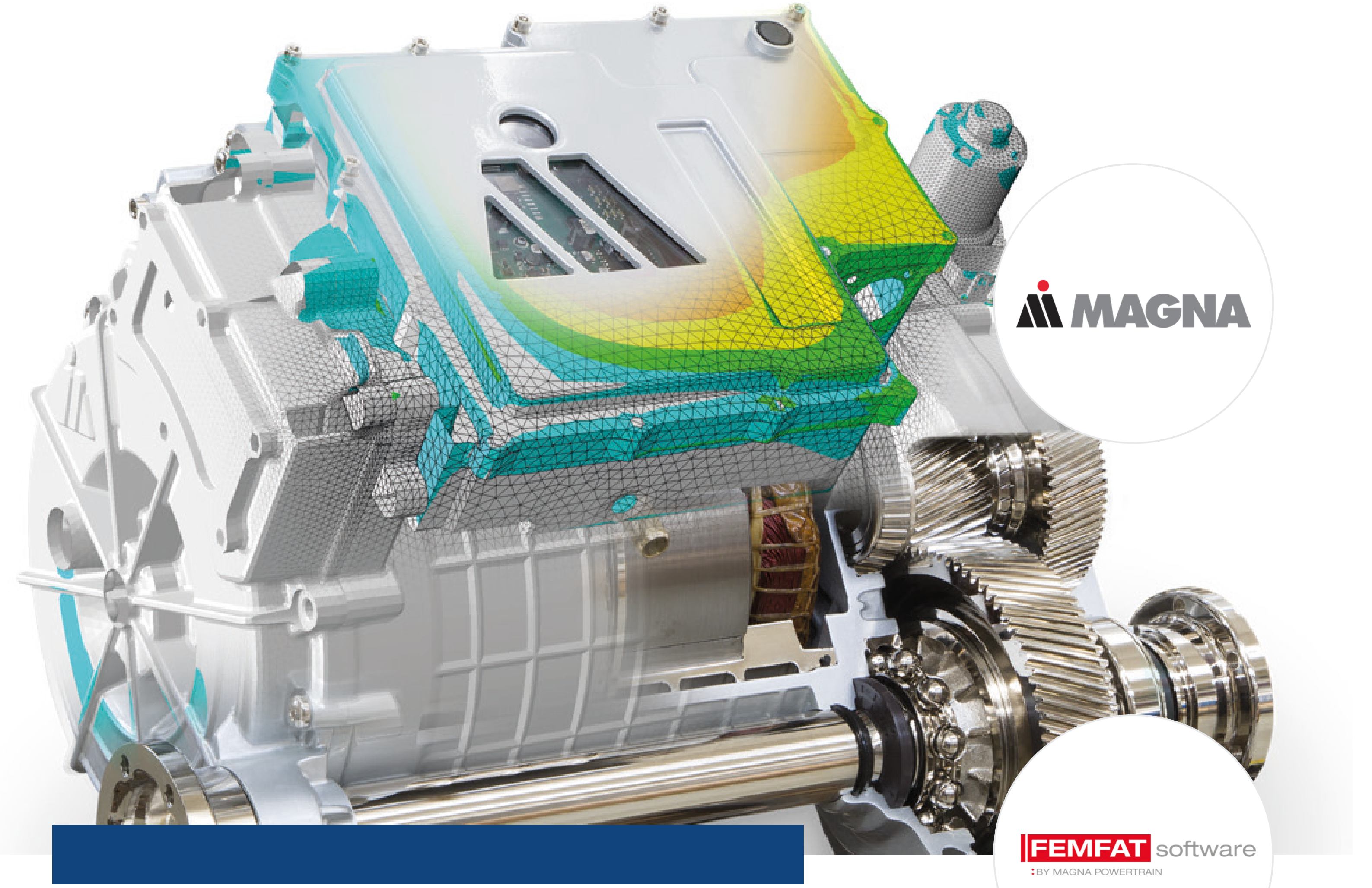

Enhanced low cycle fatigue analysis and the influence of load sequence for an e-motor's rotor

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In many engineering applications, the stresses experienced by materials can exceed their yield strength resulting in plastic deformation.
This plasticization of a material under load is a significant factor in determining the service life of a component. Accurately predicting this phenomenon is critical to ensuring reliable and enduring components.

