INSTITUT FÜR ANGEWANDTE MECHANIK

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Lifetime prediction of a typical rocket combustion chamber by means of viscoplastic damage modeling

RWTH AACHEN UNIVERSITY

Applied Mechanics – RWTH Aachen University

Lifetime prediction of a typical rocket combustion chamber by means of viscoplastic damage modeling

Von der Fakultät für Bauingenieurwesen
der Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades einer Doktorin der Ingenieurwissenschaften
genehmigte Dissertation

vorgelegt von

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Tag der mündlichen Prüfung: 02.06.2014

Applied Mechanics – RWTH Aachen University
Editor: Prof. Dr.-Ing. Stefanie Reese

Volume 1

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Shaker Verlag
Aachen 2014

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: D 82 (Diss. RWTH Aachen University, 2014)

Printed in Germany.

ISBN 978-3-8440-3134-8
ISSN 2363-488X

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

To Sebastian

Acknowledgements

Within the collaborative research program CRC/TR40 "Fundamental Technologies for the Development of Future Space-Transport-System Components under High Thermal and Mechanical Loads" supported by the German Research Foundation (DFG) I obtained the opportunity to work under the guidance of Prof. Dr.-Ing. Stefanie Reese with the topic of failure prediction by means of viscoplasticity coupled with damage.

It started in July 2008 at the Institute of Solid Mechanics of the Braunschweig University of Technology before I moved with the group to the Institute of Applied Mechanics of the RWTH Aachen University in Autumn 2009. Here I would like to express my gratitude to the ones who have supported me for the completion of this thesis.

First of all, I would like to thank Prof. Dr.-Ing. Stefanie Reese who accepted me as a doctorate student and guided me until the completion of this thesis. Her spirit and perseverance to bring the whole group forward in research activities are undoubtedly an ideal. I also thank Prof. Dr.-Ing. Peter Horst for his willingness to act as the external examiner of this work and Prof. Dr.-Ing. Markus Feldmann as the chair of the oral defense committee.

Furthermore I would also like to thank Dr.-Ing. Matthias Haupt and my colleague Dipl.-Ing. Daniel Kowollik for the excellent cooperation within the research project. My thank goes also to Dr.-Ing. Jana Schloesser for her support on tensile experiments at high temperature. There are several persons at the institutes to whom I would particularly express my gratitude to. Special thanks to Dr.-Ing. Ivaylo Vladimirov for proof reading the text and his suggestions to improve the work. My thank goes also to Dipl.-Ing. Yalin Kiliclar for being an excellent office room mate and for his friendship. I also thank Dipl.-Ing. Michael Pietryga, Dipl.-Ing. Jan Frischkorn and Dipl.-Ing. Annika Radermacher for the fruitful discussions and for always being helpful to me.

I also thank M.Sc. Markus von Hoegen and B.Eng. Gilles Cosyn for their support in preparing various numerical simulations, to Axel Mittendorf, Albert Rowein for their help on computer issues, to Eva-Maria Goertz for their support on administrative issues and to Bernd Kohl for his support on experimental work.

Special thanks to Karin Scharfe, Renè Scharfe and Doris Schützel for their friendship and for being warm hearted to me. I am especially grateful to my parents for their trust on my decisions and for letting me choose my own way.

Munich, 2014 Vivian Tini

Summary

The lifetime of a launch vehicle is determined by the cyclic lifetime of its major components. In this regard, the combustion chamber of a rocket engine is one of the most important components of a launch vehicle. It undergoes extreme cyclic thermomechanical loading during its operation. Due to its high thermal conductivity and ductile behavior, the application of copper alloy as the liner material of the cooling channels is well established. However, it is well known that after several engine cycles the wall of the cooling channels becomes thinner and bulges towards the interior of the chamber before crack of the cooling channel wall eventually occurs. This failure mode which limits the lifetime of the thrust chamber is known as the "doghouse" effect.

Due to the high cost of experimental studies, efficient numerical analysis methods for lifetime prediction of a combustion chamber are becoming more and more important. In this context, an accurate lifetime prediction of the combustion chamber requires a material model which takes viscous behavior, hardening phenomena and damage into account.

This dissertation focuses on the development of viscoplastic damage models for the lifetime prediction of a typical rocket combustion chamber. Two types of unified viscoplastic damage models were developed and implemented into a finite element software. The first type is based on a scalar damage variable (isotropic damage). The second type considers damage through a damage tensor of second order (anisotropic damage). Both types are suitable for failure prediction of ductile metallic materials.

