Institut für Angewandte Mechanik
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Jan Frischkorn

New finite element modelling techniques for functional materials and devices

Applied Mechanics – RWTH Aachen University

New finite element modelling techniques for functional materials and devices

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This document summarizes my work as a research associate at the Institute of Solid Mechanics (ifm) at TU Braunschweig (2006-2009) and the Institute of Applied Mechanics (ifam) at RWTH Aachen (2009-2013), both under the supervision of Prof. Dr.-Ing. Stefanie Reese. I would like to take the oportunity to express my words of gratitude to the persons who accompanied me during this time.

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In spring 2013 I left Aachen to start a new job in the chasis development at Volkswagen AG in Wolfsburg. I thankfully appreciate the support and motivation I recieved from my superiors Dr.-Ing. Thomas Kersten and Dr.-Ing. Georg Ungemach for finishing this thesis.

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Braunschweig, July 2019 | Jan Frischkorn

Summary

In this thesis, focus is drawn to the modelling of the mechanical behaviour of two types of products that feature increased functionality. To this end, the finite element method (FEM) is utilized and enhancements of the FEM are presented which enable an improved modelling in order to simulate the mechanical behaviour of the two products of interest.

In the first application, a new hybrid production process regarding the production of large ring-shaped devices that feature a wear-resistant outer layer is proposed. The layer itself is produced from powdery metal matrix composite (MMC) and is applied onto a substrate ring. Before the layer is applied in the conventional process, the substrate ring gets its desired shape by means of radial axial ring rolling, an incremental bulk forming process. In the novel production process, ring rolling and compaction of the layer are combined into one production step. Thereby, current limitations like the maximal producible ring size can be exceeded. For an adequate modelling of the process, a material model is derived that is able to describe the compaction of metal powders. The model features finite strains, isotropic hardening and a so-called sintering stress that allows for a compaction in the absence of external loads. The latter is necessary to model pressureless sintering. An implementation of the model into the finite element code ABAQUS is presented. Finally, the material model is applied within longitudinal and ring rolling simulations of a powder-filled bar and ring, respectively. Based on the results of the longitudinal rolling simulations, first important design guidelines concerning the integration of the powdery layer into the substrate can be deduced. It is shown that the proposed modelling approach yields results in accordance with with experimental findings and provides a promising tool to investigate the limitations of the new production process.

The second example of a product with increased functionality is concerned with stents made out of nickel-titanium alloys (Nitinol). Stents are tubular medical devices which are mostly applied to recover the lumen in stenotic arteries or to stabilize aneurysms. Nitinol stents offer a simplified application into the vessel. In contrast to stents made out of stainless steel which need to be expanded by a balloon catheter, Nitinol stents are self-expanding since they can undergo large recoverable strains based on a stress-induced phase transformation. In general, FEM simulations are utilized to guarantee a safe design of stents concerning their durability and to ensure the required opening forces. Due to the filigree structures of stents (beam-like structures with a high number of ramifications), appropriate finite element models feature a large number of degrees of freedom resulting in very long computing times. As a remedy, we present a novel finite element technology which we call solid-beam element. This element consists of an eight-noded hexahedral topology with a strongly modified description of the displacement and strain fields by means of enhanced assumed strain and assumed natural strain concepts as well as reduced integration. The element is able to adequately model beam structures with

trapezoidal cross-sections in an efficient manner by using only one element with respect to the thickness discretization. After an implementation of the novel FE technology into the FE codes FEAP and ABAQUS, the performance of the element is assessed using various benchmark problems from literature. Finally, the proposed finite element technology is successfully applied to the modelling of stent structures including a complete intracranial stent.

Zusammenfassung

Im Mittelpunkt dieser Arbeit steht die Modellierung des mechanischen Verhaltens zweier Produkte, die durch eine erhöhte Funktionalität entscheidende Vorteile bieten. Hierzu wird die Finite-Element-Methode (FEM) angewendet. In diesem Zusammenhang werden notwendige Weiterentwicklungen der FEM vorgestellt, die eine verbesserte Modellierung ermöglichen sollen.