Until now, the fatigue tool FEMFAT has used a simple approach based on stress redistribution of the rainflow matrix elements according to Neuber's approach [1]. However, this results in the loss of information about the sequence of load peaks. This can lead to inaccuracies in determining the actual plasticized state of a material.

A new approach has been developed in FEMFAT that calculates the Neuber elastoplastic stresses at each time point. This makes it possible to include the influence of the sequence in fatigue life analysis. By considering the effects of peak load sequence, plasticization can be more accurately predicted and, consequently, component life can be improved.

Isotropic and kinematic hardening

Mathematical models such as the von Mises yield criterion and strain hardening models are widely used to estimate the plastic deformation of metals. Hardening models describe the behaviour of materials under load above the yield point.

The hardening process in materials can occur by expansion or translation of the yield surface. This concept is fundamental to

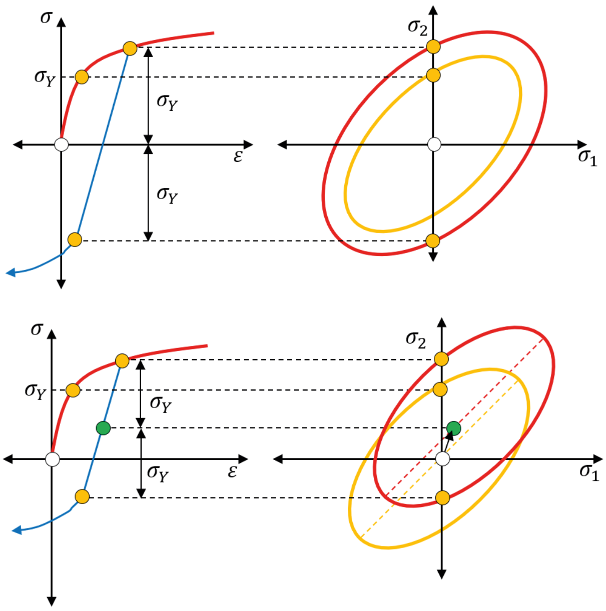

Fig.1. Yield surface for isotropic hardening (above) and kinematic hardening (bottom).

understanding the behaviour of materials under plastic deformation. The two main types of hardening mechanisms based on the nature of yield surface changes are isotropic hardening and kinematic hardening.

Isotropic hardening refers to the expansion of the yield surface uniformly in all directions. In this case, the size of the yield surface increases as plastic deformation progresses. Isotropic hardening is commonly observed in materials that undergo uniform plastic deformation, such as mild steels. As the material undergoes more plastic deformation, the yield surface expands – the yield stress increases, indicating a greater resistance to further deformation.

Kinematic hardening, on the other hand, involves the displacement of the yield surface while maintaining its size. This type of hardening is associated with materials that exhibit non-uniform plastic deformation, such as certain types of metals and alloys. As the material undergoes plastic deformation, the yield surface shifts, indicating a change in the material's ability to accommodate further deformation. Kinematic hardening is often characterized by a Bauschinger effect, where the yield strength of the material decreases after reverse loading.

The kinematic hardening model was described in terms of back-stresses α_i which depend on the material parameters C_i and γ_i.

$$\alpha_i = \frac{C_i}{\gamma_i}\left(1 - e^{-\gamma_i \varepsilon_p}\right) \quad \text{and} \quad \alpha_{total} = \sum_{i=1}^{N} \alpha_i$$

γ_i Rate of hardening coefficient reduction
C_i Initial kinematic strain hardening modulus
ε_p Plastic strain

Multiple back-stresses are used to improve the correlation between measured data and the kinematic hardening model.

However, incorporating material non-linearity into finite element analysis (FEA) can significantly increase computing time and complexity. This is a challenge for engineers who need to perform efficient and reliable low cycle fatigue analysis.

