

Regarding Influences of Production Processes on Material Parameters in Fatigue Life Prediction

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Abstract: *Fatigue life prediction has reached a high level in respect to practical handling and accuracy in the last decades. As a result of insecure or lacking input data deviations between numerical results and test results in terms of cycles till crack initiation are possible. On the one hand, the accuracy of Finite Element results gets better and better because of greatly increasing computer power and mesh density. Whereas on the other hand, the situation is much more critical regarding load data and especially regarding local material properties of the components.*

In the last few years also the possibilities of process simulation have improved in such, that at least a few local material properties or quality indicators can be predicted with sufficient reliability.

Both simulation technologies represent a current state of the art. Therefore it is reasonable to integrate the results of process simulation into fatigue analysis to improve the accuracy of fatigue life prediction. For forming simulation of steel sheet-metal as well as for sand and die casting of aluminum and magnesium this integration has recently been realized.

As an output of forming simulation the effective plastic strain can be used as an indicator for local material parameters. Also the distribution of the sheet metal thickness can be analyzed and used for stress analysis in Abaqus as well as the final fatigue analysis in FEMFAT.

With today's cast simulation tools distributions of local material parameters can be predicted. Furthermore the secondary dendrite arm spacing correlates significantly with porosity and endurance limit. For die casting, a pore free surface layer can be accounted for.

Keywords: *Fatigue Life Prediction, Fatigue Life Analysis, Finite Element Method, Vehicle Engineering, Forming Simulation, Effective Plastic Strain, Casting Simulation, Dendrite Arm Spacing.*

1. Introduction

In today's automotive engineering and development usually a long virtual simulation chain is performed before prototyping and testing phase starts (see fig. 1). This chain includes static and dynamic analysis of displacements, stresses, strains and temperature with Finite Element Analysis (FEA), Multibody Simulation (MBD), sheet-metal forming simulation, cast simulation, etc. The last limb is represented by the fatigue analysis to fix the weak points of a structure.

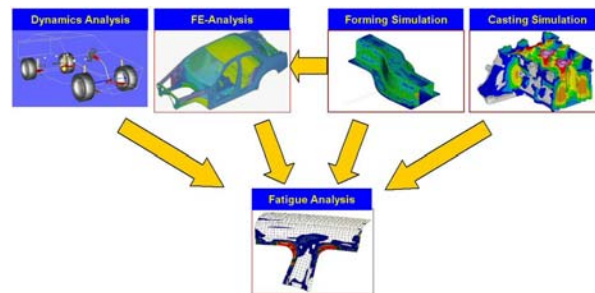


Fig. 1: Fatigue analysis data flow

Damage distributions are the basis for deciding if and how a redesign of the structure should be done. Optimization is used more and more to automatically perform these loops without continuous interaction by the structural analyst.

Software for fatigue life prediction of components has delivered valuable results for more than a decade [1-6]. Of course the results cannot be better than the quality of input data used for a fatigue analysis: FE-model and stress results, monotonic and cyclic material data and load data (spectra, histories). All these data must be carefully defined and provided by the user. More often desired data can be found in ready to use databases.

In this contribution we will focus mainly on the methods and interfaces between process simulation tools (forming analysis and cast simulation) and fatigue analysis. By using process simulation results as an input for fatigue life prediction, it is possible to quantify the influence of the manufacturing process on the fatigue life so that better fatigue analysis results are delivered.

2. REGARDING FORMING PROCESSES IN FATIGUE ANALYSES

In automotive engineering, more and more parts are attempted to be produced by metal forming. Because of production processes like deep drawing or hydro forming, thickness of the blank sheet can significantly change. Also, material parameters like strength values or cyclic material behavior are modified. As a result of these modifications the part's durability can be strongly affected (the fatigue life of a component can increase by a factor of 100 and more). If these positive effects are included into fatigue analysis the accuracy of the calculated fatigue life will be much improved.

2.1 FORMING PROCESSES

Chip less production processes are structured by aspects like dominating load or the type of the forming tool (solid, fluid or gas).

Deep-drawing and Internal High pressure Forming (IHF) is applied for a lot of vehicle parts especially for chassis, suspension and body structures. Whereas in deep-drawing thinning of sheets is sometimes well compensated by changes in material properties, effects have opposite direction in IHF. During this process tubes are expanded using a fluid (usually water or oil) with very high pressure up to 15.000 bars into a tool similar to forging. In contrast to deep-drawing,

there are areas of material where sheets are thickening although big plastic deformations take place.