Thermomechanical analyses of a combustion chamber segment incorporating these material models were performed to numerically describe the doghouse failure mode. The investigations show that with the help of the developed damage models, the observed doghouse effect can be desribed numerically. Moreover the models are suitable to be used for lifetime prediction of structures subject to low cycle fatigue failure.

The developed viscoplastic damage model coupled with isotropic damage is implemented into a computational environment which is specially developed for fluid-structure interaction analysis of a rocket nozzle defined by Astrium Space Transportation GmbH. The computation is carried out for one engine cycle and is able to predict the location of the damage downstream of the throat. With this implementation the potential of the combined numerical schemes for lifetime prediction of the combustion chamber could be shown.

Zusammenfassung

Die Lebensdauer einer Trägerrakete ist durch die zyklische Lebensdauer der Hauptkomponenten begrenzt. In dieser Hinsicht ist die Brennkammer eines Raketentriebwerks eine der wichtigsten Komponenten einer Trägerrakete. Sie ist während des Betriebs extremer zyklischer thermomechanischer Belastung ausgesetzt. Aufgrund der hohen Wärmeleitfähigkeit und des duktilen Verhaltens hat sich die Anwendung von Kupferlegierungen als Auskleidungsmaterial der Kühlkanäle etabliert. Es ist jedoch bekannt, dass nach mehreren Betriebszyklen die Wand der Kühlkanäle dünner wird und sich in Richtung der Kammer ausbeult, bevor es letztendlich zum Bruch der Kühlkanalwand kommt. Dieser Versagensmodus, der die Lebensdauer der Brennkammer begrenzt, wird als "Doghouse"-Effekt bezeichnet.

Aufgrund der hohen Kosten für experimentelle Untersuchungen gewinnen effiziente numerische Verfahren zur Lebensdauervorhersage einer Brennkammer immer mehr an Bedeutung. In diesem Zusammenhang erfordert eine genaue Vorhersage der Lebensdauer der Brennkammer ein Materialmodell, das sowohl viskoses Verhalten als auch Verfestigung und Schädigung berücksichtigt.

Diese Dissertation konzentriert sich auf die Entwicklung von viskoplastischen Schädigungsmodellen für die Lebensdauervorhersage einer typischen Raketenbrennkammer. Zwei Arten von viskoplastischen Schädigungsmodellen wurden entwickelt und in ein FE-Programm implementiert. Die erste Variante basiert auf einer skalaren Schädigungsvariablen (isotrope Schädigung). Die zweite Variante berücksichtigt die Schädigung durch einen Schädigungstensor zweiter Ordnung (anisotrope Schädigung). Beide Varianten eignen sich für die Lebensdauervorhersage von duktilen metallischen Werkstoffen.

Thermomechanische Analysen eines Segmentes der Brennkammer wurden mit diesen Materialmodellen durchgeführt, um den Versagensmodus ("Doghouse"-Effekt) numerisch zu beschreiben. Die Untersuchungen zeigen, dass mit Hilfe der entwickelten Schädigungsmodelle der beobachtete Versagensmodus ("Doghouse"-Effekt) numerisch abbildbar ist. Des weiteren eignen sich die Modelle zur effizienten Lebensdauervorhersage von Strukturen, die durch Niedrig-Lastwechsel-Ermüdung versagen.

Das entwickelte viskoplastische Schädigungsmodell gekoppelt mit isotroper Schädigung wurde in eine Rechenumgebung implementiert, die speziell für die Strömungs-Struktur-Wechselwirkungs-Analyse einer Raketendüse von Astrium Space Transportation GmbH entwickelt wurde. Die Berechnung wurde für einen Betriebszyklus durchgeführt. Sie ist in der Lage, den Schädigungsort stromabwärts des Brennkammerhalses vorherzusagen. Mit dieser Implementierung konnte das Potenzial der kombinierten numerischen Verfahren zur Lebensdauervorhersage von Brennkammern aufgezeigt werden.

Contents

Chapter 1

Introduction

1.1 Motivation

The lifetime of a launch vehicle is determined by the cyclic lifetime of its major components. In this regard, the combustion chamber of a regeneratively cooled rocket engine is one of the most important components of a launch vehicle. During its operation, it is subject to extreme cyclic thermomechanical loadings. On the one hand, the combustion gas reaches temperatures up to $3500\ \mathrm{K}$ with a pressure of 10 MPa. The heat flux at the critical nozzle throat reaches $80\,\mathrm{MW/m^2}$. On the other hand, the coolant fluid in the cooling channels is cryogenic, with temperature down to $40\ \mathrm{K}$. Therefore, during a launching mission the cooling channel walls are subject to a large thermal gradient. During the engine start-ups and shutdowns, sudden expansion and contraction of the chamber cause instantaneous change between compressive and tensile stress states in the cooling channel walls. In particular, the throat region is subjected to cyclic plastic strain which contributes to the low cycle fatigue of the engine.