The new PLAST method in FEMFAT fatigue software

To address the problem of increased analysis time due to material non-linearity, the use of PLAST methods in FEMFAT to estimate elasto-plastic stresses were proposed. The PLAST methods provide an alternative approach that reduces computing time while maintaining the same level of accuracy. The two main components of the new FEMFAT PLAST approach are:

- Fitting a kinematic hardening model to the first branch of the stress-strain curve: the kinematic hardening model captures the material's behaviour during cyclic loading and provides a more accurate representation of the stress-strain response, particularly in the plastic regime. By fitting this model to the first branch of the stress-strain curve, the PLAST method considers the hardening behaviour of the material.
- Stress rearrangement according to the Neuber or ESED (equivalent strain energy density) methods: stress rearrangement methods are used to account for the redistribution of stresses due to cyclic loading. The Neuber

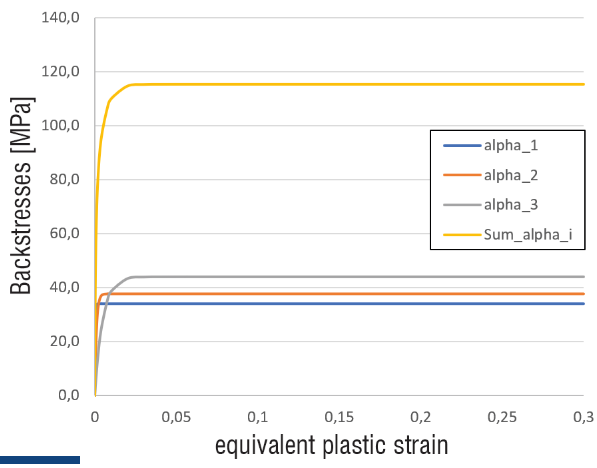

Fig.2. Kinematic hardening with three back-stresses.

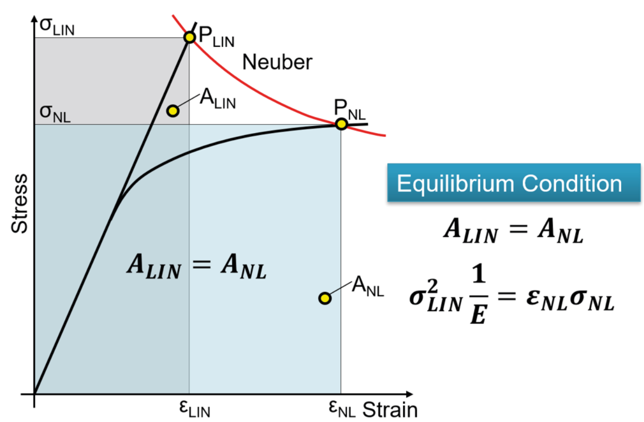

Fig.3. Stress rearrangement according to Neuber.

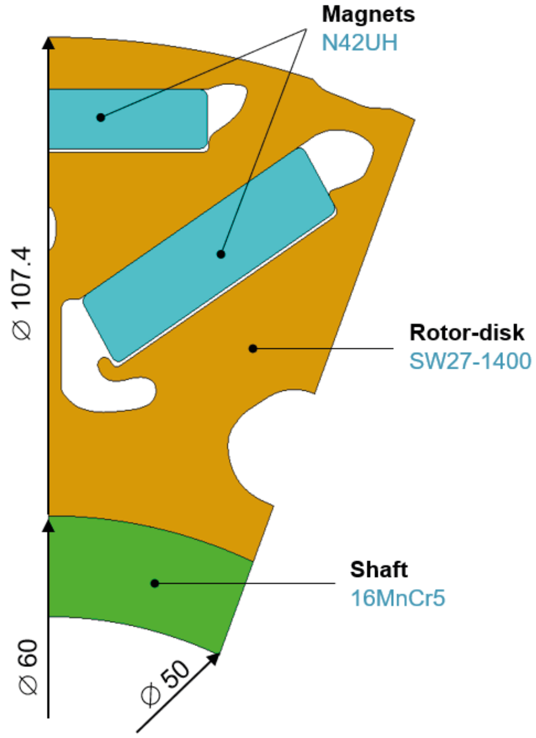

Fig. 4. Rotor plate of an electric motor.