An important parameter of forming processes is the local plastic strain (φ) which is often characterized by a scalar value called *effective plastic strain* (φ_v), see eq. (3) and fig. 2 respectively.

The plastic strain in direction of h is defined as

$$\varphi_h = \int_{h_0}^h \frac{1}{h} dh = \ln h \Big|_{h_0}^h = \ln \frac{h}{h_0} \quad (1)$$

while the distribution of the plastic strain is analyzed under the condition of volume constancy:

$$\varphi_1 + \varphi_2 + \varphi_3 = 0 \quad (2)$$

The effective plastic strain is furthermore defined as:

$$\varphi_v = \sqrt{\frac{2}{3} \cdot (\varphi_1^2 + \varphi_2^2 + \varphi_3^2)} \quad (3)$$

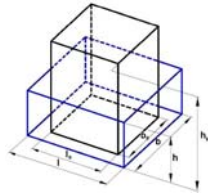


Fig. 2: Deformation under volume constancy

Forming processes mostly cause multiaxial deformations. In [7] the influence of different forming conditions and local plastic strains on the cyclic material behavior of various deep drawing steels was investigated. It was shown, that test series with similar equivalent plastic strains but different forming conditions cause similar cyclic stress-strain-behavior. Further it was noticed that material behavior is nearly independent of the load direction related to the direction of the first principal strain (φ_1).

Due to the production process, the local thickness of the blank sheet can be modified what affects the local stress distribution. Furthermore the material behavior changes by applying the process because of effects of work-hardening. All this influences the durability of the part. To integrate the effects of forming processes into fatigue analysis these modifications have to be edited as input data.

Today there exist already several commercial software products (explicit and implicit Finite Element codes, for example Abaqus/explicit) which can simulate these forming processes. Adaptive mesh refinement is automatically performed at zones of high strains to assure high accuracy.

As a result, distributions of the following parameters are obtained:

- Local sheet thickness
- Local plastic strain
- Residual stress

All these parameters affect the fatigue life significantly. Up to now it is difficult to obtain residual stresses with sufficient accuracy for fatigue life analysis, especially if explicit FE-codes are used. Therefore our focus remains on the first two influence parameters. The local sheet thickness resulting from elastic-plastic deformations has to be used as an input for the FE stress- and strain-analysis (see fig. 1) and therefore affects the fatigue life not directly. The local plastic strain has an impact on local monotonic and cyclic material parameters and is a necessary input for fatigue life prediction.

Both, monotonic and cyclic stress-strain curves are modified by the local plastic strain (effect of work-hardening). In general, monotonic stress-strain curves are more affected by forming processes than cyclic ones, see fig. 3. Reasons for that are phenomena like cyclic creeping and cyclic relaxations [9].

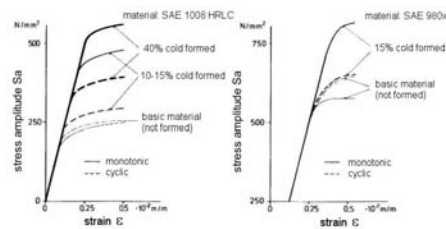


Fig. 3: Effect of work hardening [9]

2.2 INTEGRATION INTO FATIGUE ANALYSES

Since the material of the blank sheet is differently modified over the structure by the forming process, it is difficult to define the material parameters experimentally. But it would be a high benefit if all phenomena like creeping were included. As an option, cyclic material behavior can be calculated by different methods.

After investigating a number of test results, Masendorf [7] proposed a method called *Material Law of Steel Sheets (MLSS)*. Analytical expressions are given for the parameters of strain life curves and cyclic stabilized stress strain curves depending on the effective plastic strain level. As a further development Hatscher [8] published the *Method of Variable Slopes (MVS)*.

Both, *MLSS* and *MVS* use the effective plastic strain (φ_p) to describe the effects of metal forming. They mainly differ in the used points of reference, the number of materials used for investigations, and in the definition of the slopes of the elastic and plastic lines of the strain-life-curve

(parameters b and c). While these slopes are kept constant at *MLSS* they are a function of the equivalent plastic strain at the *Method of Variable Slopes*.

Based on the work of Masendorf [7] and Hatscher [8], methods which quantify the influence of forming processes on the fatigue life have been implemented in *FEMFAT* [10,11]. Specifically, analytical expressions to describe material behavior have been adapted for the usage in the software where local SN-curves are used for linear damage accumulation according to Miner's rule.

