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Development of an expert system for the simulation model for casting metal substructure of a metal-ceramic crown design

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ABSTRACT

Background and objectives: Nowadays, the integrated CAD/CAE systems are favored solutions for the design of simulation models for casting metal substructures of metal-ceramic crowns. The worldwide authors have used different approaches to solve the problems using an expert system. Despite substantial research progress in the design of experts systems for the simulation model design and manufacturing have insufficiently considered the specifics of casting in dentistry, especially the need for further CAD, RE, CAE for the estimation of casting parameters and the control of the casting machine. The novel expert system performs the following: CAD modeling of the simulation model for casting, fast modeling of gate design, CAD eligibility and cast ability check of the model, estimation and running of the program code for the casting machine, as well as manufacturing time reduction of the metal substructure.
Methods: The authors propose an integration method using common data model approach, blackboard architecture, rule-based reasoning and iterative redesign method. Arithmetic mean roughness values was determinated with constant Gauss low-pass filter (cut-off length of 2.5 mm) according to ISO 4287 using Mahr MARSURF PS1. Dimensional deviation between the designed model and manufactured cast was determined using the coordinate measuring machine Zeiss Contura G2 and GOM Inspect software.
Results: The ES allows for obtaining the castings derived roughness grade number N7. The dimensional deviation between the simulation model of the metal substructure and the manufactured cast is 0.018 mm. The arithmetic mean roughness values measured on the casting substructure are from 1.935 µm to 2.778 µm.
Conclusions: The realized developed expert system with the integrated database is fully applicable for the observed hardware and software. Values of the arithmetic mean roughness and dimensional deviation indicate that casting substructures are surface quality, which is more than enough and useful for direct porcelain veneering. The manufacture of the substructure shows that the proposed ES allows the improvement of the design process while reducing the manufacturing time.

1. Introduction

Investment casting (IC) is the most widespread technology for dental cast manufacturing, which implies mold and process automation in initial and detailed design. Investment casting or "lost-wax" casting is a precision casting process where the wax patterns are transformed into metal alloys cast. Traditional IC suffers from high tooling investments for producing wax patterns. IC is used in the automotive and aerospace industries, and dentistry for the manufacturing of complex metal shapes. In this process, the shape to be reproduced is formed in wax and coated in a chemically bonded ceramic investment material. The investment is then heated to remove the wax. Dental investment wax patterns are often formed manually on a replica of the patient's mouth, which presents the working cast [1].

List of abbreviations: CSYS, base coordinate system for positioning part and subassembly; CS0, CS1, CS2, base coordinate system for positioning model of the gate subsystem; mat1, mark of the material of the metal substructure; mat2, mark of the material of the crucible insert; magma_params, the results of the numerical simulation from MAGMAsoft; R_a, arithmetic mean roughness; t_1, time required for manufacturing the metal substructure using ES; t_2, time required for manufacturing the metal substructure without using ES; T_c, casting temperature; T_c^*, estimated casting temperature (numerical simulation into MAGMASOFT); AI, Artificial Intelligence; CAD, Computer Aided Design; CAE, Computer Aided Engineering; CAM, Computer Aided Manufacturing; CAx, Computer Aided Systems; DB, Database; ES, Expert System; IC, Investment Casting; KB, Knowledge Base; KS, Knowledge Source; Pro/E, CREO Parametric software; RE, Reverse Engineering; UDF, User-defined Feature.

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Atwood et al. [2] used computational modeling tools for cast design. The process allowed reproduction of complex shapes at relatively low cost while reducing the consumption of raw materials. The model was used to determine the influence of various sprue geometries. Bodein et al. [3] proposed a method for complex parts modeling in a commercial CAD system. Their modeling method was based on the explicit management of functional features. Product-oriented methodology is focused on the conceptual and detailed design process, providing flow of information between CAD and CAE. Cakir et al. [4] developed an ES called "DieEX" for the die and mold design. The ES developed for guiding the mold makers uses its database that is the aggregation of the knowledge gathered from several experts in the field of mold making or CAD/CAM, and collected from technical documents. It is designed to provide practical solutions in selecting the tool type, machining method, feed direction, and machining tolerances. Chen et al. [5] presented the semantics of design and information entities, relations, constraints in each view and further generalizing common entities in order to develop a consistent product information model. The user-defined feature (UDF) was proposed as information medium in order to integrate the conceptual design, detailed design and process planning. UDF association and unification are determined with relation to the consolidated feature modeling scheme for the distribution of information. They used unified feature for the integration of CAD and CAE.

