Thermomechanical Fatigue Life Prediction of Cylinder Heads in Combustion Engines

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While the deformation and damage behavior of aluminum cylinder heads under complex thermal mechanical loading has been the subject of numerous studies in the past, cast iron cylinder heads have been in the focus of thermomechanical fatigue (TMF) only to a minor extent. In this paper, a feasible procedure is presented to set up material models and estimate service life of cast iron cylinder heads under variable thermomechanical loading conditions by the use of computer-aided engineering tools. In addition, the influence of thermal load and mechanical constraints on TMF life span is shown. A specimen model is used for parameter identification in material model setup and a cylinder head model is used for correlation with cracking phenomena. Investigation of different thermomechanical load influences is conducted on the cylinder head model. The principal strain and energy based fatigue criteria are used in assessment of TMF lifetime for the cast iron family and material specific evaluation procedures are pointed out. The results highlight the importance of exact definitions of the boundary conditions and underline the sensitivity of TMF lifespan of cast iron cylinder heads with respect to the defined boundary conditions. Considering this sensitivity, an approach conforming to the engine development requirements is proposed. It is shown that both the crack location and fatigue lifetime are predicted with high accuracy. [DOI: 10.1115/1.2771251]

Introduction

Due to today's demands to reduce cost and product time to market, engineering procedures are increasingly using more sophisticated simulation techniques, instead of validation testing. In particular, the rapidly increasing specific loads of diesel engines require advanced calculation methods. One of the most challenging simulations is the thermomechanical fatigue prediction of cylinder heads. The relatively new and more pronounced challenge in engine design, thermomechanical fatigue (TMF) analysis, as the demand for high torque, high specific power, and low emissions continues to grow, is necessitated due to the increasing operating temperatures.

In TMF, the stress-strain behavior is associated with mechanical cycles as well as thermal ones. The induced severe temperature gradients due to operational loads do not occur in all components in the automotive industry but in the ones related to the engine such as cylinder heads and exhaust manifolds. It is important to notice that the TMF problems, caused due to the heating up and cooling down of the engine material, in cylinder heads are related to the start-operate-stop cycles and basically not with the combustion cycles [1]. Also, strong engine load changes (e.g., from full load to coasting or idle operation mode) contribute to the TMF of the relevant components. The large temperature changes in flame deck result in thermal expansion and contraction and accompany high amplitude low frequency plastic strains, primarily in valve bridges. Therefore, linear finite element analysis (FEA) is a degree of oversimplification to simulate the material behavior.

It has always been a question to decide on necessary and sufficient level of details to model cylinder head behavior in computer-aided engineering (CAE) environment. This decision is influenced by the boundary conditions of engine development: increasing complexity of cylinder head geometries (four-valve designs, intermediate deck, added ribbings, port design), short development times, and also the production process. In addition, the design engineer should also consider the limitations of finite element software tools and workstations, multiaxial stresses and strains on flame deck, and the testing programs required to calibrate material parameters. Figure 1 shows the details/complexity of material models generally considered in engine development process as a function of time.

As the number of material parameters increases exponentially with the use of complex models, reproducibility of simulations and material parameter calibration becomes more difficult, if not infeasible. Therefore, substantial testing programs are necessary considering the fact that the effect of simultaneously varying temperature and mechanical strain is quite sensitive to material composition, maximum and minimum temperatures, temperature range, strain rate, strain range, cycle times, etc. On the other hand, simulation of the cyclic loading until a stabilized state is obtained may lead to a transient analysis where the number of loading cycles required is intolerable. From this standpoint, an uncoupled thermal, mechanical, and fatigue analysis and a simple elasto(visco)plastic constitutive law to represent material behavior under anisothermal loading, where the number of material parameters are of order 2^2–2^3, is the favorable choice in an efficient engine development program.

In the first section of this paper, an overview of the TMF life prediction approach is presented. The materials of interest are described in the next section. The first modeling step of the approach—material model setup—is discussed in the third section, which is followed by the results comparison of materials investigated in this study. Then we present the second modeling step of the approach: lifetime prediction. Finally, application of this approach on a heavy duty cylinder head is presented and several thermal, mechanical, and material influencing factors are discussed.

Approach

TMF analysis of a cast iron cylinder head includes stress-strain determination and lifetime prediction, succeeding the thermal

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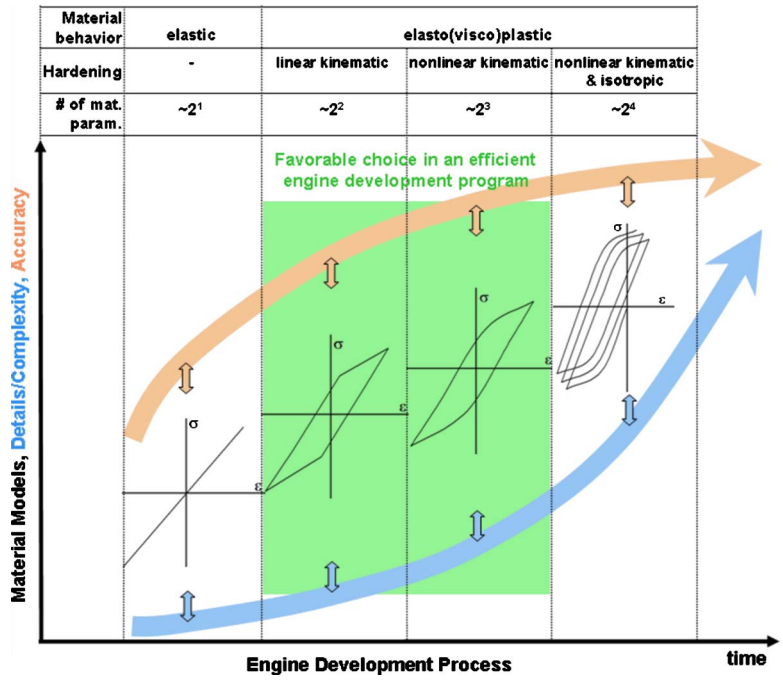

Fig. 1 Standpoint for material modeling in TMF analysis

analysis. In order to consider the boundary conditions of the engine development process, stabilized cyclic behavior (plastic shakedown) is assumed in representing the elasto(visco)plastic response of the material. Uncoupling of thermal and mechanical analysis assumption is justified by the negligible contribution of inelastic dissipation to heating. Finally, damage independent constitutive law allows time saving in calibration of fatigue parameters and lifetime evaluation.