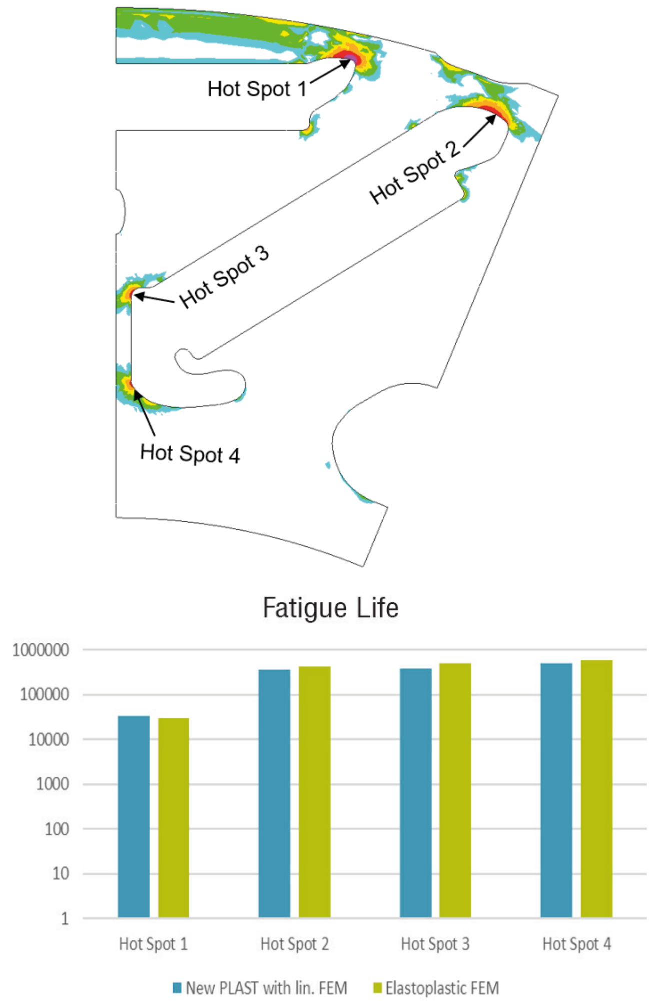

Fig.5. Comparable fatigue life results for the new PLAST approach with linear FEM and elastoplastic FEM.

and ESED methods are commonly used stress rearrangement approaches. These methods ensure that the elasto-plastic stresses are properly distributed, resulting in more accurate fatigue life predictions.

New PLAST method procedure:

- Calculation of material parameters: for each material parameter pair (C_i, γ_i), an optimization process is performed to determine the values that minimize the error to the cyclic stabilized stress-strain curve. These parameters are specific to the material being analysed and are essential for accurately predicting its behaviour under cyclic loading. The Ramberg-Osgood parameters K' and n', which define the cyclically stabilized data, are used as benchmarks for the optimization process.
- Kinematic hardening model: in the cutting plane, the equivalent stress history is rearranged using the kinematic hardening model. This model uses the optimized parameters obtained in step 1 for each sample of the load time history. The kinematic hardening model considers the material's response to cyclic loading, considering the accumulation and redistribution of plastic deformation.
- Rainflow counting: The rearranged stress history obtained from the kinematic hardening model undergoes rainflow counting.

Application: Rotor plate of an electric motor and influence of sequence

The advantage of the FEMFAT PLAST approach is that it avoids the need for computationally expensive elastoplastic FE analysis. Engineers can significantly reduce analysis time without compromising the reliability of their predictions. To demonstrate the effectiveness of the FEMFAT PLAST approach, we studied the case of the plates of a rotor in an electric motor.

The case study compares two different approaches:

- Linear elastic FEA and channel-based multiaxial fatigue analysis (channelMAX) using load signals and the new PLAST method in FEMFAT.
- Transient, elasto-plastic FEA and transient multiaxial fatigue analysis in FEMFAT (transMAX) without PLAST.

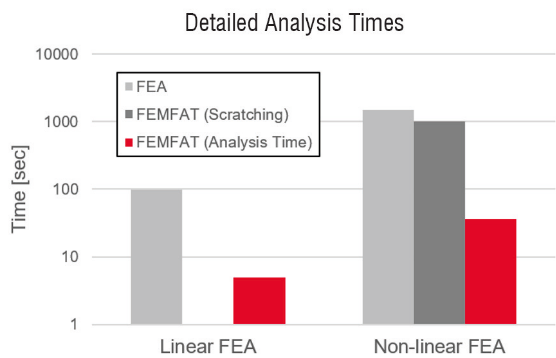

Fig.6. Analysis time for finite element analysis (FEA) and fatigue analysis.

