THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SOLID AND STRUCTURAL MECHANICS

# Modelling of cyclic and viscous behaviour of pearlitic steels

Application to tread braked railway wheels

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# Abstract

Railway wheel and rail materials are subjected to very high stresses and, in some cases, also elevated temperatures. The rolling contact loading results in a multiaxial stress state with a combination of compression and shear. The elevated temperature is caused by frictional heat generated between wheel and brake blocks at tread braking, or between wheel and rail. The main goal of this thesis is to improve modeling of the cyclic and viscous mechanical behaviour of wheel materials subjected to mechanical and thermal loadings.

Finite element analyses of generic heavy haul wheel designs, subjected to high power drag braking loads, are carried out giving global wheel behaviour e.g. in terms of axial rim displacements and residual stresses. A plasticity model and a viscoplasticity model are calibrated against results from cyclic strain controlled experiments of a railway wheel steel of ER7 grade at different temperatures. The finite element analyses show a strong influence of the material model in particular for braking with high power.

Next, a methodology to simulate full scale brake rig tests is developed. It includes three types of finite element analyses: an axisymmetric thermal analysis, a 3D mechanical wheel-rail contact analysis and a 3D thermomechanical analysis. The wheel material behaviour is modelled by a plasticity model calibrated against results from cyclic strain controlled experiments. The results from the simulation methodology in terms of ratchetting failure show rather good agreement with full scale test rig results for three cases of initial velocity and brake block material.

To further improve the material modelling, a viscoplastic model is calibrated against experimental data for cyclic loading and relaxation (low strain rates) as well as high strain rate tests. Preliminary results from the simulation methodology show that the viscoplastic model predicts larger plastic strains as compared to the plastic model.

Keywords: Railway wheels, tread braking, rolling contact fatigue, full-scale brake rig testing, plasticity, viscoplasticity, finite element analysis

# Preface

The work presented in this thesis was carried out at the Division of Material & Computational Mechanics, Department of Applied Mechanics, at Chalmers University of Technology during 2013–2016. It is part of the activities within the National Centre of Excellence in Railway Mechanics (CHARMEC), under the project name *MU32: Modelling of rail and wheel steels subjected to mechanical and thermal loadings.* The project has been supported by CHARMEC's industrial partners. Especially the support from Lucchini Sweden, Bombardier Transportation, Faiveley Transport and SJ is gratefully acknowledged.

I would like to acknowledge Chalmers Centre for Computational Science and Engineering (C3SE). The simulations in this project were performed on resources at C3SE provided by the Swedish National Infrastructure for Computing (SNIC).

I would like to express my deepest gratitude to my main supervisor Prof. Magnus Ekh and my co-supervisor Dr. Tore Vernersson for their invaluable guidance and continuous support and encouragement. Furthermore, I am deeply grateful to my co-supervisor Prof. Johan Ahlström for the thought-provoking discussions and incredibly pedagogical explanations. The work in this thesis would not have been possible to accomplish without the contribution of my supervisors.

Also, special thanks goes to the co-authors of the appended papers Dimitris Nikas, Mandeep Singh Walia and also Kazuyuki Handa and Katsuyoshi Ikeuchi from RTRI for the knowledge exchange and cooperation we had in preparing the papers.

I would like to take the opportunity to thank all my colleagues at the Division of Material and Computational Mechanics and the Division of Dynamics, for making a nice and friendly working environment and also special thanks to our football team members for the very fun (sometimes serious) football sessions.

Last but definitely not the least, I would like to give a special thank to my family for their endless support.

Gothenburg, December 2016
Ali Esmaeili

# Thesis

This thesis consists of an extended summary and the following appended papers:

**Paper A** A. Esmaeili, T. Vernersson, D. Nikas and M. Ekh. High temperature tread braking simulations employing advanced modelling of wheel materials. *Proceedings of the 11th International Heavy Haul Association Conference (IHHA 2015) Perth.* 2015, pp. 44-51

**Paper B** A. Esmaeili, M. Singh Walia, K. Handa, K. Ikeuchi, M. Ekh,T. Vernersson and J. Ahlström. A methodology to predict thermomechanical cracking of railway wheel treads: from experiments to numerical predictions. *To be submitted for international publication*

