Simulation of Manufacturing Sequences of Functionally Graded Structures

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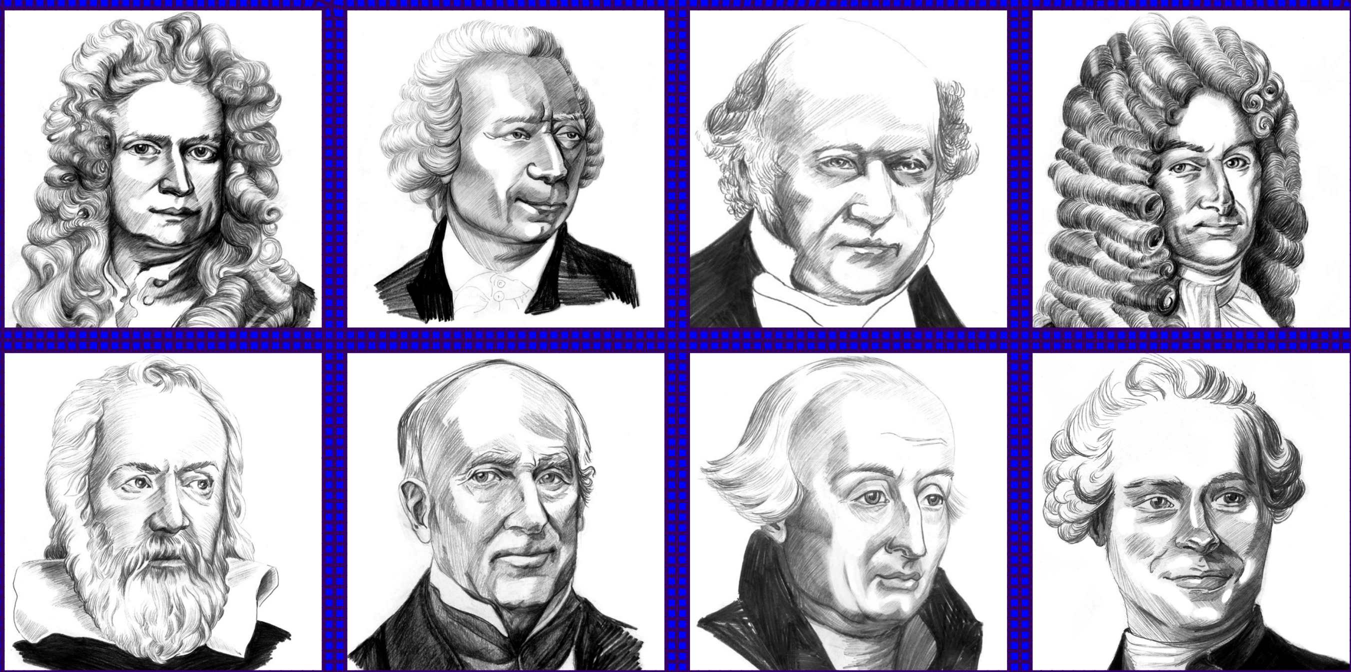

Abstract

This work deals with the numerical simulation of multi-field problems in the context of functionally graded materials. Within the SFB/TR TRR 30, functionally graded materials were examined, which had been produced in an integrated manufacturing process. This process chain is divided into the induction heating of a steel shaft, its reshaping and cooling in a forming die and the rapid cooling of the deformed steel shaft in locally defined areas by a high pressured air stream. This targeted local heating and cooling at defined time intervals controls the spatial distribution of different crystal lattice, and consequently the steel gains specific, application-oriented properties. These properties are thereby decided depending on the function of the application and can be implemented very precisely.

To attain specific properties and simultaneously avoid a large number of experimental tests, the parameters of the process chain should be investigated in simulations in advance, in order to obtain appropriate characteristics. It is crucial that these simulations are carried out in time and space with highly accurate numerical methods. In order to be economically efficient, while remaining highly accurate, different techniques need to be investigated. In this work, the numerical implementation of the first step, the induction heating, and the third step of the process chain, the rapid cooling, are investigated in detail.