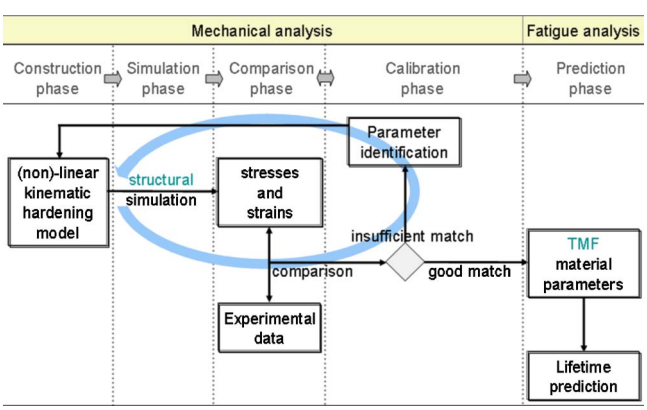

Fig. 2 TMF analysis approach for specimen model

The stress-strain and lifetime prediction modeling are crucial, and independent models allow the design engineer to evaluate the dependencies in a relatively short period of time. The thermal loading and the material behavior together with the restraining of the model are the main inputs for the mechanical analysis. As per the damage independent constitutive law, lifetime prediction can be conducted using the output of mechanical analysis and the fatigue parameters of the material. These two primary steps in a TMF analysis conducted for the specimen model are shown in Fig. 2. The global structural FEA methodology for cylinder heads is demonstrated in Fig. 14, and these analyses are carried out for cast irons in the following.

Materials

The specific materials considered in this study belong to the cast iron family. Three main classifications describing general graphite shape in graphitic cast irons are in common use: flake, compacted, and spheroidal. The cast irons with these graphite morphologies are called gray cast iron (CI-GJL according to DIN EN), compacted graphite iron (CGI-GJV), and spheroidal or

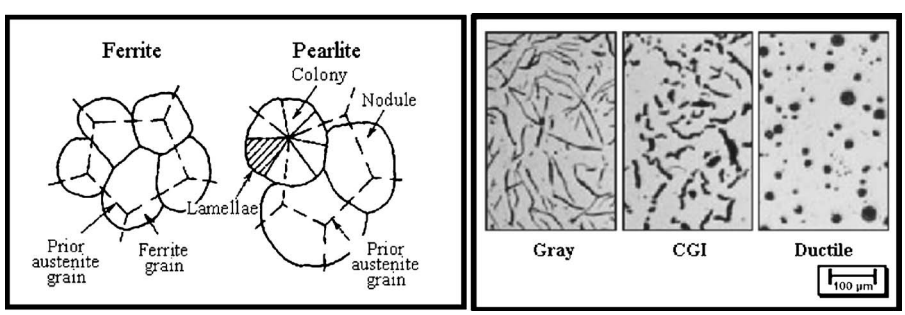

Fig. 3 The two most common matrix structures; ferrite and pearlite on the left [2] and graphite shapes on the right

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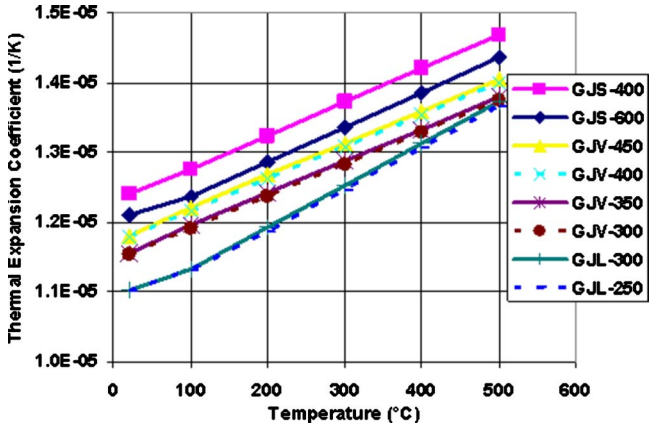

Fig. 4 Thermal expansion coefficient as a function of temperature

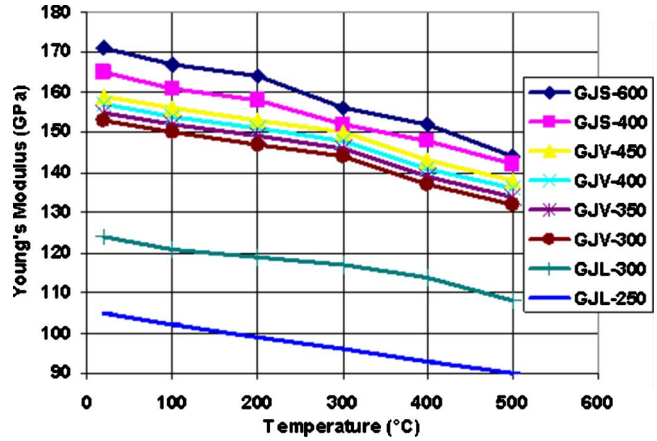

Fig. 6 Young's modulus as a function of temperature

nodular or ductile cast iron (SGI-GJS), respectively. Differences in these three main classes are in chemical composition, graphite shape, and material matrix, which lead to different material properties [2]. The most common material matrix structures and the graphite morphologies are demonstrated in Fig. 3.

The coefficient of linear thermal expansion of cast irons depends primarily on graphite structure and temperature, although it is influenced to a certain extent by microstructure. The thermal expansion coefficient curves in the temperature range of 100–500°C are presented in Fig. 4.

The thermal conductivity of cast irons is influenced strongly by graphite morphology. The conductivity is higher in gray iron because of the semicontinuous nature of the graphite flakes. The rounded edges of graphite inside CGI work together to boost thermal conductivity to that of ductile iron (see Fig. 5). In addition to graphite shape, microstructure, composition, and temperature also influence the thermal conductivity.

The tensile strength and yield strength of cast irons increase with increasing nodularity. The variation in elastic modulus as a function of graphite nodularity is similar to that observed for tensile strength (see Fig. 6).

Among the main classes mentioned and depicted above, emphasis is given to GJL-300 with flake (CI-conventional heavy duty cylinder head material), GJV-300 and GJV-450 with compacted (CGI-becoming popular with increasing demands for lightweight design and peak firing pressure increase/emissions reduction), GJS-400 and GJS-600 with spheroidal (SGI) graphite shapes. GJL-300, GJV-450, and GJS-600 have pearlitic matrix structure while GJV-300 and GJS-400 have ferritic matrix structure.

