [4].

The S-N curve for influence of degree of deformation on fatigue strength of 16MnCr4 is depicted in **Figure 7**.

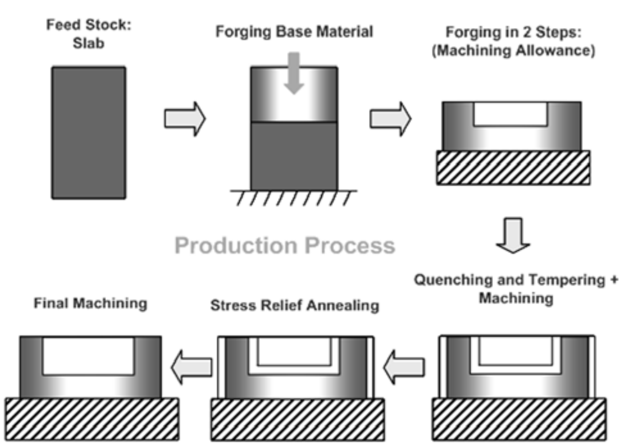


Figure 5: Principle chain of production process
Slika 5: Veriga postopkov procesa izdelave

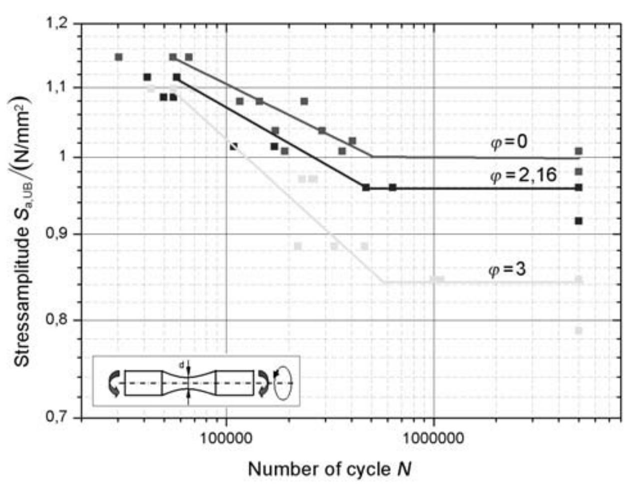


Figure 7: Influence of degree of deformation on performance of fatigue limit
Slika 7: Vpliv stopnje deformacije na velikost utrujenostne trdnosti

Rotating bending fatigue tests have been performed on un-notched specimens with local degrees of deformation $\varphi = 0$, $\varphi = 2.16$ and $\varphi = 3$. The fatigue limit shows a clear dependence on local degree of deformation. [4].

The number of cycles at fatigue limit nearly stays constant while the slope *k* of the S-N curve steepens with lowering fatigue strength. The reason for the decrease of strength is explained by metallographic analysis. Forged specimens show greater variation of grain size. This is ascribed to grain growth during the heating phase prior to the forging process. Hence, the influence of a chosen forging temperature on fatigue strength is a result of change in grain size and grain size distribution.

2.4 Influence of heat treatment on fatigue strength

Simulation of the cooling during the annealing process of a component is a big benefit for investigating the influence of heat treatment on fatigue strength. The temperature distribution during cooling calculated by simulation is shown in **Figure 8**. When combining local temperatures in dependence of time with continuous TTT curves, the composition of local microstructure can be estimated and hence the local strength calculated [4] (**Figure 9**).

