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Iterative, simulation-based shape modification by free-form deformation of the NC programs

A. Sacharow, S. Odendahl *, A. Peuker, D. Biermann, T. Surmann, A. Zabel

Institute of Machining Technology, TU Dortmund University, Baroper Str. 301, 44227 Dortmund, Germany

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ABSTRACT

In production engineering, there are several applications where the geometry of a designed workpiece has to be modified, e.g., optimization of forming tools during springback compensation in sheet metal forming. In general, the modified shape of the workpiece is given as a mesh and has to be converted to a parametric representation by surface reconstruction before manufacturing. In this paper, a new approach for obtaining small shape modifications by direct deformation of the NC programs is presented. In an iterative process, the CAM data is modified by a free-form deformation and is verified by a milling simulation so that the modified workpiece can be manufactured directly on the basis of the original CAD/CAM data without surface reconstruction.

1. Introduction

During product development in production engineering, it is often necessary to optimize the shape of the designed workpiece in order to improve the quality of the product. The shape modifications of the workpiece may be applied directly on a manufactured prototype or on the CAD representation using a specific CAE (Computer Aided Engineering) software. For example, for bulk production, the conducted modifications should be transfered to the CAD model of the workpiece by reverse engineering [1]. In this process, a new CAD model of the modified workpiece is computed on the basis of measured or simulated data using surface reconstruction.

Another challenge is the compensation of process-specific deformations of workpieces. Especially in the forming process, a need for shape modifications of the forming tool exists. Due to elastic deformations of the sheet metal, the springback effect occurs each time a forming tool is removed. This may lead to extensive deformations of a workpiece, such as bending or torsion. In order to compensate such deformations, it is necessary to modify the geometry of the forming tools, e.g., by using the displacement adjustment method [2,3]. The modifications should counteract springback and compensate the form errors. In the last years, a number of commercial software tools, e.g., AutoForm, have been developed, which allow the compensation of springback. Using the Finite Element method, it is possible to simulate the forming process and calculate the geometry of the sheet after springback. Since FE simulations are performed on the basis of polygon meshes, the compensation operation also produces the geometries of the optimized forming tools in form of a mesh. After that, in order to manufacture the modified tools, new CAM data has to be generated. However, due to discretization errors, computing NC programs based on a mesh results in unsufficient surface qualities. Therefore, surface reconstruction is necessary to create a new CAD model.

In general, the process of surface reconstruction [4] is a nontrivial and time-consuming task. Here, a special software, like Tebis or Geomagic, is used to transform a polygon mesh or point cloud data into a CAD model. In spite of continuous developments in this area of research, it is not always possible to obtain an accurate CAD model automatically. Depending on the complexity of the workpiece, the engineer has to manually define the patch layout and continuity conditions. Nevertheless, shape deviations of the generated CAD model may still occur due to approximation errors. Thus, manual reworking often has to be conducted in order to ensure the desired shape accuracy. This process requires comprehensive experience of the engineer and can take several days.

In this paper, we present a simulation-based, iterative approach for manufacturing modified workpieces, i.e., optimized forming tools, without the process of surface reconstruction. The presented method is based on the work of Biermann et al. [5] and uses adaptive free-form deformation [6] for the direct modification of NC programs. The novelty of the presented method is the iterative approach in combination with a milling simulation, which increases the shape accuracy of the manufactured workpieces.

* Corresponding author. Tel.: +49 231 755 5820; fax: +49 231 755 5141.
E-mail address: odendahl@isf.de (S. Odendahl).
URL: http://www.isf.de (S. Odendahl).

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The outline of this paper is as follows. In Section 2, a short overview of reverse engineering and free-form deformation is provided. Section 3 presents the new iterative approach for the shape modification. The presented method is validated in Section 4 using three examples from mechanical engineering. Finally, a summary and an outlook are given in Section 5.