**Paper C** A. Esmaeili, M. Ekh, T. Vernersson and J. Ahlström. Modelling of temperature and strain rate dependent behaviour of pearlitic steel - in block braked railway wheels. *To be submitted for international publication*

# Contents

# Part I
# Extended Summary

# 1 Introduction

## 1.1 Background and motivation

In railway industry, due to increasing axle loads and running speed of trains in the recent years, the maintenance costs and the causes of disturbances in the railway operations have increased. Fatigue failure, wheel wear and tread damage are reasons for premature wheel removal and major cost factors for railroad and car owners. Furthermore, the performance of rails and wheels is important for the safety of operations of railroads. Hence, there are many challenges for the metallurgists, engineers, and railway managers responsible of railway operations, cf. [1].

For block (tread) braked wheels heat is generated when brake blocks are pressed towards the tread of the rolling wheel. The tread material is subjected to rolling contact stresses and also stresses induced by constrained thermal expansion. The rolling contact loading, between rail and wheel tread, results in a multiaxial stress state with a combination of compression and shear.

An important question is how wheel and rail material behave under these conditions and how this can be modeled. The main goal of this study is to improve modeling of the behaviour of wheel material subjected to cyclic multiaxial mechanical and thermal loadings. In fact, the material model is a key component when developing simulation tools that can predict accurate temperature and stress fields in railway components e.g. in the vicinity of the wheel-rail contact. Also, it is desirable to investigate damage mechanisms and develop a method for prediction of these in the components.

In high power braking (e.g. drag braking), wheels are subjected to high thermal loadings. The resulted constrained thermal expansion may influence the global behaviour of the wheelset in terms of axial rim displacements during and after braking, and also residual stresses after braking. This plays an important role in designing of the wheelset to fulfill the requirements according to the European standards. A goal in the current study is to perform predictions and analyse results of axial rim displacement and residual stresses for different wheel designs for a high power braking loading case.

## 1.2 Tread braked railway wheels

Tread (block) braking is still one of the most common braking systems on railway vehicles. Block braking is commonly used on freight wagons but also on passenger trains, often in combination with disk brakes and electrodynamic brakes. The tread braking action is carried out by pressing one or several brake block(s) against the tread (running surface) of the wheel. The tread is also in rolling contact with the rail, see Fig. 1.1. Nowadays, a brake block is generally manufactured from cast iron, organic composite or sintered material, see [2].

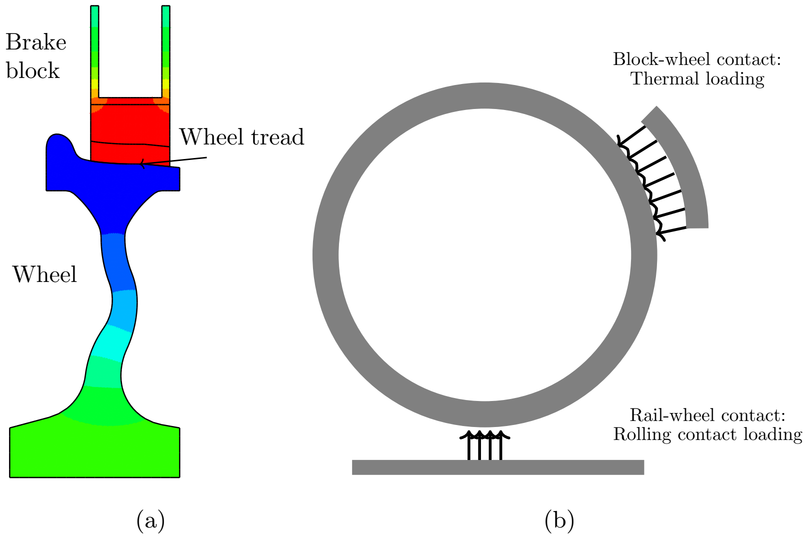


Figure 1.1: Schematic diagram of wheel, block and rail subjected to combined thermal and contact loading.

Railway wheels are generally forged and heat treated. It is desirable to obtain a combination of good strength and wear properties, and because of this, medium carbon pearlitic steels are often used. The ER7 grade with around 0.55 wt.% carbon is one of the standard grades used in wheels for freight trains and for many passenger coaches in Europe. The wheels are rim chilled; a heat treatment yielding a microstructure just below the wheel tread that consists of mostly pearlite with some 5–10 vol. % pro-eutectoid ferrite, cf. [3]. The rim chilling increases the yield strength of the material and introduces compressive stresses.