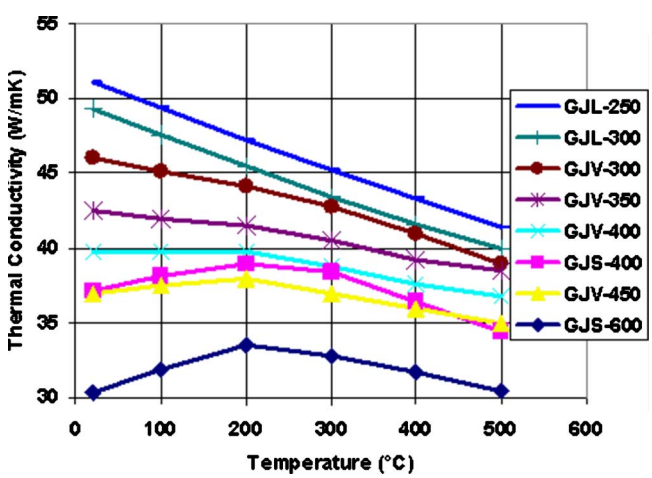

Fig. 5 Thermal conductivity as a function of temperature

Material Modeling

Material behavior is affected by loading conditions, which results in mechanical fatigue, by time, which is also known as creep, and by oxidation, which is caused by environmental effects. When time effects and oxidation are neglected, yielding depends only on instantaneous increments of stress or strain and on the previous history of the material. This kind of material behavior, which is independent of time, is known as elastoplastic behavior [3].

For modeling purposes, it is important to know how the material behaves under the investigated loading conditions. The damaging cycle of a cast iron cylinder head corresponds to a heat-up and cool-down cycle. The operational temperature range of cast iron cylinder heads could be specified up to approximately 420°C, 450°C, and 480°C for gray cast iron, compacted graphite iron, and spheroidal graphite iron, respectively. Above these temperatures, grain growth and matrix decomposition (pearlite to ferrite transformation) are responsible for reduction in material strength of pearlitic cast irons [4]. When these temperatures are set as a predefined upper limit, creep and oxidation effects are negligible, if existing. In addition, cylinder head is subjected to out-of-phase loading (maximum strain occurs at minimum temperature). Nevertheless, creep damage is dominant under in-phase loading conditions. Hence, considering the upper temperature limits that should not be exceeded and the loading conditions of the cylinder head, the assumption of elastoplastic material behavior for modeling is justified.

It should be noted that, for exhaust manifolds where the maximum temperature is up to 900°C (for gasoline turbocharged engines temperatures may even exceed 1100°C), elastoviscoplastic behavior of the material has to be considered in order to model the material behavior properly. Therefore, creep must be taken into account for exhaust manifolds and to represent the viscous behavior of the material at high temperatures elastoviscoplastic constitutive laws should be utilized [5].

For the analysis of strain and stress distributions in a material loaded beyond the elastic limit (elastoplastic material behavior), a constitutive theory of plasticity must specify the yield condition under multiaxial states of stress. The uniaxial condition $I\sigma I = \sigma_y$ (yield stress) is inadequate if there is more than one stress component. The constitutive theory must define the postyield behavior, answering the following questions:

(1) Yield Criterion. What stress combinations cause plastic deformation?

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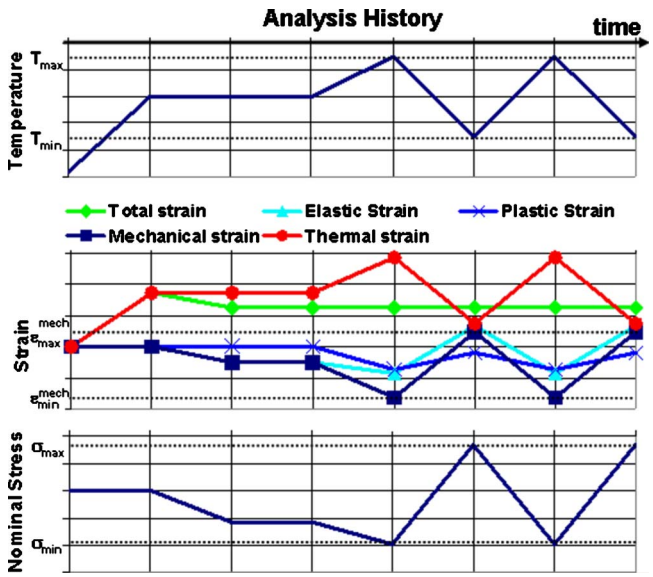

Fig. 7 Analysis history for parameter identification, temperatures, and stresses and strains over time

(2) Postyield Behavior. How are the plastic deformation increments related to the stress components? How does the yield condition change with work hardening?

Based on the previous standpoint, linear kinematic hardening model with von Mises yield criterion and an associated flow rule is selected as the base model to be used for simulating cast iron response under anisothermal cyclic loading. In addition, nonlinear kinematic hardening model is also utilized so as to compare the uniaxial and multiaxial influences on material response.

In order to calibrate the material parameters, a specimen model is used for temperature varied strain controlled simulations to have comparable results with the experimental results at hand. The output of the analysis after conducting several iteration cycles is the validated material model on the one hand and the stresses and strains to be used in fatigue life prediction on the other hand.

Simulation history for material parameter identification is constructed to be consistent with the experiments from Hallstein [6]. The specimen tests were done with a fixed minimum temperature and variable temperature amplitude for the cast irons. As the specimen is fixed at both ends (100% restraining), heating up to maximum temperature results in compressive stresses (material tends to expand but it is not allowed because of fixation) and cooling down to minimum temperature leads to tensile stresses (material tends to shrink but it is not allowed because of fixation). Temperature variation over time and the induced strains and stresses for GJL-300 are depicted in Fig. 7 as an example.

Material Models, Results, and Comparison

Maximum and minimum stress versus temperature amplitude is provided in Fig. 8 for the fixed minimum temperature of 150°C. Displayed simulation results are from the stabilized cycle (third cycle). The results of temperature amplitude of 75°C and 100°C do not exist for GJL-300, as plasticity does not occur under these circumstances. Also for gray cast iron, temperature amplitude effects on maximum and minimum stress are negligible. For the pearlitic spheroidal graphite iron (GJS-600), a different behavior is observable, which means that not only the microstructure but also the chemical composition and graphite morphology have significant effects on material behavior.