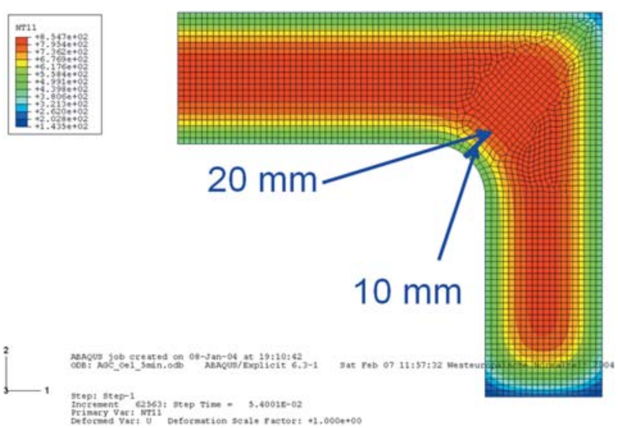


Figure 8: FE Simulation of annealing
Slika 8: Simulacija žarjenja s končnimi elementi

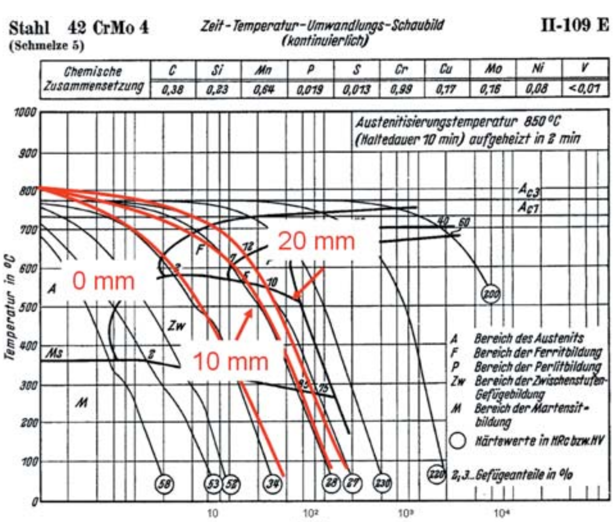


Figure 9: Continuous TTT curve of 42CrMo4
Slika 9: Kontinuirni TTT-diagram za 42CrMo4

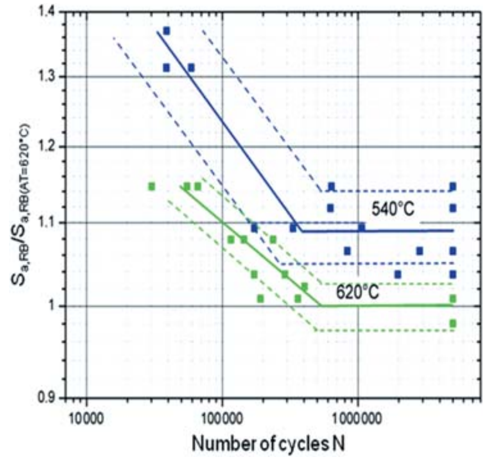


Figure 10: Influence of tempering temperature on fatigue strength
Slika 10: Vpliv temperature popuščanja na trdnost pri utrujenosti

In the example shown below, the microstructure of the heat treated component shows a higher amount of martensite on the surface than 10 mm below the surface, which corresponds to the machining allowance.

Hence, on the surface of the machined component a considerably different microstructure with different strength characteristics exists. The influence of micro-structural difference on the fatigue strength is shown in the S-N curve in **Figure 10**. For the investigated material the fatigue strength shows an increase of 7 % when tempered at 540 °C instead of 620 °C.

2.5 Technological influence on cast aluminum components

The technological influences, like casting process and refinement of microstructure, have an important effect on the fatigue behaviour of cast aluminum alloys. Furthermore, the local dendrite arm spacing (DAS) and, the distribution and size of pores can change the lifetime

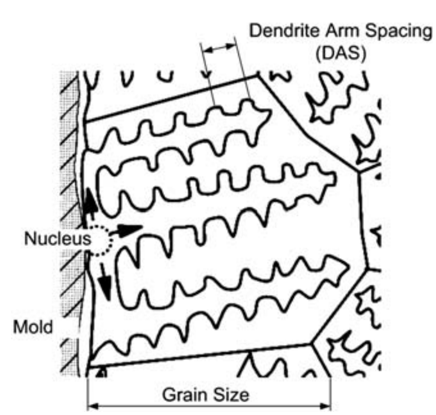


Figure 11: Definition of DAS [5]
Slika 11: Definicija DAS [5]

behaviour of the components. DAS and porosity are mainly affected by the freezing rate, which depends on the casting process, wall thickness, etc. Additionally, oxides and impurities affect fatigue strength.