## 1.3 Research collaborations

The work in this thesis has been carried out within the CHARMEC project MU32 “Modelling of thermomechanically loaded rail and wheel steels”. This project is conducted in collaboration with the CHARMEC project MU28 ”Mechanical performance of wheel and rail materials” at the Dept. of Materials and Manufacturing Technology. In MU28 mechanical tests have been performed on pearlitic steels at elevated temperatures. These give knowledge and understanding of how the material behaves in realistic loading situations which are used in the current project to formulate, calibrate and validate material models. The project also interacts with the CHARMEC project SD10 ”Enhanced mechanical braking systems for modern trains” at the Dept. of Applied Mechanics where e.g. simulations of the contact between brake block and wheel including temperature elevation are developed. Also, full-scale tests featuring three series of repeated stop braking cases have been performed by the Railway Technical Research Institute (RTRI) in Japan and the results are in this project compared to finite element simulations.

# 2 Material modelling

A main scope of this study is the proposal of a constitutive model allowing for reliable predictions of the thermomechanical fatigue life of a railway wheel tread. In this context, the proposed constitutive model should be able to capture the main features of ER7 wheel material behaviour. For example, under cyclic loading phenomena like cyclic hardening/softening, Bauschinger effect, ratchetting and shake down behaviour can occur. The base material model used in this study is plasticity or viscoplasticity with combined nonlinear isotropic and kinematic hardening, see e.g. [4], which we below denote as the Chaboche model.

The evolution of the kinematic hardening in the Chaboche model has been further extended in literature see, e.g., Ohno & Wang 1993 [5], Jiang & Sehitoglu [6], Bari & Hassan 2002 [7], Chaboche 2008 [8] with the purpose to improve ratchetting or mean stress relaxation predictions. The parameters for these models can be identified for uniaxial cyclic experiments including ratchetting or mean stress relaxation. However, in the current project no experiments are available yet for ratchetting or mean stress relaxation of ER7 material and therefore the Chaboche model is used.

The models above have been reported, cf. Burlet and Cailletaud (1987) [9], Chen 2005

[10], to over-predict multiaxial ratchetting. Hence, a modification of the dynamic recovery of the kinematic hardening was proposed by Burlet & Cailletaud [11] which has been used in **Paper C** and an initial parameter study is performed to analyse its influence on strain accumulation in a tread brake simulation.

Cyclic strain controlled experimental data sometimes show cyclic softening. This can be modelled using either negative evolution of isotropic hardening or a dependence of the accumulated plastic strain on the dynamic recovery, see Chaboche 2008 [8], Brommesson 2014 [12]. In the current work a negative isotropic hardening is adopted, see **Paper B**.

In order to examine the behaviour of ER7 subjected to thermal and cyclic loading, uniaxial cyclic strain controlled low cycle fatigue (LCF) experiments at temperatures from 20 °C to 625 °C have been carried out, see more details in [3]. A 30 min. hold time with constant strain in compression is included in the tests which reveals the viscous behaviour of the material in terms of stress relaxation. Already at 300 °C some viscous behaviour is observed in the experiments. An additional observation is that a considerable increase in hardness of the material due to strain aging is obtained at temperatures between 300-400 °C. In the current work the relaxation in the tests are used in **Paper A** and **Paper C** to determine viscoplastic model parameters whereas in **Paper B**, for simplicity, only cyclic data is used.

A proper material model for ER7 in a tread braking simulation, should be able to cover the full range from nearly rate independent behaviour at low temperatures to significant rate dependent behaviour at higher temperatures. The high temperatures due to the thermal loading at braking result in slow time dependent behaviour such as creep, relaxation and static recovery of the wheel material. In a viscoplastic model this is captured by an overstress function and static recovery of the hardening variables. In **Paper A**, where only thermal (slow) loading is considered, a Norton overstress function is adopted together with static recovery.