In order to achieve a fine match between the experimental and simulation results, parameter identification is carried out in the calibration phase based on the experimental results and other data

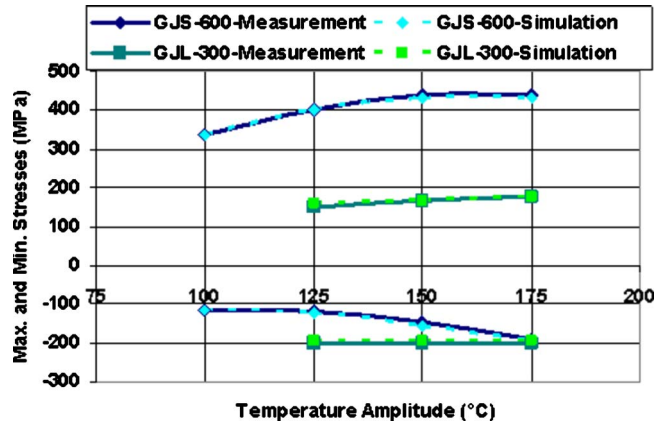

Fig. 8 Maximum and minimum stresses as a function of temperature amplitude: $T_{min}=150°C=\text{const}$, $\varepsilon_{m,t}^{GJS\text{-}600}=4‰$, $\varepsilon_{m,t}^{GJL\text{-}300}=-1‰$

found in literature [7–11]. Parameter identification using temperature dependent material data only, to define material plasticity, did not lead to a good match for materials other than GJL-300. The reason for this is that material behavior changes as the maximum temperature, the material is subject to in his history, is different. Therefore, the material model developed using local temperatures does not represent the exact material at wide temperature ranges.

In order to represent the exact material behavior, which after a few hundred hours of engine operation shows different values of yield strengths in different areas of the material according to the temperature in that area, a material model, with different proportional limit and kinematic hardening modulus values corresponding to an additional field variable (here equal to the maximum temperature at a particular area of the material), is built.

In Fig. 9, mean stress as a function of mean strain at half number of cycles to failure for temperature amplitude of 150°C when the minimum temperature is also 150°C is shown. Fine match of measurement and simulation results is primarily achieved by fine-tuning of kinematic hardening modulus. Note that this mean strain is the externally applied mean strain as the experiments are mean total strain controlled experiments together with temperature control. The induced mean stresses because of the cyclic plastic com-

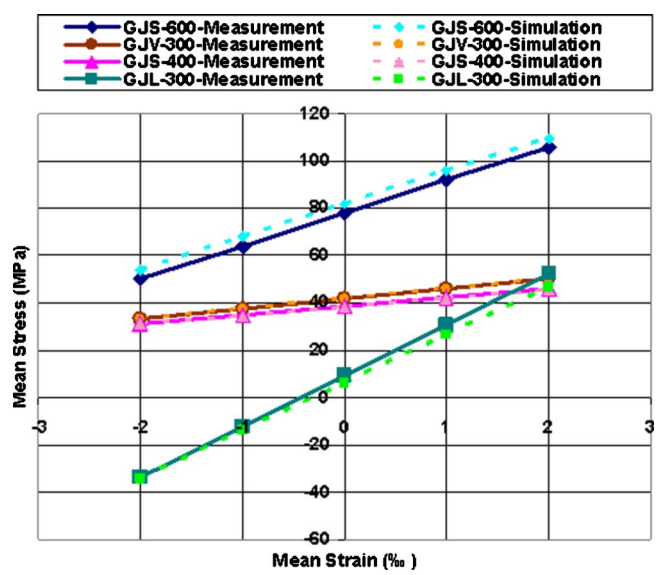

Fig. 9 Mean stress as a function of mean strain for GJL-300, GJV-300, GJS-400, and GJS-600. $T_{min}=150°C$, $T_{amplitude}=150°C$.

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Table 1 TMF life prediction approaches [12–16]

Manson–Coffin	$\varepsilon_{pl,amp}=\varepsilon_t'\ (2N)^c$
Total strain approach	$\varepsilon_{mech,amp}=\sigma_t'/E\ (2N)^b+\varepsilon_t'\ (2N)^\varepsilon$
Morrow equation	$\varepsilon_{mech,amp}=(\sigma_t'-\sigma_m)/E\ (2N)^b+e_t'\ (2N)^c$
SWT parameter	$\sigma_{max}\ \varepsilon_{mech,amp}\ E=(\sigma_t')^2\ (2N)^{2b}+\sigma_t'\ \varepsilon_t'\ E\ (2N)^{b+c}$
Energetic approach	$\Delta W\ N^\beta=C$

pression strains can be read where the mean total strain equals zero. For GJL-300, this induced mean stress is tensile (positive).

Mean stress dependency on mean strain is more pronounced for the pearlitic irons. An important and interesting concern is the examination of mean stress effects on fatigue life on the thermal cyclically loaded materials. According to Fig. 9, almost no effects are present for the ferritic materials. However, this is not the case for pearlitic irons, and with increasing tensile stress fatigue life decreases significantly. Additionally, for the pearlitic materials, with increasing compressive stresses or decreasing tensile stresses, matrix structure becomes dominant in determination of the lifetime. In the next section, lifetime prediction is handled considering these facts.

Lifetime Prediction, Methods, and Application

Increase in operating temperatures was the main driving force for the efforts to predict TMF of cylinder heads in the near past. Many high temperature material relations and TMF theories have been published over years. TMF life assessment approaches could be classified as strain based, energy based, damage parameters, fracture mechanics, cumulative, and microstructural approaches. Independent of the theory used, the life prediction is based on functions of the induced strains and stresses due to thermomechanical loading and the material parameters.

Strain based approaches are highly utilized in automotive industry due to their simplicity and reliability. The damage parameter proposed by Smith, Watson, and Topper (SWT) considers the mean stress effects and has proven its reliability especially for components with tensile mean stresses. On the other hand, energy based approaches gained respect in the last decade especially for their conformability to multiaxial loading conditions.

In the following, strain based approaches (Manson–Coffin criterion, total strain approach, and Morrow equation), SWT damage parameter, and energy based approach are applied to the specimen and cylinder head models. These approaches are shown in Table 1. The aim is to find material specific evaluation strategy.

Among the class of strain life (ε-N) approaches, Manson–Coffin criterion, which describes the relation between plastic strain amplitude and life, stands for simplicity and robustness. Total strain approach and Morrow equation (total strain approach with mean stress correction) are based on total mechanical strain amplitude. It is clear that the Manson–Coffin criterion is independent of mean stress. However, for some materials, such as GJL-300, mean stress effects are also important in the low cycle fatigue region. In order to correlate only the plastic strain with lifetime, the mean stress effects have to be incorporated to the Manson–Coffin criterion; in practice, fatigue parameters have to be modified. Regression analysis is carried out to find the dependencies and to construct the function for the fatigue parameters with mean stress effects.