Generally a dendrite grows from a single nucleus, which could be foreign particles or fragments of other grains as shown in **Figure 11**. The dendrite arm spacing is only affected by the local freezing rate or solidification time, whereas the grain size especially depends on the number of nuclei in the melt. Therefore a correlation between grain size and freezing rate cannot be shown.

The grain of a cast material can be built up by different dendrites of same origin. While grain size depends on number of apparent nuclei, DAS is only affected by local freezing rate and respective solidification time. In this way no correlation can be found between grain size and solidification time.

2.5.1 Die casting

For dimensioning dynamically loaded components with regard to fatigue lifetime, the knowledge of the local S-N-curve is necessary. These local S-N-curves, determined by the material, are essentially influenced by component specific effects, such as type of loading, size, stress gradient, temperature and the production process. In the case of cast components the technological influences can be described by DAS. DAS is not constantly spread within the component. Its distribution depends on the conditions under which the local solidification occurs. As models for the simulation of solidification are known and available local DAS can be determined in a very early stage of the development process. Based on the S-N-curves obtained by simulation and the local stress concept, which takes into account the local stress gradient, fatigue lifetime of geometrically complex, cast components can be calculated. [1]

For the die casting process DAS is a good parameter for characterizing the microstructure with respect to fatigue strength. Beside DAS, size and distribution of porosity also influence fatigue strength of cast aluminium alloys. Simulation of the freezing process allows the calculation of DAS with respect to local freezing rate. The S-N curves in **Figure 12** show the strong influence of DAS on fatigue strength of cast aluminium alloys. Specimen with DAS of 30 μm show a higher fatigue strength than the ones with 70 μm, additionally the slope of the S-N curve increases with greater DAS, and the number of cycles at fatigue limit decreases [6].

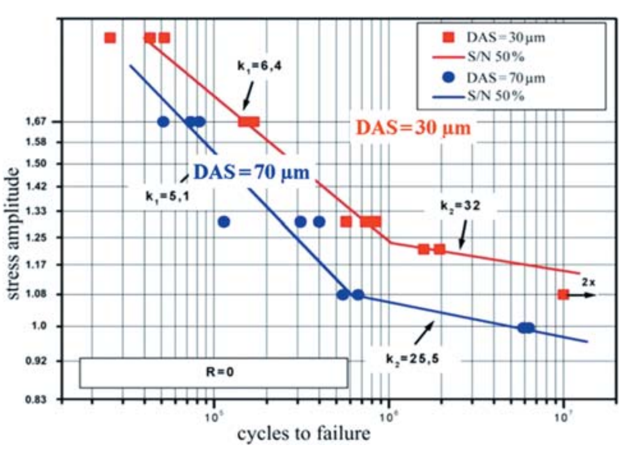


Figure 12: S-N curves for specimens with different DAS [6]
Slika12: S-N-krivulje za različen DAS[6]

2.5.2 High-Pressure die casting

While for die casting DAS is very important for fatigue strength, gas porosity plays a main role for high pressure die casting due to turbulent flow conditions which can't be avoided completely.

In [7] geometry and distribution of pores has been investigated using computer tomography (CT). CT analy-