Im ersten Beispiel geht es um die Herstellung großer ringförmiger Bauteile mit einer äußeren Verschleißschutzschicht mittels eines neuen hybriden Produktionsverfahrens. Der Verschleißschutz wird dabei aus einem pulverförmigen Metall-Matrix-Verbundwerkstoff (metal matrix composite – MMC) auf den Substratring aufgebracht. Zuvor erfolgt die Formgebung des Substratringes durch Radial-Axial-Ringwalzen, ein inkrementelles Massivumformverfahren, welches bei erhöhter Temperatur stattfindet. In dem neuen Herstellungsverfahren erfolgt das Walzen des Ringes und das Kompaktieren des Schichtwerkstoffes in einem Prozessschritt. Dadurch können bestehende Grenzen bezüglich der maximal produzierbaren Ringgröße überwunden werden. Zur Modellierung dieses Prozesses wird ein Materialmodell zur Beschreibung von Verdichtungsprozessen in Metallpulvern hergeleitet. Das Modell basiert auf großen Deformationen, berücksichtigt isotrope Verfestigung und eine sogenannte Sinterspannung, die eine Verdichtung ohne Einwirkung einer externen Last ermöglicht. Letztere ist zur Modellierung des drucklosen oder freien Sinterns notwendig. Eine Implementierung des Materialmodells in das kommerzielle FEM-Programm ABAQUS dient zur FEM-Simulation von Längs- und Ringwalzprozessen des hybriden Herstellungsverfahrens. Aus Simulationen des Längswalzprozesses können bereits wichtige Richtlinien zur Gestaltung der Pulverintegration in das Substrat abgeleitet werden. Längs- sowie Ringwalzsimulationen zeigen eine gute Übereinstimmung mit experimentellen Ergebnissen, so dass hiermit ein vielversprechendes Werkzeug zur Verfügung steht um die Grenzen dieses neuen Produktionsverfahrens simulativ zu erfassen.

Das zweite Beispiel für ein Produkt mit erhöhter Funktionalität befasst sich mit Stents aus Nickel-Titan-Legierungen (Nitinol). Stents sind röhrenförmige medizinische Geräte, die weitestgehend dazu verwendet werden um den Blutfluss in, durch Stenose verengten, Blutgefäßen wieder herzustellen oder um Aneurysmen zu stabilisieren. Nitinol-Stents bieten ein vereinfachtes Einsetzen in den menschlichen Körper und haben Vorteile bezüglich der Biokompatibilität. Im Gegensatz zu Stents aus rostfreiem Stahl, welche durch einen Ballonkatheter aufgeweitet werden müssen, sind Nitinol-Stents selbstexpandierend. Verantwortlich hierfür ist eine spannungsinduzierte Phasentransformation im Nitinol, welche sehr große pseudoelstische Deformationen ermöglicht. Allgemein werden mittlerweile FEM-Simulationen dazu genutzt um eine sichere Konstruktion von Stents bezüglich Dauerfestigkeit und Funktionalität zu gewährleisten. Die filigrane Topologie von Stents (balkenförmige Strukturen mit vielen Verästelungen) bedingt jedoch FEM-Modelle mit einer hohen Anzahl an Freiheitsgraden, was zu sehr langen Rechenzeiten führt. Die in dieser Arbeit vorgestellte 'solid-beam' Finite-Elemente-Technologie (FET) kann eine Verbesserung hinsichtlich dieser Problematik leisten. Diese Technologie basiert auf einer achtknotigen Hexaedertopologie mit einer stark modifizierten Beschreibung der Verschiebungs- und Dehnungsfelder auf Basis der Konzepte 'Enhanced Assumed Strains' und 'Assumed Natural Strains' sowie reduzierter Integration. Somit ist eine adäquate Modellierung von Balken trapezförmiger Querschnitte bereits mit einem Element in Dickenrichtung möglich. Die Leistungsfähigkeit der neuen Elementformulierung wird anhand zahlreicher Beispiele aus der Literatur gezeigt und dabei mit herkömmlichen Balkenformulierungen verglichen. Hierzu wird die neue FET in die Finite-Elemente-Programme FEAP und ABAQUS integriert. Abschließend wird gezeigt, dass die neue FET bei der Modellierung von Nitinol-Stents entscheidende Vorteile gegenüber der Verwendung herkömmlicher 'Solid'-Elemente bietet. Dies wird abschließend anhand eines Faltvorganges eines kompletten intrakraniellen Stents demonstriert.

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