Influence coefficients on the fatigue limit f_β and the slope of the SN-Curve f_k modifying the basic material's SN-curve were developed. Further factors on the cyclic coefficient of hardening $f_{K'}$, on the cyclic exponent of hardening $f_{n'}$ and on the cyclic yield strength $f_{Rp'0.2}$ for building cyclic stress-strain curves were generated.

Also monotonic material parameters are influenced by effects of forming processes. Therefore the fatigue-limit-diagram by Haigh is modified by coefficients changing the static yield strength $R_{p0.2}$ and the tensile strength R_m .

Coefficients according to *MLSS* are declared as:

$$f_\beta = 1 + \frac{13036}{10370} \cdot \varphi_V \quad (4)$$

$$f_k = 1 \quad (5)$$

$$f_{K'} = \frac{f_\beta}{\left(1 - \frac{1.1878}{1.5262} \cdot \varphi_V\right)} \quad (6)$$

$$f_{n'} = 1 \quad (7)$$

$$f_{Rp'0.2} = f_{K'} \quad (8)$$

Material Law of Steel Sheets was developed by analyzing 5 different fine steel sheets (UTS between 300 and 600 MPa). Material parameters like slopes of the elastic and plastic strain life curves are equal for all materials.

MVS was developed by investigating more than 25 different materials. Coefficients according to *MVS* are defined according to eq. 9 – 13 where N_D and $N_{0.2}$ are characteristic numbers of load cycles depending on the material. While b_0 and c_0 are the slopes of the elastic and plastic lines of the basic materials strain life curves, b and c represent the influenced slopes according to the analytical expressions of [8]. The constant factors δ and γ are material dependent parameters.

$$f_\beta = (1 + \varphi_V) \cdot \left(\frac{N_D}{N_{0.2}}\right)^{(b-b_0)} \quad (9)$$

$$f_k = \frac{b_0}{b} = \frac{\lg\left(\frac{\delta}{\gamma}\right)}{\lg\left(\frac{\delta}{\gamma \cdot (1 + \varphi_V)}\right)} \quad (10)$$

$$f_{K'} = (1 + \varphi_v) \cdot 0.002^{\left(\frac{b_0 \cdot b}{c_0 \cdot c}\right)} \quad (11)$$

$$f_n = \frac{b \cdot c_0}{c \cdot b_0} \quad (12)$$

$$f_{R_{p0.2}} = 1 + \varphi_v \quad (13)$$

The above described influence factors are always bigger than 1, what means that the effective plastic strain has always a positive influence on the fatigue life, see figure 4a.

Figure 4 compares SN-curves and cyclic stress-strain-curves at various plastic strains calculated by both the MLSS and the MVS hypotheses.

The basic material's SN-curve is only moved to higher values of fatigue strength when modified by coefficients based on *MLSS*, see fig 4a. If *MVS*-coefficients are used to modify material behavior the slope of a part's SN-curve will be dependent on the equivalent plastic strain. So effects of cyclic creeping and cyclic relaxations which exist at high stress-amplitudes (higher than yield strength) are modeled accordingly. This means that the effect of forming processes diminishes at higher local stress amplitudes.

The effects of forming processes on the material behavior of standard deep drawing steels and fine steel sheets are characterized in figure 4b.

The monotonic and cyclic material behavior of stainless, austenitic steels is much more affected by the local plastic strain. Therefore the fatigue life computed by the previously described methods is lower than the observed fatigue life. As a consequence a special influence coefficient on the fatigue limit f_{fl} was developed for stainless steels [12], leading to the approximate formula:

$$f_{fl} = 1 + 3\varphi_v \quad (14)$$

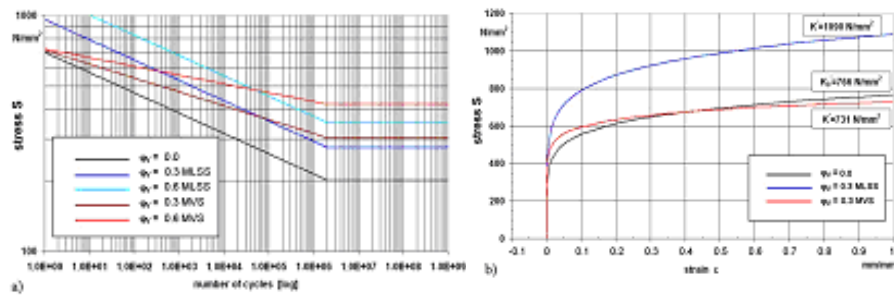


Fig. 4: Effects of plastic strains on
a) SN-curves and
b) cyclic stabilized stress strain curves.