Due to the highly non-linear material properties of this steel shaft, corresponding phenomenological material models must be applied. In the context of induction heating, these non-linear material properties lead to a strong coupling of the electromagnetic and thermal fields. Using a general derivation of the MAXWELL equations and the heat conduction equation, the multi-field initial boundary value problem can be formulated so that all interactions of the contributing fields can be considered in the balance equations and the constitutive laws. In preparation for the numerical solution of the multi-field initial boundary value problem, the balance equations of the strong form are transferred to a spatially weak form and, due to the non-linearity, linearized with respect to the field variables. The numerical solution of this problem is accomplished by using the finite element method, a particular time integration scheme and the NEWTON-RAPHSON iteration. The finite element discretization in tensor notation allows a standardized formulation for one-, two- and three-dimensional continua. By means of a p-version of the finite element method with classical LAGRANGIAN shape functions, any number of dimensions and an arbitrary polynomial degree can be selected for the individual balance equations of the general multi-field problem. As part of the time integration of the non-linear initial boundary value problems of first and second order, the generalized NEWMARK-α method, the family of the RUNGE-KUTTA methods and the discontinuous and continuous GALERKIN time integration methods are introduced. All the time integration methods have different strengths, which are analyzed and studied in the respective examples. For the assessment of the error, general error estimators and corresponding special error estimators of the individual method classes are presented and investigated. These error estimators create the opportunity to achieve highly accurate simulation results, when using the RUNGE-

Kutta and Galerkin time integration methods. Furthermore, with the help of different adaptive techniques, the time increment can be adjusted in order to keep the simulations efficient, in addition to retaining high accuracy. The sequential implementation of spatial and temporal integration methods leads to a modular combination of the introduced numerical methods. For this reason, several algorithms are introduced, which allow the application of different element, model and material routines and different time integration methods.

In the case of inductive heating, a monolithic approach and different partitioned approaches in the linear and the non-linear case are introduced and analyzed. The advantage here is the ability to directly compare robustness, accuracy and efficiency. All features must be in line in order to be able to perform realistic simulations. In the context of the cooling process, a purely partitioned approach is chosen. In this process, the thermal field and the fluid field, which have been programmed in two different programming languages and with two different spatial discretization methods, are coupled with the aid of an additional library (CTL - Component Template Library) and a master program. The heat conduction equation is solved using the finite element method and the finite volume method is applied for the compressible Navier-Stokes equations. This library has the advantage, that the different programs can run on different computers. With the help of this master program, the two different program codes can be connected through various coupling strategies, which have different properties. Depending on the desired properties and the objectives, a block-Jacobi method or a block-Gauss-Seidel method can be selected. While in the case of inductive heating, both the thermal field and the electromagnetic fields are solved in a volume-coupled procedure, the thermal-fluid-structure interaction is computed with an edge coupling of the thermal field and the fluid field.

As it is well known in the literature, fluid-structure interaction problems that are determined in a partitioned manner, require many fixed point iterations per time step. This results in an exceptional amount of computing time for computer simulations. For this reason, various relaxation methods and extrapolation methods for reducing the fixed point iterations per time step are investigated in connection with a purely thermal-fluid-structure interaction. The effects of both techniques are analyzed separately as well as coupled. In order to simultaneously attain a high accuracy and an adaptive time scheme, all featured extrapolation methods are derived, presented and analyzed in an adaptive variant. This general formulation provides the ability to implement the various extrapolation methods independent of a time integration scheme in an existing code.

By means of various examples, the introduced numerical methods are studied for each of the individual fields (electric, magnetic and thermal), as well as for the multi-field problem of the inductive heating. Several coupling strategies for induction heating and thermal-fluid-structure interaction are examined in detail. In both parts of the process chain the high accuracy in the spatial domain (using the p-version of the finite element method) and in the time domain (using high order Runge-Kutta and Galerkin time integration methods) is in the foreground, as well as the focus on an efficient solution, taking into account special error estimators.