Strain based approaches and SWT parameter are corresponding to isothermal uniaxial loading conditions. Therefore, we calculate equivalent strain amplitudes and the mean stress using critical cutting plane approach [17] and calibrate the material parameters with consideration of the operational temperature range to apply these criteria for cylinder heads subjected to multiaxial anisothermal loading. In contrast, energy based approach, which correlates

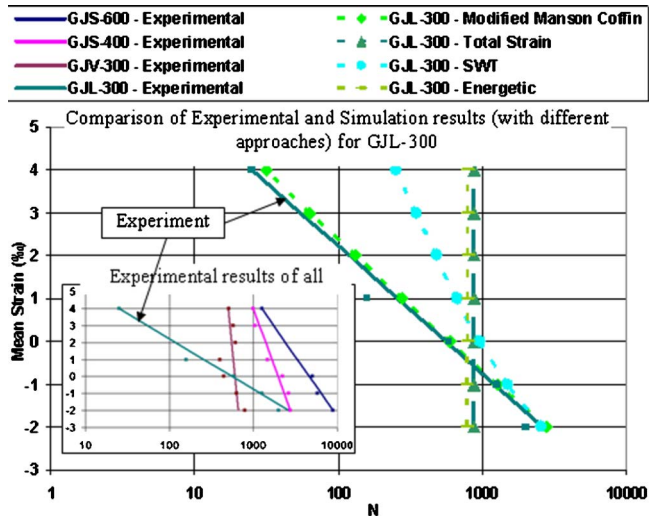

Fig. 10 Number of cycles to failure as a function of mean total strain. $T_{min}=150°C$, $T_{max}=450°C$.

lifetime with dissipated energy per cycle, is a multiaxial fatigue criterion and does not require additional calculations but lacks the mean stress effects.

In Fig. 10, the number of cycles to failure is depicted as a function of externally applied mean strain. GJL-300 has highest dependency on externally applied mean strain (which in turn results in mean stress). Negative mean strains result in higher number of cycles for both the pearlitic cast irons. Note that lifetime of the pearlitic cast irons does not differ much from each other with negative mean strains applied and is even the same for a mean strain of −3‰. So we can state that, when compressive stresses are applied, material matrix becomes more dominant than the graphite shape in influencing the lifetime of the specimen made of pearlitic cast irons.

The calculation results, which are mean stress independent, are straight lines parallel to the vertical axis as expected. Consideration of mean stress influence is vital for the calculations and a good match for GJL-300 is achieved with modified Manson–Coffin criterion as can be seen from the figure. For the other pearlitic cast irons, SWT damage parameter provided the best fit to the experimental results.

When mean stress effects are negligible—the case for ferritic irons—energetic approach came out to be the best method covering a wide temperature range with a very narrow deviation band. The comparison of approaches for temperature amplitude variation at constant mean strain is depicted below in Fig. 11 for GJV-300.

Considering all experiments and calculations done with different parameter variations and material specific approaches (see Table 2), fair agreement between measured and computed results for lifetime is observed as all data points lie inside $2N$ and $0.5N$ lines (see Fig. 12). In the second part of the study, the validated TMF life analysis approach is safely applied to a cylinder head example.

Application of TMF Assessment Approach to a Heavy Duty Diesel Cylinder Head

Heavy duty engines developed for future requirements of higher power density and low emission are subject to high thermal load and peak firing pressure. The problem of cracks in-cylinder heads due to thermal fatigue is well known for these engines with high specific power output (see Fig. 13 for an example—cast iron cylinder head). However, it is still difficult to predict the lifetime of a new cylinder head due to the number of influencing parameters and the complexity of the material behavior [18]. Material

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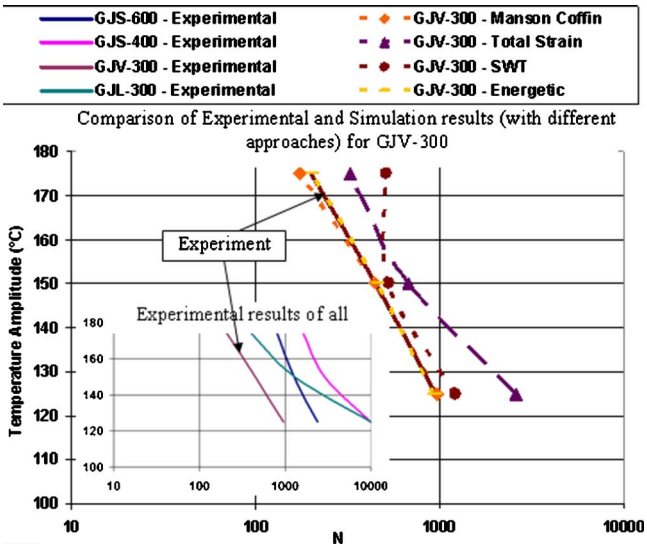

Fig. 11 Number of cycles to failure as a function of temperature amplitude. $\varepsilon_{m,t}^{GJS-600}=4‰$, $\varepsilon_{m,t}^{GJS-400}=0‰$, $\varepsilon_{m,t}^{GJV-300}=0‰$, $\varepsilon_{m,t}^{GJL-300}=-1‰$.

data describing the properties under complex thermal and mechanical loading conditions do generally not exist, and if at all, exist only for specific temperature ranges. Also, there is no standardized TMF testing method established yet. Therefore, validated material parameters under uniaxial loading in the previous section are used in the analysis of cylinder head, which is subject to multiaxial loading.

In order to simulate the thermal cycles, thermal and mechanical analyses are necessary assuming that the 3D computational fluid

Table 2 Material specific approaches and fatigue ductility exponent (FDE)—for strain based evaluation—or dissipated energy exponent (DEE)—for energy based evaluation—of cast irons

Material	Lifetime prediction approach	FDE/DEE
GJL-300	Modified Manson-Coffin	−0.587
GJV-300	Energetic approach	−0.925
GJV-450	SWT parameter	−0.800
GJS-400	Energetic approach	−0.920
GJS-600	SWT parameter	−0.770