Another practical question is how to transfer (“map”) the results from the forming simulation Finite Element mesh (shell thickness, strains) to the structural Finite Element mesh which is

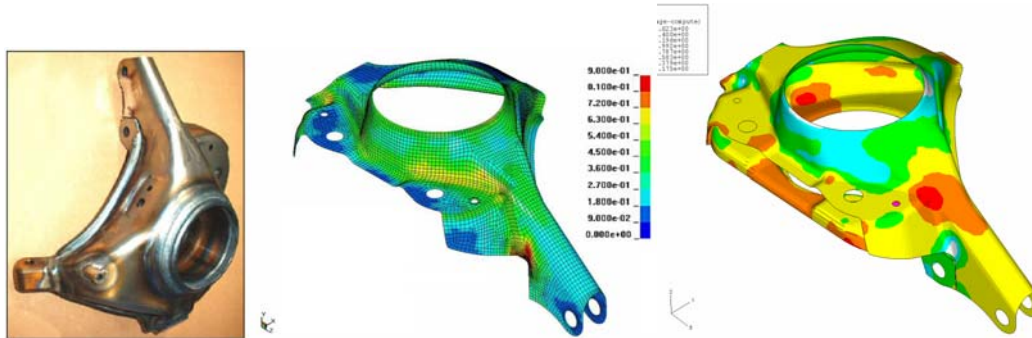
finally used for fatigue analysis. This procedure is not as easy as it seems because of big differences in element size, possibly orientation of meshes and part dimensions. Whereas process simulation features the original part length during forming, subsequent operations like cutting or stamping will usually reduce the size. Furthermore deviations between the designed shape and the one received by forming simulations are possible, making an error-insensitive mapping process necessary.

Some forming simulation software tools already provide such a feature (e.g. *LS-Dyna*). Otherwise general purpose tools which originally have been developed for submodel analysis, can be used for mapping [18].

2.3 EXAMPLE

2.3.1 Deep-drawn swiveling bearing (kindly provided by Magna Cosma International)

A swiveling bearing, whose main components are two sheet metal shells produced by multistage deep drawing processes, was analyzed, see fig. 5a. The shells are made of fine grain steel ZStE380 and the blank sheet has a thickness of 3mm. The forming simulation was performed in *Abaqus/Explicit* while the mapping of the results was done in *LS-Dyna*. The distribution of the equivalent plastic strain mapped on the upper shell of the knuckle is pictured in figure 5b. The distribution of the initial thickness is pictured in figure 5c and used for the stress analysis. Afterwards stresses were derived in *Abaqus/Standard* to be used as input data for fatigue analyses in *FEMFAT*.



**Fig. 5 a) Deep drawn swiveling bearing;
b) distribution of the equivalent plastic strain mapped on the upper shell.
c) distribution of the initial thickness.**

The prototype was tested in 19 test-series with 4 different load cases (longitudinal-, lateral-, braking force and force through steering arm). Each test was done under fully reversed load till initial cracks appeared. Whereas 3 load cases only produce cracks at welding seams, load case longitudinal force also generates cracks without welding influence.

The observed fatigue life for longitudinal force is between 100.000 and 143.000 load cycles. A number of different versions with various influences were calculated to identify the relevant effects. In all calculated cases the critical location is equal to the location of the initial crack occurred in the fatigue test, see figure 6. The determined fatigue life time due to the load case longitudinal force was compared to the measured fatigue life, see fig. 7.

The first version *V1* was calculated as it has been common practice in automotive engineering. That means without influence of sheet thickness on stress amplitude and mean stress and without local material properties caused by the effects of metal forming.

In *V2* only the change of local sheet thickness was considered. Due to the smaller sheet thickness stress amplitudes increase in the critical area and fatigue life drops. Changes of the thickness and the modification of the material behavior have been considered in *V3 (MLSS)* and *V4 (MVS)*.

Figure 7 shows that the values of predicted fatigue life – using the developed influence coefficients in calculation – are in the range of the measured values. The results are much more accurate than the ones derived by common methods.