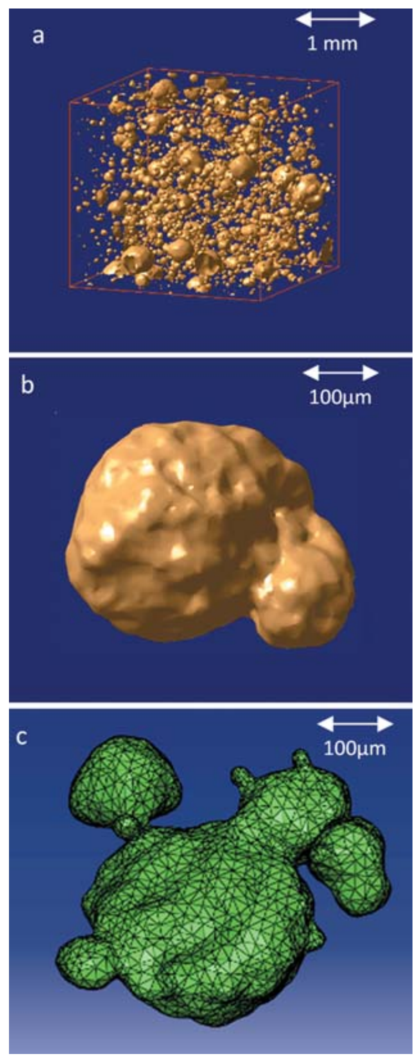


Figure 13: Results of computer tomography: a – Overview of tomographed cube; b – pore pressed by dendrites; c – meshed pore.
Slika 13: Rezultati računalniške tomografije: a – pogled na tomografirano kocko, b – pore, ki jih stiskajo dendriti, c – zamrežene pore

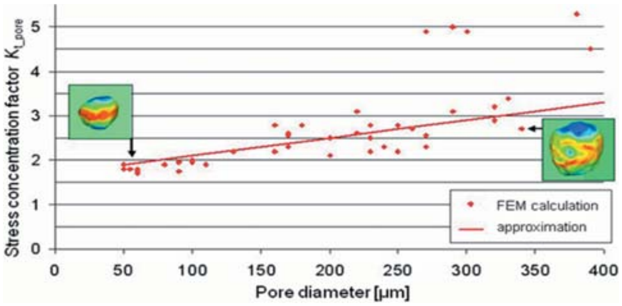


Figure 14: FEM calculation for tomographed spherical gas pores with varying diameters [7]

Slika 14: FEM-izračun za tomografirane sferične plinske pore z različnim premerom[7]

sis shows that the shape of gas pores obviously differs from a sphere as shown in **Figure 13**.

By finite element calculations, the impact of gas pores on the stress state in specimen has been examined. Local stress elevations which result out of irregular shape and notches show values in a range from 1,8 to 2,9. The larger the size of a pore, the stronger are the dendrites pressed into the surface, thus resulting in sharper notches.

Figure 14 shows the correlation between local stress elevation of approximately spherical gas pores and the pore diameter for tomographed pores with a range in diameter from 50 µm to 350 µm.

2.5.3 Calculation of pore distribution in high pressure die casting components

In [8] for calculation of pore distribution in a high pressure die casting component the use of the so called statistical porosity model is suggested. For a defined temperature range, post pressure and hold pressure, the corresponding Weibull distribution of porosity in the component is calculated by (15)

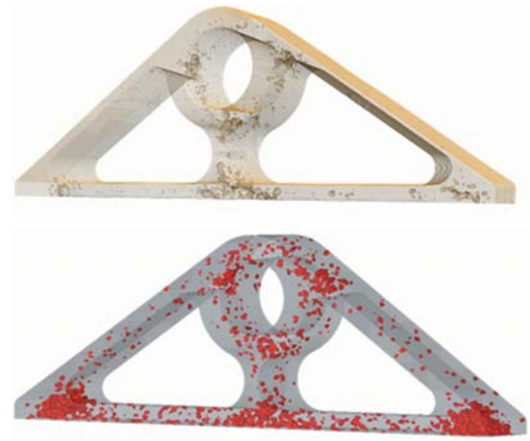
$$\begin{aligned} k_{\mathrm{Weibull}} &= (c_1 p_{\mathrm{solid}}^2 + c_2 p_{\mathrm{solid}} - c_3) T_{\mathrm{rel}} + (c_4 p_{\mathrm{solid}}^2 - c_5 p_{\mathrm{solid}} + c_6) \\ d_{\mathrm{Weibull}} &= (c_7 p_{\mathrm{solid}} - c_8) T_{\mathrm{rel}} + (c_9 p_{\mathrm{solid}} - c_{10}) \end{aligned} \tag{15}$$

Exact position of a pore in a component is not predictable, but distribution of porosity within a defined domain is. The porosity distribution provides information regarding the percentage of elements within a domain, defined by the temperature distribution during the freezing process.

