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# CONSTITUTIVE MODELING OF ALLOYS UNDER HIGH TEMPERATURE LOW-CYCLE AND THERMAL- MECHANICAL FATIGUE: A KEY ISSUE IN COMPONENT DESIGN

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## Abstract

Dissipated plastic energy is a convenient and widely used criterion to assess the life of components experiencing high temperature low-cycle fatigue and thermal-mechanical fatigue. However, component design relies on efficient and accurate constitutive models. Elasto-viscoplastic models are enriched using dislocation density as an internal variable to account for recovery or overaging effects in precipitate strengthened alloys. Examples are shown for components made of cast iron, welded stainless steels and cast aluminum alloys.

## 1. Introduction

Hot section components are exposed to high temperature operation and thermal transients. This is especially the case in automotive industry where environmental regulations require cleaner and lighter engines while competitive markets call for performance. This context increases the risk of thermal fatigue crack initiation that must be integrated in component design protocols. However, part design and life prediction are the result of a whole chain of loading analyses, constitutive modelling and life criteria or damage models. In the automotive industry, simple energy-based fatigue criteria are often used with quite satisfying results [1]. While tests on simple structures are appropriate for appraising life predictions resulting from the entire design chain, thermal-mechanical fatigue (TMF) testing enables to check independently prediction of constitutive models and fatigue criteria or damage models [2]. The stress-strain response under high temperature excursions or thermal transients is however, usually based on isothermal data and basic low-cycle fatigue tests. Better knowledge of alloys behavior was achieved during recent years with thermal-mechanical fatigue testing. Traditional assumptions on material constitutive behavior may thus default in some loading cases.

## 2. Results

The introduction of more physically based models could improve current design procedures. Multi-scale approaches combining crystal plasticity and dislocation theory tools are still too expensive in terms of computation cost for industrial components when made of materials with complex microstructure and temperature dependent behavior. A better description of deformation mechanisms at work, or the introduction of microstructure sensitive modelling have been used during the last decade. However, cost effective modeling is indeed mandatory in automotive industry. A compromise is here proposed using mean field models with dislocation density taken as internal variable and accounting for the interaction with precipitate microstructure [3]. Examples are shown on iron-based and cast aluminum alloys used respectively for exhaust manifolds and cylinder heads. Static recovery, or aging during high temperature exposure is shown to be described more easily than in pure phenomenological models. The reduced number of adjustable parameters, combined with dedicated identification procedure, results in an increased robustness, required for component design.

Cast iron behavior is illustrated first with validation on component bench tests. Both the location of cracks and the life to crack initiation in exhaust manifolds are predicted as well as component distortion due to ratcheting effects. For equivalent welded components, the TMF behavior of stainless steels cannot be directly predicted with usual viscoplastic models and isothermal fatigue database. Static recovery has to be introduced in a dislocation density based constitutive model. In addition, the application to welded hot parts requires a multi-scale lifespan approach [2]. Finite element modeling at the mesoscale of welded specimens is first used. TMF damage is mostly micro-crack growth. The growth law is therefore integrated at the mesoscale to provide a fatigue crack initiation criterion at the macroscale of the welded component. A good location of crack initiation in the component and lifetime prediction are achieved.

Precipitate strengthened cast aluminum alloys are a more complex case. A deterministic design approach is currently used to take into account material ageing. However, more severe thermal-mechanical loading due to downsizing requires checking the relevance of aging conditions used for component design [4]. A detailed microstructure investigation, combining microhardness, transmission electron microscopy and monotonic or cyclic tests has been used to build a microstructure sensitive model [5]. This model gives the basis of an engineering strategy to improve the design against thermal-mechanical fatigue that involves overaging of precipitates. Dendrite microhardness is used as an indicator of yield strength degradation due to overaging. An overageing model is thus provided that can predict yield strength gradients in components as well as life assessment.

## Conclusions

Physically-based constitutive models were shown to bring better accuracy for high temperature operation with thermal transients in the case of automotive applications. Good description of ratcheting and location of crack initiation are achieved for components made of cast iron as well as welded stainless steel. For cast AlSiCuMg alloys that are strengthened by non shearable precipitates, microstructure sensitive modelling enables to rationalize the effect of overageing during service operation of cylinder heads that reduces their yield strength. Such models can be used to calibrate engineering models for design over a range of compositions.

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## References

[1] Constantinescu, A., Charkaluk, E., Lederer, G., Verger, L, A computational approach to thermomechanical fatigue. *Int. J. Fatigue*, 26; 2004; 805–818.

[2] Luc Rémy, Low Cycle Fatigue of Alloys in Hot Section Components: Progress in Life Assessment, *Procedia Structural Integrity,* 14; 2019; 3-10.

[3] Fabien Szmytka, Pierre Osmond, Luc Rémy, Pierre-Damien Masson, Agathe Forré, Some recent advances on Thermal-Mechanical Fatigue design and upcoming challenges for the automotive industry, *Metals*, 9; 2019; 794.

[4] Francois-Xavier Hoche, Loeïz Nazé, Luc Remy, Alain Koster, Pierre Osmond, Effect of Thermomechanical Fatigue on Precipitation Microstructure in Two Precipitation-Hardened Cast Aluminum Alloys, *Metallurgical and Materials Transactions,* 52A; 2021; 3232- 3246.

[5] P. Osmond, L. Rémy, L. Nazé, Cyclic stress-strain behaviour of particle-hardened cast aluminium alloys: Microstructure sensitive modelling of the effect of non-shearable precipitates, *Materials Science and Engineering A,* 820; 2021;141492.