Fatigue analysis regarding the effects of forming processes correlate very well with the test results as can be seen in figures 6 and 7.

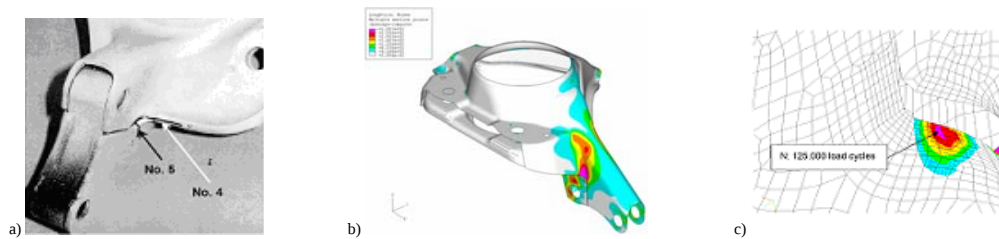


Fig. 6 a) crack locations due to load case Longitudinal Force.
b) stress distribution considering longitudinal force.
c) damage distribution considering MLSS (*V3*).

Crack No. 4 appeared at a weld seam where local effects of welding dominate.

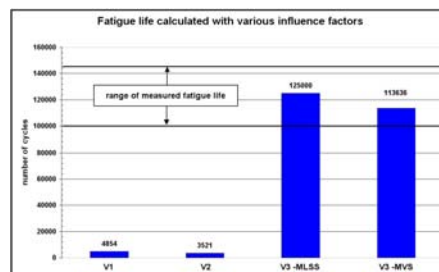


Fig. 7: Fatigue life at the location of the initial crack.

Including no influence of the forming process, or only the change of thickness results in conservative predictions. As a consequence components are designed too rugged and this results in more weight and more cost.

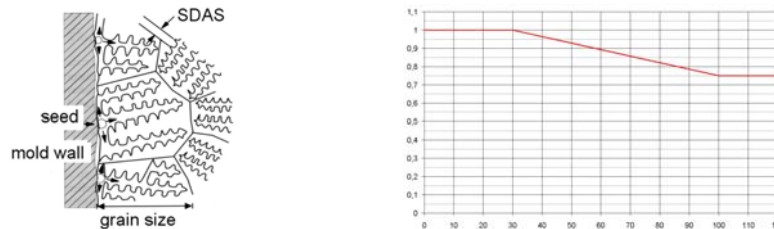
3. REGARDING THE EFFECTS OF CASTING SIMULATIONS IN FATIGUE ANALYSES

3.1 SAND AND PERMANENT MOLD ALUMINUM CASTING

Similar to the sheet-metal forming, simulations for sand or permanent mold aluminum casting deliver distributions of quantities which affect the fatigue life of components significantly. These quantities are:

- Secondary dendrite arm spacing (SDAS)
- Solidification time
- Cooling rate
- Porosity

The first 3 outputs have a very direct connection because cooling rate imposed by the mold determines solidification time and grain size directly. Grain size is quantified by the Secondary Dendrite Arm Spacing (see fig. 8 a).



**Fig. 8: a) Definition of secondary dendrite arm spacing.
b) Example for a fatigue limit influence factor in dependence on the SDAS [μm].**

The University of Leoben has done some important investigations concerning the influence of the SDAS on the fatigue behavior for sand cast aluminum AlSi7Mg [13,14]. It has been found that increasing the SDAS decreases the local fatigue limit as shown in fig. 8 b because there is a correlation between SDAS and level of porosity [15]. Stress concentrations by pores cause a dramatic reduction of fatigue limit and change of fatigue prediction results [16].

3.2 EXAMPLE

Swiveling bearings in automotive structures have to endure high forces from mounting as well as from road loads. So it is of eminent importance that in areas of high stresses the casting quality is high in terms of low residual stresses and good microstructure. This is accomplished by casting simulation. During virtual prototyping the results from casting simulations are used to successfully improve the accuracy of fatigue life prediction [17].

The investigated swiveling bearing, see fig. 9, is made of the aluminum material *AlMgSi1F32T6*.

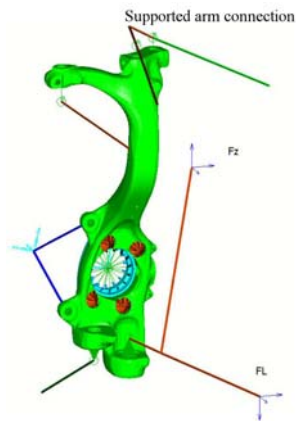


Fig. 9: Boundary conditions at swiveling bearing.