Pore diameter is an essential input in the fracture mechanics material model described in (8) in order to calculate the pore size dependence of fatigue strength. Hence, with the help of (16) the local porosity in the component has to be converted to a single pore of an equivalent diameter.

$$d_{\mathrm{equ}} = \sqrt{\frac{4 A_{\mathrm{element}} \,\mathrm{Porosity}[\%]/100}{\pi}} \tag{16}$$

wherein, A_{element} corresponds to the area of the element, which originally was used for porosity calculation.



a)

b)

Figure 15: Pore distribution in real component (computertomography) (a), calculated pore distribution (b)

Slika 15: Porazdelitev por v realnem elementu (računalniška tomografija) (a), izračunana porazdelitev por (b)

Multiplying porosity with element area gives the area of the pore within the element. The area equivalent diameter d_{equ} can be calculated using this equation. If two small pores exist in an element in the original calculation the recalculation will result into one big pore which will further lead to conservative results. Calculated pore distribution in comparison to real pore distribution is presented in **Figure 15** and an obvious and pretty good correlation between both is observed.

The calculated pore distribution depends on post pressure and shows a different pore distribution for each calculation cycle as it relies on a random function. This reflects reality in a good way, as components even if they are of the same charge never show exactly the same pore distribution. But in a statistic point of view, the results can be compared by looking at the density and size of pores.

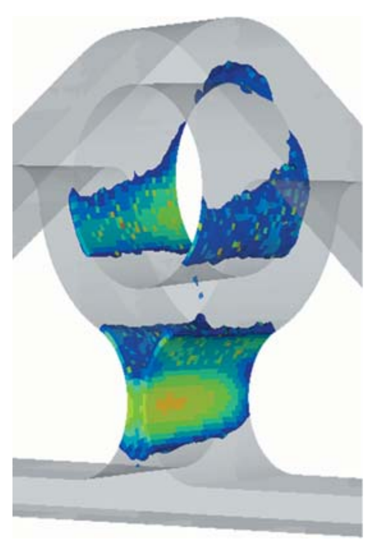


Figure 16: Distribution of safety against cyclic failure in the component

Slika 16: Porazdelitev varnosti priti ciklični obremenitvi komponente

2.5.4 Calculation of safety against cyclic failure

A fracture mechanic model defines the correlation between fatigue strength and pore size [8]. With this model, the local load capacity depending on the pore size can be calculated in each element. The load in the component is further calculated by FEM. Local safety for each element is due to the correlation between local load capacity and local load. The distribution of safety against cyclic failure for the above shown reference component is depicted in **Figure 16**.

3 CONCLUSION

For further optimization of components with the focus on higher utilisation of materials beside the knowledge of local stresses also knowledge of local strengths is needed. The later shows distinction on many different influences

- Kind of loading (Push/Pull, Bending , Torsion)
- Geometry and size
- Temperature
- Mean Stress
- Surface Layer (Surface topography, residual stress, microstructure, hardness)
- Load sequence
- Production process, Casting, Deforming, Cutting or Welding
- etc.

All these influences lead to higher or lower strength of the component. When occurring simultaneously the effects can either strengthen or attenuate each other. The experimental investigation of all these effects on fatigue strength in its whole sum is due to time and cost factors nearly impossible and can only be performed punctual, additional simulation is needed for calculation.

On the basis of stress calculations with FEM and simulation of casting and deforming process the dimensioning process of components was shown. These examples show how interdisciplinary work enhances the significance of strength calculations.

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