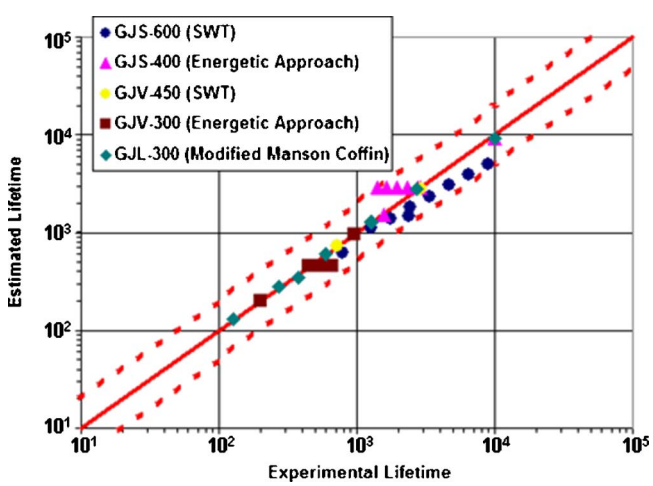

Fig. 12 Correlation of experimental and simulation results

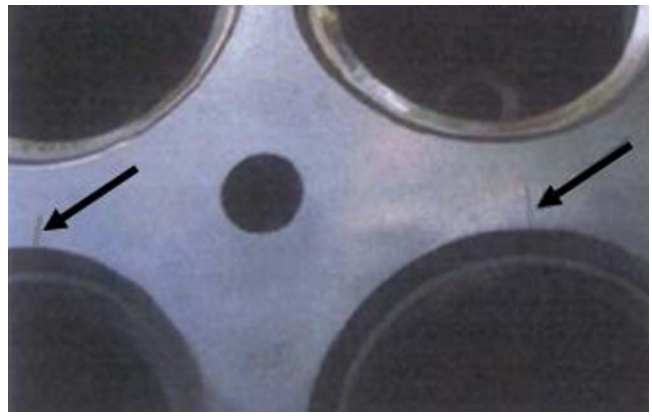

Fig. 13 TMF cracks on a heavy duty diesel cast iron-GJV-450-CH

dynamics (CFD) analysis results for coolant and gas side heat transfer are available. In particular, (a) thermal computation simulating heating of the part and (b) a mechanical computation, which includes the assembly of the model (bolt preloading, seat-ring and valve guide press fits) and the thermal cycles (heating up to max. temperature and cooling down) are carried out and the mechanical fields are an input to the next step, which is the lifetime prediction using a fatigue criterion.

Together with these steps, the whole analysis loop is sketched in Fig. 14.

Several factors affect the TMF life span while some are given (parameters) and direct influencing is not possible and some are changeable (variables) with direct influence:

- influence of thermal load
  - (a) cylinder power (variation of engine load)
  - (b) cooling (coolant temperatures, system pressure, global/local flow rates)
- influence of mechanical loads/constraints
  - (a) friction between gasket and cylinder head (mainly material dependent)
  - (b) interference fit of valve seat rings (variation of interference)
- influence of structural design
  - (a) cylinder head stiffness (e.g., fire deck thickness)
  - (b) valve arrangement (parallel, twisted, tandem)
  - (c) length (single, block cylinder head)
  - (d) water jacket design (cast design, cooling bores)
- influence of material
  - (a) CI, CGI, SGI (thermal conductivity, Young's modulus, coefficient of thermal expansion, etc.)

In the following, some analysis examples of the above listed parameters are depicted for the heavy duty diesel cylinder head. Results presented below belong to the stabilized cycle (third cycle).

Influence of Thermal Load. A significant influence on the TMF life span is due to the temperature loading. Various engine parameters are influencing the temperature of the cylinder head. The main drivers are the engine power and the cooling system, but also extreme ambient conditions may impact the thermal load cycle. Depending on the engine application, the critical TMF load cases have to be specified. Being aware of the importance of a correct temperature field on the lifetime, 3D-CFD coolant and

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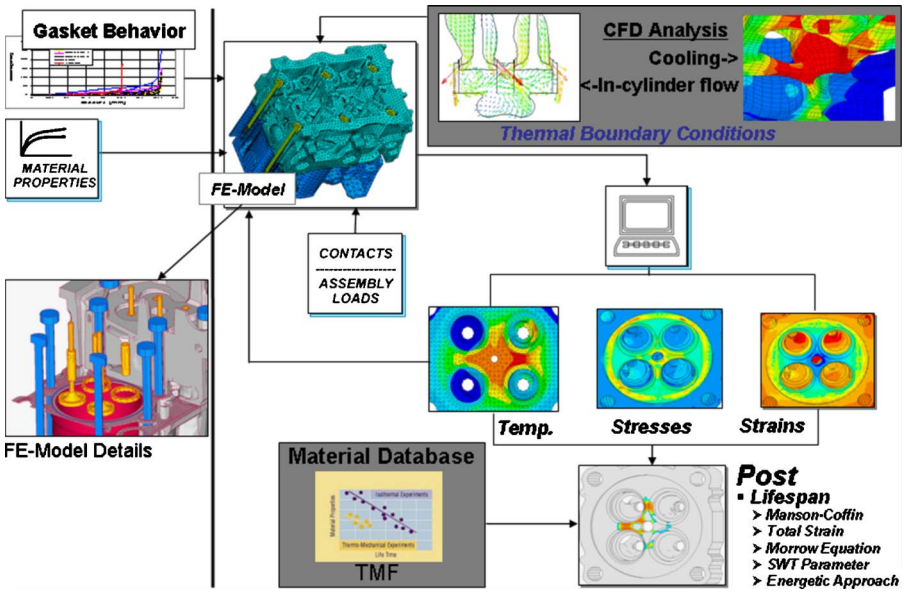

Fig. 14 TMF analysis approach for CH

in-cylinder flow analysis results are prerequisite simulations to derive most accurate boundary conditions for the thermal analysis. Alternatively conjugated heat transfer simulations can be conducted to determine the temperature distribution within the cylinder head, while these results have to be mapped onto the structure of FEA model.

Temperature field not only determines the critical locations but also it is decisive in limiting the number of cycles to failure. In addition, consideration of mean stress effects does not change the critical locations but negative mean stresses on flame deck surface lead to increased lifetime in critical locations for cast iron.

The influence of power increase on lifetime is investigated in order to distinguish the temperature amplitude effects from the effects of temperature distribution. It is assumed that the distribution of temperature and heat transfer coefficients does not change and only scaling up is necessary. An increase of 16% in power leads to a 50% decrease in lifetime of the cylinder head made of gray cast iron. The temperature and lifetime plots are depicted below in Fig. 15. The critical locations are marked as N1 and N2, lifetimes corresponding to these locations at nominal power are set as reference (100%).