In fig. 10 the damage distribution of the swiveling bearing from a fatigue analysis in *FEMFAT* without regarding the influence of the casting process is pictured.

Nominal material data determined from cast specimens were used together with one block of a multi-axial load spectra.

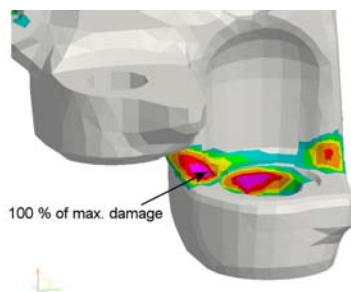
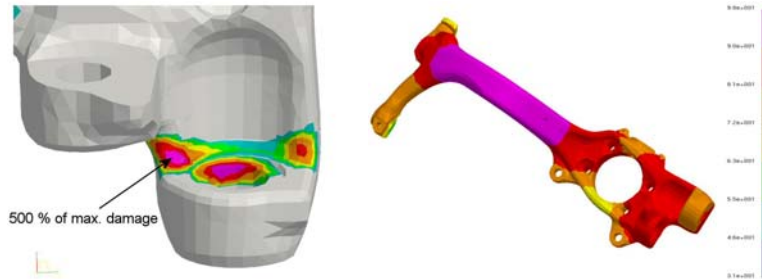


Fig. 10: Damage distribution of the bearing without influences of casting processes.

3.2.1 Sand aluminum casting

In this case the bearing was analyzed regarding the effects of a sand casting process. In fig. 11 the resulting damage distribution is shown.

Compared to the calculation without considering sand casting of the part the maximum damage value has increased by a factor of 5.



**Fig. 11: a) Damage distribution including sand casting process.
b) Plot of secondary dendrite arm spacing (SDAS).**

In fig. 11b the corresponding secondary dendrite arm spacing (SDAS) is shown.

The distribution of SDAS values shows higher levels than a typical separately cast specimen in all thick-walled regions including the critical location.

3.2.2 Permanent mold aluminum casting

Analogous fatigue analysis was done considering the secondary dendrite arm spacing according to permanent mold casting. The resulting damage plot can be seen in fig. 12.

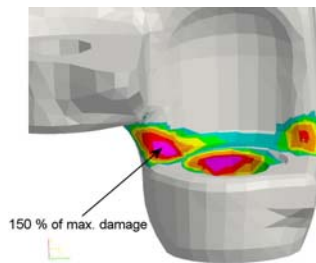


Fig. 12: Damage distribution including permanent mold casting process.

In case of regarding effects of permanent mold aluminum casting, the maximum damage is only 1.5 times higher than in case of not considering any process effects. This can be explained by consistently smaller SDAS values which results from better cooling compared to sand casting.

3.3 DIE CASTING

Components produced by aluminum or magnesium die casting processes are characterized by nearly pore-free surface layers. This results from very intensive cooling rates during the first phase of mold filling. The fatigue behavior of these layers is significantly better compared to the one of the pored basic material. To integrate the effects of pore-free material layers into fatigue analyses with FEMFAT the “Boundary Layer Analyses Model” was developed.

By using this model the fatigue behavior of the boundary layer can be analyzed without modeling the pore-free layer explicitly by layers of thin Finite Elements. Consequently some input data has to be defined for each surface node:

- Material properties of the pored material (standard)
- Material properties of the pore-free boundary layer
- Thickness of the boundary layer d

For each surface node two analysis results are automatically computed. While the material behavior of the pore-free boundary layer and the stresses at the surface nodes are applicable for the first run, the pored basic material and stress values at the assessment point are used for the second run, see fig. 13. The 3D-stress tensors at the border between boundary layer and basic material as well as the corresponding stress gradient are determined by *FEMFAT* without user interaction.

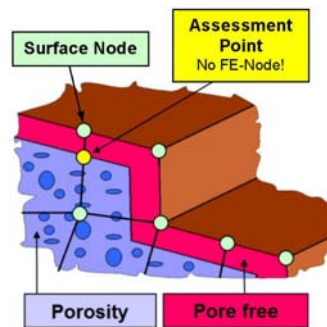


Fig. 13: The Boundary Layer model.