Cleary et al. [6] used MAGMAsoft software to simulate two casting processes - high-pressure die casting and gravity die casting. Darwish and El-Tamimi [7] developed a modular, rule-based, parametric ES for the selection of casting processes. The selection procedure involved the identification of relevant possible casting processes and their ranking according to their performance. Deng et al. [8] developed a CAD/CAE integrated design system from the earlier developed CAD and CAE systems. The authors used feature-based modeling and analysis process for CAD/CAE integration. The general structure of the expert system was organized into four layers: a CAD and CAE platform layer, a CAD/CAE feature layer, a model layer and a graphical user interface layer. Dwivedi and Sharan [9] developed a modular, object-oriented expert system for the diagnosis of defects in cylinder block casting. The criteria for diagnosing those defects, which were classified into different groups, included location, shape of defects and whether the defects appear before or after machining. The ES operated as an interactive system, responding to questions, making recommendations, and aiding in making decisions. Er and Dias [10] developed ES for casting process selection. The rule-based ES assisted the designers in selecting the most appropriate casting process. The casting selection system was developed using modular approach.

Gujarathi et al. [11] created a CAD/CAE integration method using a common data model, which contains required information for CAD modeling and CAE analysis. The model was generated by built-in knowledge. This informational model was used as a DB of the CAD/CAE object-oriented features. The concept of the common data model contains CAD data model, and CAE data model. CAD and CAE work as different modules interconnected through module, which integrates application programming interfaces and rules used in the KB. Their integration of CAD and CAE enables to solve the problem of the association of the CAD/CAE. The authors used geometric information and production rules to develop the design module.

Jevremovic et al. [12] tested mechanical properties of the Cr-Co dental alloy. The results obtained for this alloy and other materials were used for creating the material database of our proposed ES.

Ji et al. [13] integrated CAD/CAE modular system using C++ environment. This ES was built using a parametric design template connected to commercial systems such as UG and ANSYS. Lee [14] developed a model containing both CAD and CAE features and explored the advantages of a common modeling environment and bidirectional CAD and CAE integration with multiple feature representations and limited automation.

Lou et al. [15] developed knowledge-based system integrated with Pro/E. This CAD/CAE/CAM system incorporated some kind of geometrical, precision and non-geometry information. Matin et al. [16] presented some aspects of the prototype integrated system and supporting procedure for the manufacture of metal substructure of metal-ceramic crowns. Galanis et al. [17] developed a semi-automatic computer-aided system for planning the dental implant therapy. Authors presented the developed methodology for planning a dental implant as a supportive tool for a dentist, helping to propose initial solutions based on the established clinical and biomechanical criteria by processing CT data with the increased accuracy. Sun et al. [18] developed a system for the design of a complete removable denture. The object-oriented and parametric database consisted of the CAD models of artificial teeth and set of parameters needed for selection. ES was applied for modeling removable denture, semiautomatic design aesthetic and individualized artificial gingival and base plate. The first phase consisted of utilizing the laser scanner for data collection, and CAD systems for the integrated design of the complete removable denture. Based on a review of the feature-based and object-oriented technology, Yin and Ma [19] focused on the modeling of relationships among the features of different design aspects. The authors classified the features into conceptual, assembly, component basic, and component detailed features. Similar feature classification could be applied for the development of ES. Park and Dang [20] built a system on a modular basis, integrated with a commercial system CREO (Pro/E). They developed robot external body parts by applying CAD/CAM/CAE in an integrated manner.

Wu et al. [21] used MAGMAsoft for the numerical simulation of the dental castings on a centrifugal casting machine to design runner and gate subsystem. Authors used four various sprue design subsystems for single crown casting and the other four to improve three-unit-bridge-casting. Wu et al. [22] determined a method to fabricate dental crowns by means of integrating laser measurement, numerical simulation and rapid prototyping for the manufacture of wax patterns for the IC process. Authors used numerical simulation of the IC process for the gate subsystem design of partial dental frameworks.

Up to date, many design techniques and systems have been developed. Most of them apply artificial intelligence (AI) techniques to generate simulation models and casting process designs. The expert engineering techniques, which enable the building of an interactive ES, are the following: linear programming, non-linear programming, simulated annealing, iterative redesign, parametric design template, gradient algorithm, branch and bound, heuristic rules, rule-based reasoning, case-based reasoning, meta-heuristic search, genetic algorithm, and analogical reasoning. Each technique has specific properties, which make them suitable only for particular problems.

Two numerical methods are used to determinate IC parameters and increase the yields of casts in commercial simulation software. One is the finite-difference method and the other is the finite element method. The finite-difference method is commonly used for predicting the filling flow, thermal transfer, and solidification in many casting simulation suites, e.g., MAGMAsoft, PAM-CAST, and AnyCasting. Several software solutions are also presently available for the determination of mold parameters such as ProCAST, Starcast, Solidcast, etc. Numerical simulation in the IC process helps designers visualize several parameters regarding the flow of the molten alloys in the mold, such as solidification, shrinkage and stress in the castings.

It can be concluded that the various authors used different approaches to solve the problems of IC technology using ES. They