



Isogeometric Analysis and thermomechanical Mortar contact problems



M. Dittmann^a, M. Franke^b, İ. Temizer^c, C. Hesch^{b,*}

^a Chair of Computational Mechanics, University of Siegen, Paul-Bonatz-Str. 9-11, Siegen 57068, Germany

^b Institute of Mechanics, Karlsruhe Institute of Technology (KIT), Otto-Ammann-Platz 9, Karlsruhe 76131, Germany

^c Department of Mechanical Engineering, Bilkent University, Ankara, Turkey

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ABSTRACT

Thermomechanical Mortar contact algorithms and their application to NURBS based Isogeometric Analysis are investigated in the context of nonlinear elasticity. Mortar methods are applied to both the mechanical field and the thermal field in order to model frictional contact, the energy transfer between the surfaces as well as the frictional heating. A series of simplifications are considered so that a wide range of established numerical techniques for Mortar methods such as segmentation can be transferred to IGA without modification. The performance of the proposed framework is illustrated with representative numerical examples.

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1. Introduction

In this contribution, we address transient isogeometric thermomechanical contact and impact problems in the context of nonlinear elasticity. Thermoelastic material models have been investigated in detail over the past two decades, see Reese and Govindjee [32], Miehe [25] and Holzapfel and Simo [15] among many others. Corresponding formulations for thermomechanical frictional contact and impact interfaces have also been investigated and analysed in, e.g., Zavarise et al. [42], Strömberg et al. [35], Saracibar [6] and Laursen [18]. Based on the first and second laws, the thermodynamic foundations of frictional interfaces govern the formulation of appropriate constitutive laws and additionally play a major role in the construction of the accompanying numerical schemes. The emphasis of the present contribution will be on the numerical aspects.

The spatial discretisation of the bodies in contact will be carried out in the context of NURBS based Isogeometric Analysis (IGA), see Cottrell et al. [4] for a comprehensive review. Contact problems for IGA have been addressed in a series of papers throughout the past years, see De Lorenzis et al. [20,21] and Temizer et al. [38,36,39]. In these works, a Knot-to-Surface (KTS) method has been developed and extended to Mortar based contact formulations. Recently, Matzen et al. [24] have proposed a collocation based approach, analogous to the well-known Node-to-Surface (NTS) method. See also Kim and Youn [17] for a Mortar approach and Lu [22] for an alternative contact treatment.

Mortar formulations in the context of IGA domain decomposition problems have been presented in Hesch and Betsch [14]. In the present contribution, we extend the ideas developed therein to thermomechanical contact in order to achieve a variationally consistent Mortar formulation for the discrete contact interface. In particular, the Mortar projections will be calculated via a newly developed segmentation procedure of the surface intersections, see Puso et al. [31] for a discussion

* Corresponding author. Tel.: +49 721 608 43716.

E-mail address: christian.hesch@kit.edu (C. Hesch).

about different spatial integration schemes. For the thermal contributions, the Mortar concept will be applied by introducing triple Mortar integrals to accurately capture the frictional dissipation contribution to the contact heat flux and to establish a correct thermal interaction among the contacting surfaces. See also Hübner and Wohlmuth [16] for Mortar methods applied to thermoelasticity.

For transient impact problems, the bodies will be discretised in time using structure preserving integration schemes, following the approach in Hesch and Betsch [10]. This allows us to investigate the effect of different integration schemes for the contact contributions, following Franke et al. [8] in the context of purely mechanical NTS methods. Specifically, we will devote particular attention to the conservation of angular momentum and its possible violation.

An outline of the paper is as follows. The underlying thermomechanical framework for the bodies and the frictional contact interface is presented in Section 2. The spatial discretisation using IGA as well as the Mortar formulation for the semi-discrete system is developed in Section 3. The temporal discretisation is outlined in Section 4, followed by representative numerical examples in Section 5 and conclusive remarks in Section 6.