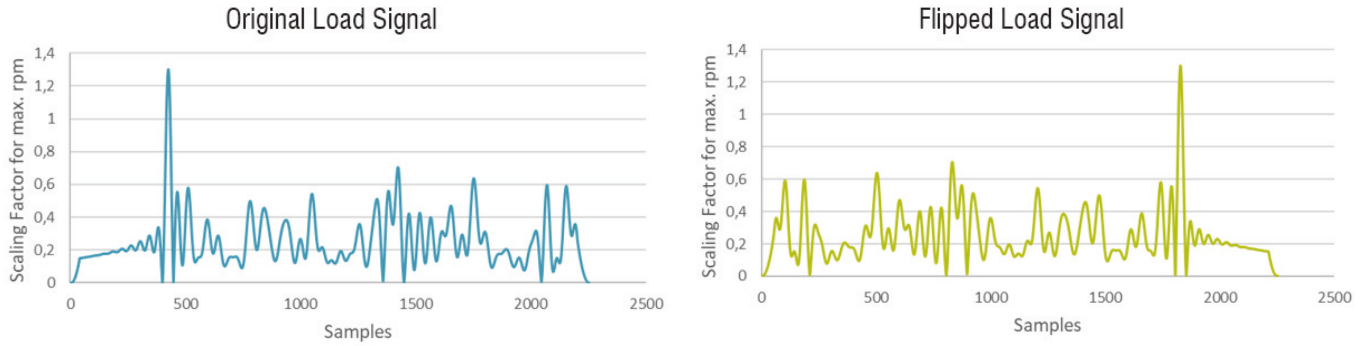

Fig.7. Original signal (left) and flipped signal (right) to study the influence of sequence.

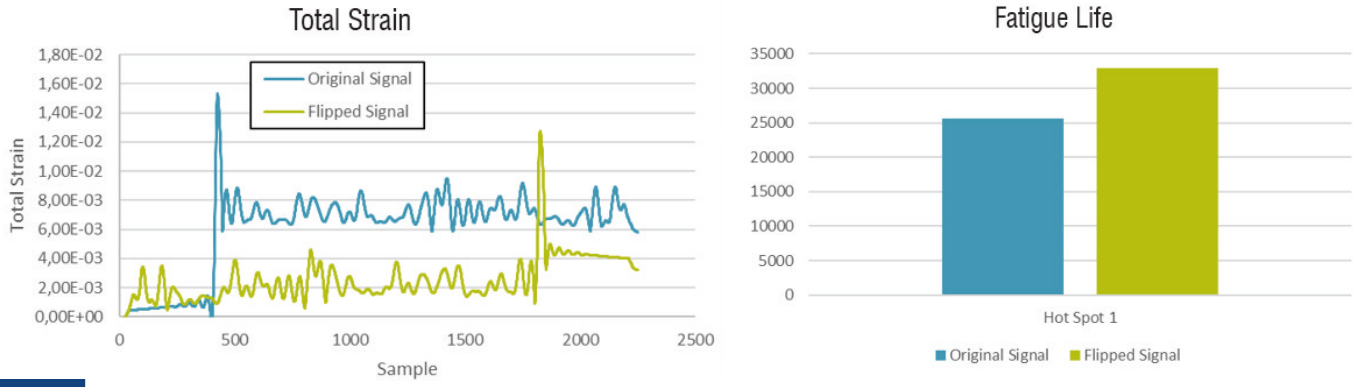

Fig.8. Original signal (left) and flipped signal (right) to study the influence of sequence.

The results obtained using the new PLAST approach were compared with those obtained from elastoplastic FE analysis.

The results show that the PLAST approach yields similar results to the elastoplastic FE analysis while significantly reducing analysis time.

The fatigue results in Fig.4 are very similar between the new FEMFAT PLAST approach with linear FEM and the standard approach with elastoplastic FEM. However, the total analysis time (FEM + fatigue analysis) of the new method is about 25 times faster!

Influence of load sequence on damage outcome:

In general, damage depends on the sequence of load peaks. If a high load peak occurs at the beginning of load history, the resulting residual stresses will have a positive effect on the subsequent load cycles.

To illustrate the influence of sequence, two signals that generate the same rainflow matrix are analysed. The second signal was generated by simply reversing the first signal.

Both signals were analysed using the new the FEMFAT PLAST method. The stress peak at the beginning leads to plastic hardening, thus reducing the damage of the subsequent cycles.

Conclusions

The enhanced low cycle fatigue analysis with the new FEMFAT PLAST method provides a practical and efficient solution for engineers to accurately predict the fatigue life of components subjected to high-stress applications.

By incorporating kinematic hardening into multiaxial fatigue analysis, the influence of the sequence of high load peaks can be predicted with high accuracy, even for long time histories.

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