3.3.1 EXAMPLE

An engine support bracket, see fig. 14, produced by aluminum die casting was analyzed regarding the effects in notched and more uniformly stressed locations. As pored basic material *GD- $AlSi9Cu3$* aluminum cast alloy was used. For the pore free boundary layer strength and fatigue data of this material were modified. The thickness of the boundary layer was defined as 0.5 mm over the whole component.

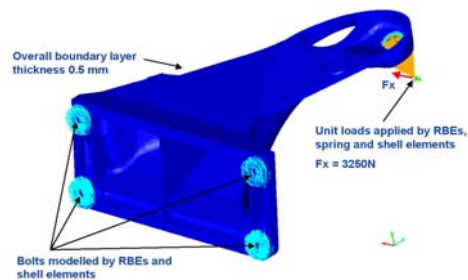
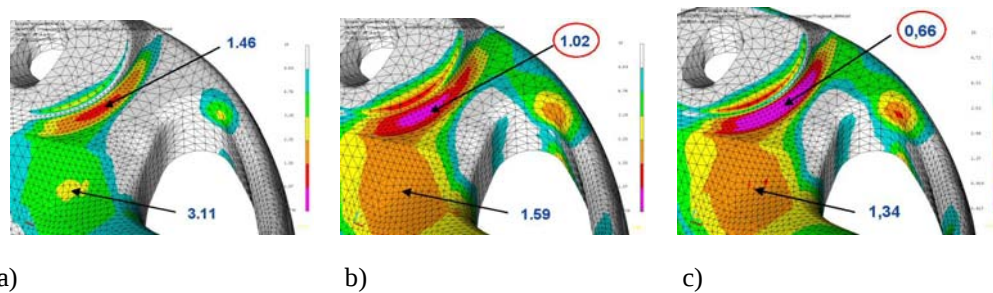


Fig.14: FE-model of the engine support bracket.

In figure 15a the endurance safety factors at the surface of the component are pictured. The material of the boundary layer is pore-free, therefore the safety factors are higher than at the transition layer between pore-free and pored material, see figure 15b.

By using pored material behavior for the whole structure (pore-free layer is not considered) the resultant safety factors of endurance are very conservative, see figure 15c. The most critical safety factor is about 30% below the safety factor at the transition layer of the structure analyzed by regarding the pore-free boundary layer.



**Fig. 15: a) Endurance safety factors at the surface of pore-free material.
b) Endurance safety factors at the border between pore-free and pored material.
c) Endurance safety factors at the surface without considering pore-free boundary layers.**

These results explain why many predictions of die casting components tended to be very conservative in the past. In contrast to this, the results utilizing the “Boundary Layer Analysis Model” correlates very well with test results.

In figure 16 the results of fatigue tests are compared with results of different fatigue analysis.

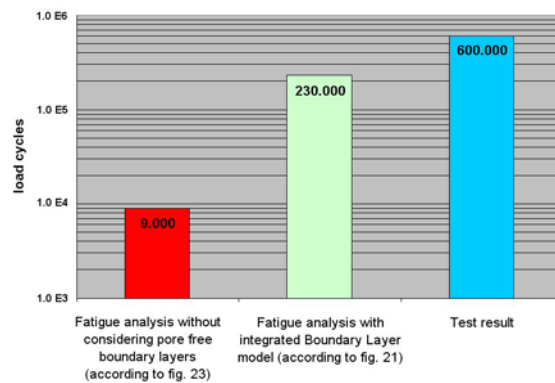


Fig. 16: Results of fatigue analysis versus test results according to load cycles till initial crack.

4. CONCLUSION

By including the effects of manufacturing processes, significant improvements regarding correlation between fatigue life predictions and test results can be reached.

Considering the effects of forming processes (distribution of sheet metal thickness over the formed structure and modification of the material behavior) as well as influences of casting processes for sand aluminum-, permanent mold aluminum- and aluminum die-casting is possible in fatigue life prediction. The results calculated with the developed methods correlate very well with test results.

These methods will be enhanced in future regarding more local effects (e.g. influence of residual stresses at forming processes).

Benefits from applying these new features are high at reasonable efforts because results from process simulations are usually available during concurrent engineering.

In the future effects from many other manufacturing processes like forging, rolling, massive forming or welding have to be considered to reach a significant higher level of fatigue life prediction accuracy.

It can be expected that this will mean additional attraction to develop components by virtual prototyping CAE-methods.

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