2. Governing equations

In this section we summarize the variational form of the thermomechanical theory along with a most general description of frictional contact contributions, embedded within the thermomechanical framework. In particular, we consider Lipschitz bounded domains $\mathcal{B}_0^{(i)} \subset \mathbb{R}^n$, $n \in [2, 3]$ in their reference configuration, where the upper index (i) will denote the respective body in the remainder of this article.¹ Furthermore, we introduce the mapping

$$\boldsymbol{\varphi}(\mathbf{X}, t) : \mathcal{B}_0 \times \mathcal{I} \rightarrow \mathbb{R}^n, \quad (1)$$

to characterise the time dependent deformation along with the absolute temperature

$$\theta(\mathbf{X}, t) : \mathcal{B}_0 \times \mathcal{I} \rightarrow \mathbb{R} \quad (2)$$

for the time interval $t \in \mathcal{I} = [0, T]$ elapsed during the motion. Here, $\mathbf{X} \in \mathcal{B}_0$ labels material points in the reference configuration and both fields are assumed to be sufficiently smooth.

2.1. Finite strain thermoelastodynamics

In a first step we postulate that the material behaviour is governed by a Helmholtz energy density function $\Psi(\mathbf{C}, \theta)$, where $\mathbf{C} = \mathbf{F}^T \mathbf{F}$ denotes the right Cauchy–Green tensor and $\mathbf{F} : \mathcal{B}_0 \times \mathcal{I} \rightarrow \mathbb{R}^{n \times n}$, $\mathbf{F} = D\boldsymbol{\varphi}$ the deformation gradient. Accordingly, we define the local constitutive relations

$$\boldsymbol{\Sigma} = 2 \frac{\partial \Psi}{\partial \mathbf{C}}, \quad (3)$$

$$\eta = - \frac{\partial \Psi}{\partial \theta}. \quad (4)$$

Therein, $\boldsymbol{\Sigma}$ represents the second Piola–Kirchhoff stress tensor and η the local entropy density. A third constitutive relation is required to account for the heat transfer

$$\mathbf{Q} = -\hat{\mathbf{K}}(\mathbf{C}, \theta) \nabla_{\mathbf{X}}(\theta), \quad (5)$$

known as Duhamel's law of heat conduction, where $\hat{\mathbf{K}}(\mathbf{C}, \theta)$ is the material thermal conductivity tensor. Introducing the space of virtual or admissible test functions for the deformation as well as for the absolute temperature

$$\mathcal{V}^\varphi = \{ \delta \boldsymbol{\varphi} \in \mathcal{H}^1(\mathcal{B}_0) \mid \delta \boldsymbol{\varphi} = \mathbf{0} \text{ on } \partial \mathcal{B}_0^\varphi \}, \quad (6)$$

$$\mathcal{V}^\theta = \{ \delta \theta \in \mathcal{H}^1(\mathcal{B}_0) \mid \delta \theta = 0 \text{ on } \partial \mathcal{B}_0^\theta \}, \quad (7)$$

where \mathcal{H}^1 denotes the Sobolev functional space of square integrable functions and derivatives, the weak form of the balance of linear momentum and the energy balance equation reads

$$G_\varphi := \int_{\mathcal{B}_0} \rho_0 \delta \boldsymbol{\varphi} \cdot \ddot{\boldsymbol{\varphi}} + \boldsymbol{\Sigma} : \mathbf{F}^T \nabla_{\mathbf{X}}(\delta \boldsymbol{\varphi}) dV - \int_{\mathcal{B}_0} \delta \boldsymbol{\varphi} \cdot \bar{\mathbf{B}} dV - \int_{\partial \mathcal{B}_0^\varphi} \delta \boldsymbol{\varphi} \cdot \bar{\mathbf{T}} dA = 0, \quad (8)$$

$$G_\theta := \int_{\mathcal{B}_0} \delta \theta \dot{\eta} - \mathbf{Q} \cdot \text{Grad}(\delta \theta) dV - \int_{\mathcal{B}_0} \delta \theta \bar{R} dV - \int_{\partial \mathcal{B}_0^\theta} \delta \theta \bar{Q} dA = 0. \quad (9)$$

Note that $\dot{\eta}(\mathbf{C}, \theta)$ can be decomposed into components denoted as heat capacity and latent heat, where the latter one is responsible for the Gough–Joule effect. The external contributions at the boundary are specified by Dirichlet and Neumann boundary conditions on the mechanical and thermal field, respectively

¹ If convenient and unique the superscript index will be omitted for the ease of exposition. Moreover, we make use of the summation convention for repeated indices.

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