On the other hand, in **Paper C**, we also need to account for high strain rates caused by the rolling contact loading. Different approaches have been suggested in literature to capture wide loading rate ranges and associated physical mechanisms in viscoplastic models. In Liang, Khan (1999) [13] different constitutive viscous models and their performance to predict the response of BCC and FCC metals are examined. The formulations of the models correspond to overstress functions of exponential type. The models are capable of capturing the response for a wide range of loading rates. Furthermore, different overstress functions and their behaviour are examined in Chaboche 2008 [8] where it is concluded that the exponential and sinh (proposed by Delobelle) overstress function yield similar response. To limit the stress values at very high strain rates a possibility is to use a limit/dynamic yield surface cf. Ekh [14], Becker-Hackenberg [15], and thereby for such strain rates obtain a rate independent response. In **Paper C** two alternative overstress functions, the Norton power law and the Delobelle sinh function are used. In addition to the cyclic data with relaxation for ER7, data from Split Hopkinson's tests of a 42CrMo4-FP steel [16] with ferritic-pearlitic microstructure and similar chemical decomposition as ER7 is used to characterize the viscous behaviour of ER7 at high strain rates. An example of a simulation result using the Delobelle overstress function is shown in Figure 2.1b

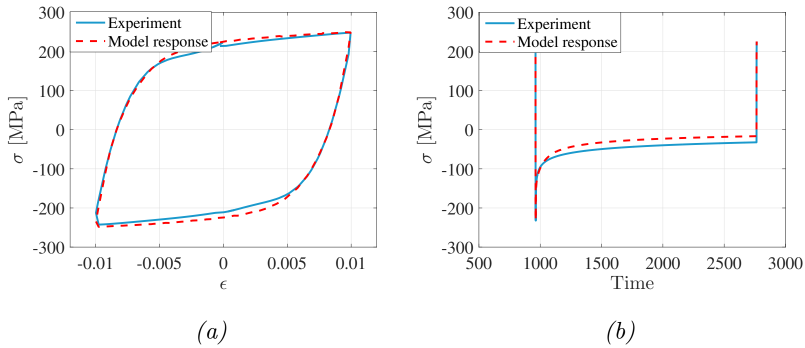


Figure 2.1: Modelling of cyclic and viscous phenomena at 600 °C for 1 % strain amplitude (a) stress vs strain for the cycle before the hold time (captured by the hardening variables) and (b) relaxation behaviour captured by the overstress function and the static recovery.

# 3 Simulations of tread braked wheels

During tread braking, the frictional heat is partitioned between the wheel and the block at their contact interface and further conducted from the hot wheel into the cold rail [17]. Temperatures build up in the wheel and introduce change of the global wheel behaviour, i.e. axial rim displacements during and after braking, and also residual stresses after braking [18]. The thermal capacity of tread brakes can be limited by this global thermomechanical behaviour of the wheels [19], but also by how the elevated temperatures influence the rolling contact fatigue damage introduced to the tread [20].

Simulation of global wheel behaviour requires knowledge of the temperature distribution in the wheel and of the material response at elevated temperatures. Global wheel temperatures are then often analysed using some simplifying assumptions on heat generation and heat partitioning in the system, allowing for the wheel temperatures to be determined from a purely thermal analysis [21]. Material models used for thermomechanical assessment of wheel behaviour are generally of plasticity type [22, 23], but also viscoplasticity models are used [18].

In **Paper A** we assume a condition of severe thermal loadings (e.g. high power drag braking loads) and investigate the impact of material modelling on calculated wheel behaviour. To this end, the global behaviour of the wheel, i.e. axial rim displacement during and after braking and also residual stresses after braking, is studied for one plasticity type of material model and one viscoplasticity type. The study shows that the choice of material model is important for simulation of wheel behaviour for situations when substantial stresses build up in the rims of wheels at severe braking cases. Wheel tread damage caused by rolling contact fatigue is a source for premature machining of wheels, which shortens their expected service life [24]. An overview of wheel tread damage and also thermal effects is given in [25]. The study of rolling contacts often start out from Hertzian contact theory [26] and utilization of Shakedown maps for assessing the damage. However, for detailed study of the impact from combined thermal and mechanical loads, as imposed by braking and rolling contact, numerical modelling using the finite element method is preferred. In previous work within CHARMEC [27], a combined experimental and numerical approach is taken to study thermal cracks on the wheel tread. Simulation results are compared to one case of repeated stop braking (initial speed 160 km/h, 20 tonne axle load, sinter material brake block), produced in collaboration with the Railway Technical Research Institute (RTRI) in Tokyo Japan. Numerical modelling of the frictional rolling contact during braking was found to give a calculated ratcheting fatigue life that was in reasonable agreement with the experimental brake rig results. For the numerical model a material model of plasticity type was employed and the traversing contact load on the wheel tread was based on an assumption of Hertzian contact theory.