Influence of Mechanical Constraints. Combination of thermal and mechanical loads results in complex stress states, which in turn decrease the lifetime of the structures. The friction between cylinder head gasket (CHG) and cylinder head (CH) is one of the mechanical constraints that deteriorates the lifetime in combination with the thermal load. Two extreme cases are investigated below one without friction and the other with a high friction coefficient. The outcome of the analysis highlights a 10–35% decrease in number of cycles to failure in the most critical area with the introduction of friction between gasket and CH (see Fig. 16). In this case, the more deteriorative effect of friction is on intake side. The lifetime corresponding to critical locations without friction are set as reference (100%) for both materials. Compacted graphite iron is affected more severely than gray cast iron with its higher Young's modulus. It is clear that friction is a given parameter; nevertheless, the results point out the sensitivity of the radial constraining.

Influence of Material. The temperature field corresponding to nominal power condition is plotted in Fig. 17 for different types of cast irons. Application of thermal boundary conditions from 3D-process simulation for the flame deck surface and water jacket (including nucleate boiling) results in a temperature distribution with a significant difference between intake and exhaust valve

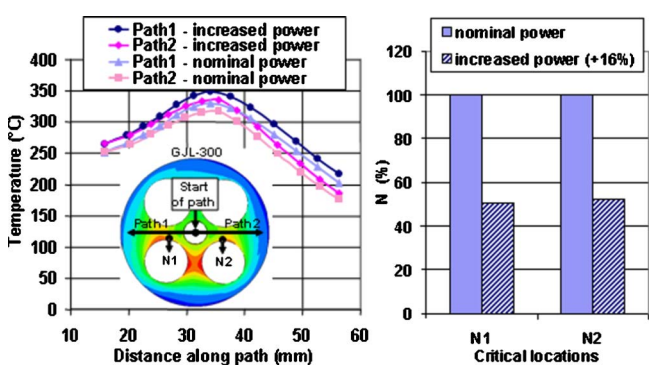

Fig. 15 Temperature comparison (left) and life span comparison with respect to Modified Manson–Coffin (right) of nominal rated and increased power for GJL-300

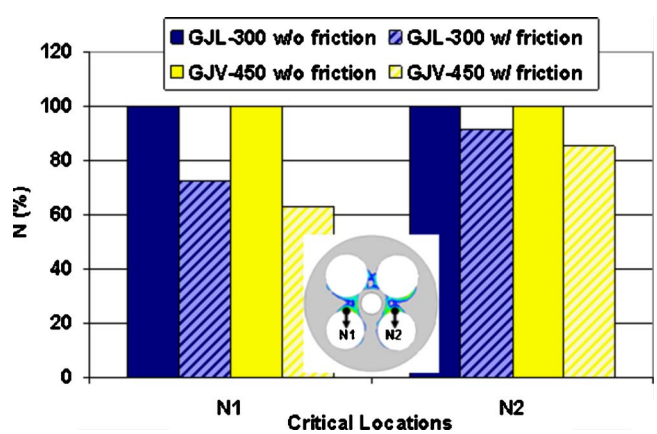

Fig. 16 Influence of friction between CH and CHG on lifetime with respect to Modified Manson–Coffin and SWT parameter for GJL-300 and GJV-450, respectively, at increased power

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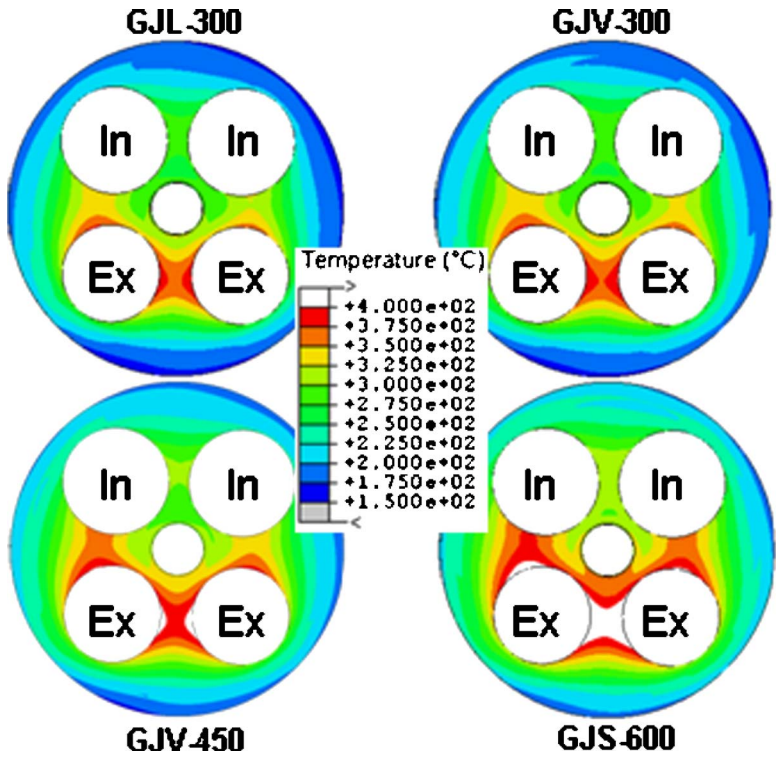

Fig. 17 Temperature distribution at nominal rated power for different types of cast irons

bridges. Highest temperatures in exhaust valve bridge occur at a distance of 35 mm from the center, which is due to the impact of high local heat flux at piston bowl rim.

Lifetime comparison for the cylinder head with respect to material specific evaluation approaches is depicted in Fig. 18.

Note that critical locations are the same as crack locations in Fig. 13. In addition, the computed number of cycles to failure agrees very well with the running time of the test engine up to the macroscopic crack observation.

Some calculation results do not match the trends of the uniaxial experimental results in terms of material thermal fatigue resistance and here, some important remarks should be stated:

- Experimental conditions are the same for all material specimens. Temperature is varied between the minimum and maximum temperatures, which are the same for the investigated materials [6]. However, in a 3D analysis of cylinder head, thermal conductivity plays an important role in temperature field and different materials have different maximum temperatures (see Fig. 17)
- The increasing lifetime with increasing tensile strength of material in experimental results is based on 0% mean total strain in the specimen for all materials. On the contrary, nonlinear temperature dependent material properties result in different mean stress distributions on the flame deck surface for investigated materials. In the current design, resulting mean stress distributions favors the lifetime of GJL-300 (negative mean stresses on flame deck surface) and deteriorates the lifetime of GJS-600 (positive mean stresses on flame deck surface)
- The fatigue parameters are calibrated according to the uniaxial experimental results (see Figs. 8–11). The use of the same parameters in multiaxial case is unavoidable but one should be aware of the importance of norm calculations. This fact underlines an important design criterion: the evaluation of lifetime according to the design variations using the same material and fatigue parameters is more reliable than material comparison for the same design.
- Assuming that the transfer from the uniaxial validation to multiaxial calculations is achieved correctly, under the applied boundary conditions and in the case of GJL-300 as the material for the cylinder head (see Fig. 18), one should try to optimize the structural design in a way that compressive mean stresses occur on the flame deck surface.
- Finally, before concluding it is important to note that the best interpretation could be achieved by calibrating the material models with experiments, which have exactly the same conditions of the real application (e.g., cylinder head component test bench capable of testing thermal cycles). FEV currently investigates the possibilities of efficient component testing. Only then the sensitivity of the TMF behavior with respect to the loading conditions could be accurately determined.