With the increasing demand for cost efficiency, engineers are looking for solutions to improve the lifetime of launch vehicles as well as to increase the payload by reducing the structural weight. This creates a major engineering design problem in which the most advanced numerical methods are required. Among these, the application of the finite element method (FEM) to address various engineering design problems has helped to identify important design parameters and contributed to faster design cycles. One of the most important aspects to obtain a realistic solution is the choice of a proper material model. In general, a good model is able to capture relevant physical phenomena caused by various loads on an engineering structure without too many material parameters. In this context, considering the severe cyclic thermomechanical loading acting on a rocket engine, material models incorporating elastoviscoplastic behavior, isotropic/kinematic hardening and damage propagation are needed.

Due to its high thermal conductivity and ductile behavior, the application of high performance copper alloys as combustion liner material is well established. However, it is well known that after several runs of the rocket engine, the wall of the cooling channels becomes thinner and bulges towards the interior of the chamber before a crack eventually occurs. This failure mode which limits the lifetime of the thrust chamber is called the "doghouse" effect.

This dissertation focuses on the development and application of viscoplastic damage models for the lifetime prediction of combustion chambers. The finite element method is utilized to perform structural thermomechanical analysis of a combustion chamber segment. The feasibility of the developed material models for lifetime prediction purposes is investigated. Considering the priority to minimize computation time, the viscoplastic damage model coupled with isotropic ductile damage is incorporated into a computational environment for fluid-structure interaction (FSI) analysis and is applied in a 3D FSI analysis of a test case rocket nozzle.

1.2 Overview of a regeneratively cooled rocket engine

The state-of-the-art technology for the current and next generation of heavy launchers are regeneratively cooled rocket engines. Therefore, keeping up with the latest technology in rocket engine design, throughout this dissertation focus is given on combustion chambers featuring a regenerative cooling system. In a rocket engine with a regenerative cooling system, such as the Vulcain 2 engine (shown in Figure 1.1), one of the propellants is used as coolant. Therefore it is passed through cooling channels or tubes around the combustion chamber and nozzle extension to cool down the engine walls. Figure 1.2 gives the schematic description of the regenerative cooling system used in the Vulcain 2 engine of Snecma [2012], which is a gas-generator cycle rocket engine. The cooling of the engine walls starts before the ignition of the engine.

The Vulcain 2 rocket engine is a bipropellant rocket engine, with liquid hydrogen (LH2) as fuel and liquid oxygen (LOX) as oxidizer. Parallel to the main combustion, a small amount of the propellants is fed into a gas-generator to produce hot gas, which propells two turbopumps. These turbopumps deliver LOX and LH2 at a total mass flow rate of 326,6 kg/s (Astrium [2013]) with a power up to 12 MW (Vulcain [2012]).

LH2 is injected into the cooling channels in the nozzle extension and flows through the throat region and the combustion chamber up to the injector plate at the top of the combustion chamber. Afterwards it is injected with the liquid oxygen in the combustion chamber and the combustion process delivers hot gas with a temperature up to 3500 K and a pressure of 10 MPa. The nozzle downstream the combustion chamber converts the slowly moving hot gas at high pressures into a cooler gas at low pressures but high velocity. This produces the thrust for the lift-off of the rocket (Braeunig [2012]). The throat of the nozzle is the critical area which is subjected to a maximum heat flux up to $80\,\mathrm{MW/m^2}$ (Riccius et al. [2001]).