In **Paper B** and **Paper C**, the detailed study of wheel tread material behaviour when subjected to thermomechanical loading from simultaneous braking and rolling contact loads is continued. In this regard, the conditions observed in brake rig experiments are again used as input in the numerical analysis, now introducing results from two additional brake rig tests of repeated stop braking. **Paper B** introduces a 3D computational framework that allows for the analysis of the wheel tread material subjected to thermal and mechanical loading when employing a plastic material model. The FE-modelling in this study involves sequential thermal and mechanical analyses conducted in three steps.

1. Heat partitioning between brake block, wheel and rail during stop braking is accounted for in axisymmetric thermal analyses using models developed in [17, 28].
2. Wheel-rail contact is simulated for indentation type of loading using a detailed FE-model.
3. Wheel temperature histories, obtained in the first step, and the mechanical rolling contact stresses, obtained in the second step, are finally applied in a 3D structural analysis.

The modelling aims at reproducing brake rig experiments and for this reason three different thermal patterns on the treads of the wheels are introduced. They account for so-called banded contacts between brake block and wheel that occur during braking because of frictionally excited thermoelastic instabilities. The material response of the wheel is evaluated by studying the stress-strain cycles in the most critical material points that are found close to the tread below the rolling contact load. In **Paper C** the analyses are repeated using a viscoplastic material model.

In the current studies, the dominating mechanism behind wheel tread fatigue is found to be plastic deformations resulting from the combined thermal and mechanical loading. Two methods for assessing fatigue life are utilized in **Paper B**; one is based on ratchetting failure (RF) and the other is based on low cycle fatigue (LCF) damage [29]. It is found, for the considered types of stop braking, that the LCF damage mechanism has a low influence on the failure of the material and that ratchetting failure is the dominant damage mechanism. Based on a comparison between experimental and simulated results, an estimate for the critical strain that controls the ratchetting life is obtained.

# 4 Summary of appended papers

## 4.1 Paper A

The main goal of this study is to improve the modelling of wheel materials subjected to thermal loading due to tread braking and also to highlight the importance of viscoplastic material modelling. In this regard, finite element analyses of generic heavy haul wheels, subjected to high power drag braking loads, are carried out and comparisons between analyses with plastic and viscoplastic material models are shown. Results are presented for simulated global wheel behaviour, i.e. axial rim displacements during and after braking, and also residual stresses after braking. A conclusion is that the obtained results for a generic wheel with an S-shaped web, which builds substantial stresses in the wheel rim during braking, is rather sensitive to the choice of material model. Substantial differences are found already at 400 °C. Moreover, the results indicate that a generic Low-stress wheel, which builds lower stresses in the rim during braking, is less affected by the choice of material model. However, at temperatures above about 500 °C also the results for this wheel are significantly affected by the choice of material model.

## 4.2 Paper B

In the present study, thermal cracking of railway wheel treads is studied by full-scale brake rig tests and finite element simulations. The main goal of the paper is to perform thermomechanical rolling contact fatigue life predictions. The wheel tread material is subjected to simultaneous mechanical and thermal loads due to rolling contact and stop braking, respectively. Full-scale tests featuring three series of repeated stop braking cases have been performed at the Railway Technical Research Institute (RTRI) in Japan in a brake rig featuring a tread braked wheel that is in rolling contact with a railwheel. The brake rig test conditions have been simulated numerically using the finite element method where the effect of "hot bands" on the tread is accounted for as indicated by the experimental findings. Stresses induced by temperature from braking as well as tractive rolling contact loading on the tread are considered. The mechanical response of the wheel material ER7 is obtained from a plastic Chaboche material model calibrated against data from cyclic experiments from room temperatures up to 625 °C. Finally, a strategy for prediction of fatigue life with respect to ratchetting failure is discussed.