Conclusion

A complete TMF prediction methodology is presented in the case of cast iron cylinder heads. In order to avoid on the one hand the prolonged experimental programs to determine required material parameters and on the other hand significant calculation times, simple constitutive law uncoupled from damage is proposed.

Material models for different types of cast irons are validated for large temperature ranges. Different fatigue criteria are efficiently applied in finite element code so as to allow comparison for uniaxial and multiaxial loading. The outcome of the analysis is material specific evaluation approaches, which lead to a good correlation with experimental results.

Several influencing factors are investigated. Material comparison in diesel cylinder head yields contradictory results compared to uniaxially loaded specimen. For the same thermal load applied to the specimen, the number of cycles to failure increases with increasing material strength. However, when a cylinder head is of

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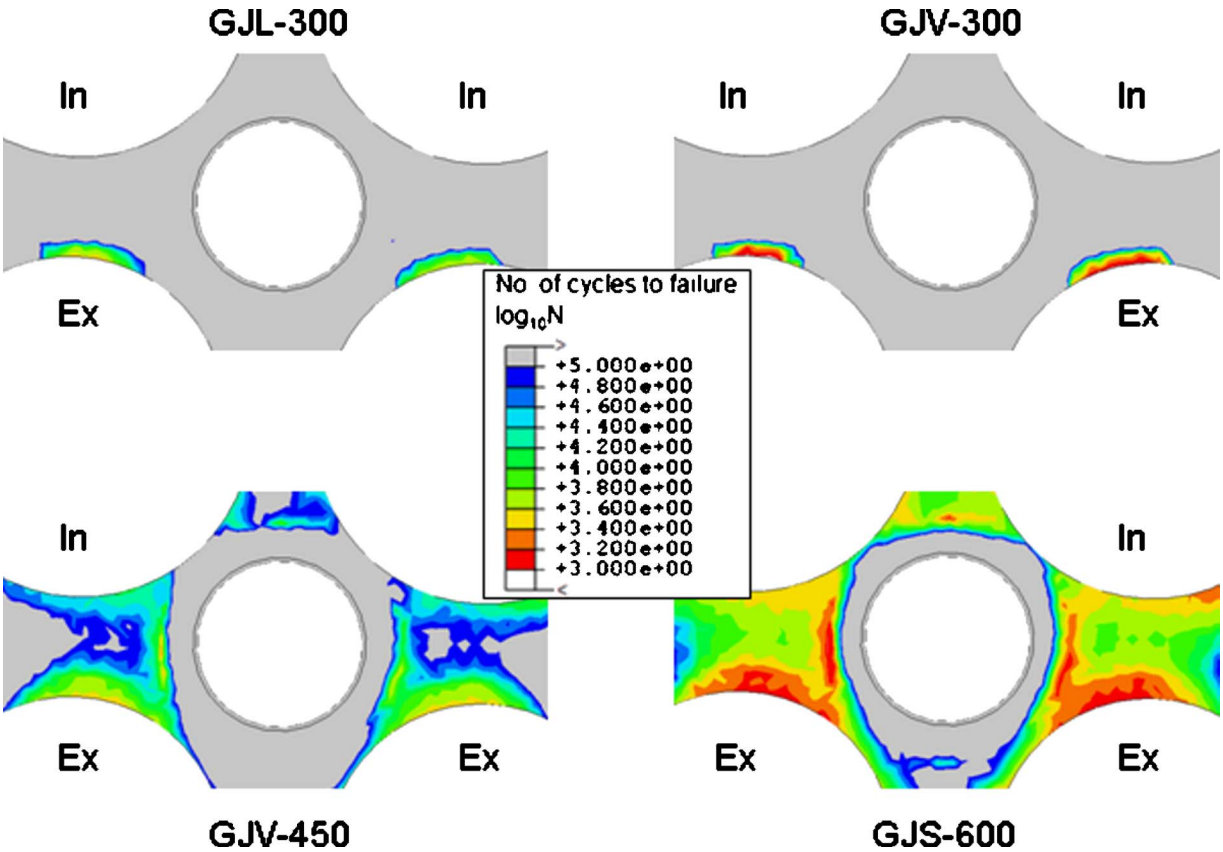

Fig. 18 Lifetime distribution at increased power (+16%) for different types of cast irons, flame deck surface injector-valve bridge area

interest instead of a specimen, temperatures on flame deck surface resulting from the same applied thermal load differs due to the different thermal conductivities, of the cast irons.

A central question is if and where a break point in comparison of two different cast irons in terms of thermal fatigue resistance exists. Depending on the application field of the engine, different requirements (maximum power, durability, emissions/peak firing pressure, weight, production costs, etc.) lead to different design measures. Rough guidelines could be constructed but each design should be investigated in its own to end up with accurate results.

Nomenclature

b = fatigue strength exponent
β = accumulated energy to fracture exponent
c = fatigue ductility exponent
C = accumulated energy to fracture parameter
E = Young's modulus
ε_f' = fatigue ductility coefficient
$\varepsilon_{\mathrm{mech,amp}}$ = mechanical strain amplitude
$\varepsilon_{m,t}$ = mean total strain
$\varepsilon_{\mathrm{pl,amp}}$ = plastic strain amplitude
N = number of cycles
σ_f' = fatigue strength coefficient
σ_m = mean stress
$\sigma_{\max}$ = maximum stress
ΔW = energy dissipated per cycle

International Material Cross Reference:

DIN EN		ASTM
1561, EN-GJL-250*	=	A48, Class 40 B
1561, EN-GJL-300	=	A48, Class 45 B
1560, EN-GJV-300	=	A842, Grade 300
1560, EN-GJV-350	=	A842, Grade 350
1560, EN-GJV-400	=	A842, Grade 400
1560, EN-GJV-450	=	A842, Grade 450
1563, EN-GJS-400-15	=	A536, Grade 60-40-18
1563, EN-GJS-600-3	=	A536, Grade 80-55-06

*The three digit numbers in cast iron classification represents the ultimate tensile strengh value of the material.

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