Figure 1.1: *Vulcain 2 rocket engine (Snecma [2012]).*

1.3 State-of-the-art in the lifetime prediction of combustion chamber

In the context of computational structural mechanics, the application of FEM for lifetime prediction of rocket thrust chambers started in the 1970s. Miller [1974] performed low cycle fatigue analysis of an oxygen-free high thermal conductivity (OFHC) rocket combustion chamber utilizing an elastoplastic constitutive model where the influence of

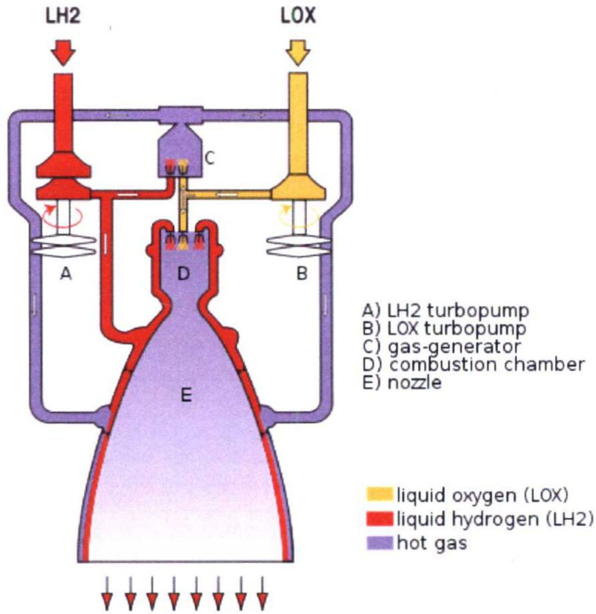
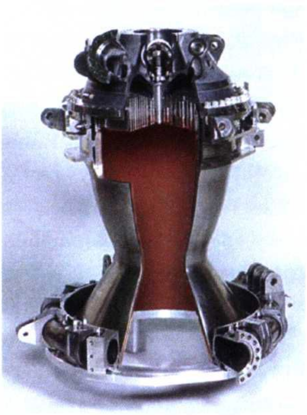


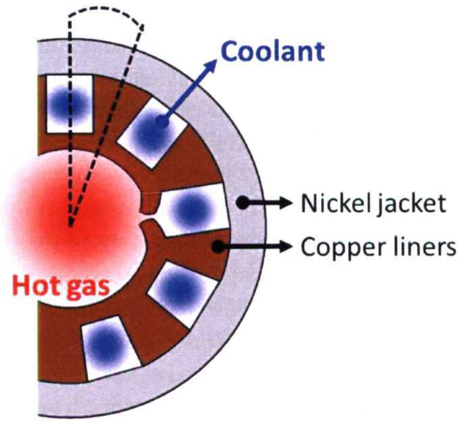
Figure 1.2: *Gas-generator cycle of Vulcain 2 and its regenerative cooling (Winterfeldt et al. [2005]).*

cyclic hardening and damage were not considered. In Badlani et al. [1983] an analytical method for lifetime prediction of a rocket engine thrust chamber was proposed and its results were compared to the ones from a finite element analysis. Hardening behavior in the material (NARloy-Z), which may prolong the lifetime of the chamber, was not quantified and therefore hardening effects were neglected in the analyses.

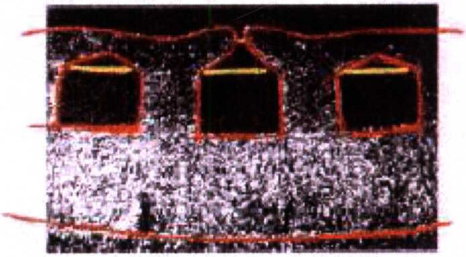
In addition, experimental work was performed by Esposito and Zabora [1975] to identify mechanical and physical properties of six high performance copper alloys which were possible candidates for application in rocket nozzles. An attempt to gain insight into the deformation process of rocket combustion chambers led Hannum and Price Jr. [1981] to a cyclic testing program of five rocket combustion chambers with three different liner materials. The experimental results showed that ratcheting occured in all of the five chambers tested. Post-failure inspection recognized the thinning and bulging of the cooling channel wall towards the chamber interior characterized by a "doghouse" shape



(a) A typical rocket combustion chamber Astrium [2012].



(b) A schematic cross section of a typical rocket combustion chamber.



(c) The doghouse failure mode (Riccius and Zametaev [2002]).

Figure 1.3: *Schematic cross section of a typical rocket combustion chamber and the doghouse failure mode.*

of the channel cross section at failure sites. Depending on the liner material, strain hardening or strain softening phenomena occured. Roughening of the hot gas side surface was reasoned to increase the heat transfer coefficient at the hot gas side wall. These results provided several clues: kinematic hardening can not be neglected in the material modelling; chemical reaction taking place between the combustion gas and the liner material influences the combustion chamber lifetime.