## 4.3 Paper C

Block braked railway wheels are subjected to thermal and rolling contact loading. The thermal loading results in high temperatures and thermal stresses which cause slow time dependent behaviour such as creep, relaxation and static recovery of the wheel material. At the same time, the rolling contact loading is applied very fast. This paper is focused on material modeling of pearlitic steel for a wide range of loading rates at elevated temperatures. The starting point is a viscoplastic model including nonlinear isotropic and kinematic hardening. The viscoplastic model includes static recovery of the hardening and an overstress function of Delobelle type. Experiments for the pearlitic steel ER7 in terms cyclic strain-controlled uniaxial tests with hold-time at different temperatures are used to calibrate the material model. Experimental data for ER7 at high strain rates and temperatures is not available in literature. Hence, experimental results from Split-Hopkinson's tests of a 42CrMo4-FP steel have been used to calibrate the high strain rate response of the model with the purpose to investigate the importance of including such behaviour in the modelling of block braked railway wheel. The paper is concluded with a numerical example of a block braked wheel where the importance of the viscoplastic modelling is highlighted.

# 5 Conclusions and Outlook

In **Paper A**, two material models have been calibrated against experimental data for the pearlitic wheel steel ER7, one viscoplastic material model that can mimic the stress response both for cyclic loading and relaxation, and one plastic model that can mimic the stress response only during cyclic loading. Simulation results are presented for the global wheel behaviour of two generic wheel designs subjected to high power (drag braking) thermal loading. The wheel designs are a traditional S-shaped wheel and a Low-stress wheel. The results indicate that the S-shaped wheel is more sensitive to the choice of material model than the Low-stress wheel. Clearly, this is caused by that the S-shaped wheel is subjected to higher stresses than the Low-stress wheel.

Since only thermal loading is considered in **Paper A**, the material parameters for the rate dependence were only identified against the low strain rate LCF tests. However, in **Paper C** the combination of thermal and rolling contact loading will result in a wide range of strain rates in the material, which indeed is a great challenge for viscous modelling. In this context, to obtain a realistic response of the viscoplastic material model the model parameters need to be identified using both low and high strain rate tests.

In **Paper B**, a methodology to simulate the conditions in full scale brake rig experiments is presented. In the test rig, the wheel is subjected to both thermal and mechanical loading from frictional sliding contact with a brake block and rolling contact with a rail-wheel. A material model of plasticity type, with a combination of nonlinear isotropic and kinematic hardening, was calibrated against data from LCF tests of ER7 steel at different temperatures. The model is able to capture the cyclic behaviour of the material. The results from the simulation methodology in terms of ratchetting failure show rather good agreement with full scale test rig results for three cases of initial velocity and brake block material.

The viscous behaviour of ER7 steel was not accounted for in **Paper B**. The main goal of **Paper C** is to improve the material model in terms of cyclic and viscous behaviour. To do so, the experimental data from LCF tests with hold time and results from high strain rate tests are used to calibrate viscoplastic models. Experimental data for fast loading at elevated temperatures is not available for railway wheel material ER7 in the literature. Instead data from Split Hopkinson's tests of a 42CrMo4-FP steel [16] with a ferritic-pearlitic microstructure and a similar chemical decomposition as ER7 is used to calibrate the viscoplastic model. In the viscoplastic model the Norton and the Delobelle overstress functions are utilized. Both of these can capture the material behaviour at a wide range of strain rates rather well. However, to provide a more reliable conclusion it would be valuable to produce experimental data for ER7 steel at high strain rates and varying temperatures and not rely on data from 42CrMo4-FP steel. The applied evolution equation for kinematic hardening in this thesis includes dynamic recovery. In literature this evolution equation is known to over-predict the multiaxial ratchetting and modifications have been suggested. However, to identify parameter values in such modifications data from multiaxial/biaxial experiments are needed. Furthermore, such experiments can hopefully also provide data for multiaxial thermomechanical fatigue criteria. The challenging research task of finding or formulating and validating such a criterion will be addressed in future work.

Finally, finite element simulations of tread braking of railway wheels are very computationally expensive. The reasons are that 3D models are necessary to use and that the wheels are subjected to very many loading cycles. Other finite element approaches such as sub-modelling techniques and arbitrary Lagrangian-Eulerian formulations [30] could be considered in future work.

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