In the early 1990s viscoplastic material models were applied in finite element (FE) computations to simulate the rate-dependent and cyclic response of rocket thrust chambers. Arya [1991] pioneered FE computation of a rocket nozzle model using Freed's viscoplastic model (Freed and Verrili [1988]). Arya and Arnold [1992] employed Robinson's viscoplastic model (Robinson and Swindeman [1982]) for an FE analysis of an experimental cylindrical combustion chamber liner. Butler Jr et al. [2005] discussed the use of Robinson's viscoplastic model and the power-law creep model in combination with a higher order theory for functionally graded materials to simulate the thrust cell liner response. These studies mainly focus on a suitable material modelling to describe the doghouse failure mode (see Figure 1.3(c)).

Dai and Ray [1995] applied sandwich beam theory to obtain the deflection at the middle of the cooling channel ligament. Several simplifications such as uniaxial loading condition, neglection of the ligament curvature and shear deformations were made to obtain closed form solutions of the radial deflection at the midplane of the ligament. Despite its limited scope, the authors concluded the numerical efficiency of this method compared to a finite element model.

The above mentioned works were initiated and supported by several NASA research centers in the United States. In Germany, the German Aerospace Center (DLR) supported several works in the context of the application of numerical methods for the lifetime prediction as well as design optimization of rocket combustion chambers. Riccius et al. [2001] discussed the influence of several design parameters such as wall thickness, width and height of the cooling channel and width of the fin on the thermal and mechanical loading as well as on the lifetime of the chamber wall. Nonlinear FE analyses were performed in the framework of a conjugate gradient and a gradient free optimization procedure. To reduce computation time several simplifications such as 2D plane strain structural analysis and neglection of damage were made.

Coupled FSI analyses of a rocket combustion chamber segment, incorporating the coolant flow and an elastoplastic material model with pure kinematic hardening were presented in Kuhl et al. [1998] and Kuhl et al. [2002]. Riccius et al. [2004] discussed the influence of transient thermal analysis and rate-dependent material behavior on the estimated lifetime. In these works 2D plane strain structural analyses were performed. The aforementioned works did not incorporate damage evolution in the material behavior.

In Schwarz et al. [2011a] a viscoplastic model coupled with anisotropic damage was utilized in a 3D thermomechanical FE analysis of a thrust chamber segment. Incorporating ageing as well as the crack-closure effect, the doghouse failure mode could be well reproduced. The crack-closure effect can be easily imagined when an existing microcrack in a material is fully or partially closed upon compressive loading.

It is mentioned that the model leads to an overestimation of the lifetime by 25%. In Schwarz et al. [2011b], the influence of damage anisotropy and the crack-closure effect on the doghouse effect as well as the lifetime of the thrust chamber are quantified. The author concludes that damage anisotropy as well as the crack-closure effect cannot be neglected to reproduce the doghouse effect. However, simplications of the model such as to include only isotropic damage and neglecting the crack-closure effect are admissible for the purpose of lifetime prediction.

In France, the PhD thesis of Petry [2006] contributes to the state-of-the-art of the research in this subject. In his work, elastoviscoplastic material models in the context of small and large strain formulations are coupled with cavitation and cracking damage variables to simulate the doghouse effect. Unfortunately, no access can be gained to the results of the work due to confidentiality reasons.

The increasing computing capacity and the maturity of some numerical methods in solving multiphysics problems give chance to take the interaction of different physical phenomena in the modelling into account. This leads to the idea to apply a viscoplastic damage model in a 3D FSI analysis of a typical liquid rocket engine. The results of this work are presented in Tini et al. [2011] and Kowollik et al. [2013b]. In Blades et al. [2010] results of 3D FSI simulations of rocket engine side loads during a portion of the engine startup are presented. However, the material behavior is considered to be linear elastic. Therefore, to the knowledge of the author, the work presented in Kowollik et al. [2013b] is the first attempt to account for viscoplasticity and damage in a 3D FSI analysis of a liquid rocket engine.

The present dissertation results from a project within the collaborative research program CRC/TR40 "Fundamental Technologies for the Development of Future Space-Transport-System Components under High Thermal and Mechanical Loads" supported by the German Research Foundation (DFG).

1.4 Outline of the dissertation

Following this introduction, the theoretical background of the material modelling is presented in Chapter 2. It begins with the motivation by a rheological model, in which the classical rheological model of Armstrong-Frederick kinematic hardening is extended to a viscoplastic model and coupled to a scalar isotropic damage variable using the principle of strain equivalence. Afterwards the extension within a small strain formulation is presented. Results of numerical investigations on the influence of the damage parameters on the model response are shown.

Having understood the behavior of the model with isotropic damage, a second-order