2. Related work

Reverse engineering (RE) is a process in which a computer-aided representation of a physical object is generated. In general, this process can be divided into three fundamental phases: scanning, point processing and surface reconstruction [1]. The first two phases are needed if the 3D shape data of the object has to be acquired first. In many industrial applications, e.g. compensation of springback, the shape data already exists as a mesh, thus, only the surface reconstruction is required. In this process, a set of implicit or parametric surfaces has to be fitted to the underlaying mesh. The general approach for surface reconstruction divides into two important steps [4]. First, a patch layout or a curve network must be created. To accomplish this, segmentation methods [7–9] or feature-based curve extraction [10,11] can be used. In the second step, parametric surfaces are fitted into the segments considering continuity constrains along the boundaries [12–14]. In general, the generation of a CAD model from a mesh or point cloud data is a very time-consuming and error-prone process. Approximation errors or discontinuities on the reconstructed surface may occur and, thus, decrease the quality of the CAD model. Overall, the process of surface reconstruction depends on the experience of the engineers and generally cannot be done automatically.

In Ref. [5] a new approach for manufacturing modified workpieces without surface reconstruction is presented. The authors used a free-form deformation technique for the direct manipulation of NC programs with respect to a discrete deformation field. Free-form deformation (FFD) is an important technique in computer graphics and geometric modeling. It is used for the manipulation or deformation of geometric objects. Barr [15] presented solid modeling operations like twisting, bending, tapering, or similar transformations. By combining the deformations in a hierarchical structure, complex objects can be created from simpler ones. The normal and tangent vectors of the new object are calculated directly from the corresponding vectors of the undeformed surface and the transformation matrix. Sederberg and Parry [16] developed a more general method for the manipulation of solid geometric models by deforming the space in which they are embedded. They defined the deformation function by a trivariate tensor product of Bernstein polynomials (Bézier volume). It allows deformations by moving the control points of the volume. This technique was adapted and extended by several authors. Hsu et al. [17] developed a method for the direct manipulation of a B-spline-based FFD using the pseudoinverse. Hu et al. [18] extended the method for the direct manipulation of FFD for the NURBS volume and used a constrained optimization method for solving this problem. Sarraga [19] presented a method for the manipulation of CAD/CAM surfaces with respect to displacements defined at a finite set of points. He modeled the volume deformation by a trivariate tensor-product B-spline solid and obtained a smooth behavior of the deformation by minimizing the bending energy of the volume.

3. New approach for shape modification

In this section, we present an iterative, simulation-based method for the manufacturing of workpieces modified with respect to a given deformation field. This method is based on the work described in [5] and uses the same basic concept. The main principle is to use the free-form deformation technique for the direct manipulation of the NC programs. Since this CAM data also describes a geometrical representation of an object, it can be deformed by a free-form deformation function in the exact same manner as the corresponding mesh or CAD model so that the manufactured workpiece conforms to the modified geometry. Nevertheless, approximation and process-related errors may cause slight shape deviations. The innovation of the new method is the possibility for accuracy control by the iterative execution in conjunction with the use of a milling simulation. Fig. 1 shows the iterative procedure of the new approach for shape modification.

The input data is the CAD model, the NC programs for the designed workpiece, and the shape modification field D, which is calculated by the deformation analysis or the form-error compensation procedure. First, the free-form deformation $\boldsymbol{F}$ is calculated with respect to the vector field D. Then, the NC programs for the original workpiece are modified by $\boldsymbol{F}$. Since the manufacturing of forming tools is a very costly process, the modified NC programs have to be verified by the milling simulation first. Furthermore, the simulation is also able to analyze and optimize the milling process and model the surface of the workpiece [20,21]. In order to achieve the required accuracy, the simulated surface is compared to the target surface and the remaining deviations in form are calculated. The comparison of two shapes is realized in general by the use of registration methods [22–24], which produce a field of deformation vectors. If required, the corrective volume deformation is generated in the next step and the NC programs are adapted again with respect to the newly calculated shape deviations. In the end, the target workpiece is manufactured using the deformed NC program for the designed shape.

Below, the main steps of the manufacturing method are presented. In Section 3.1, we introduce the free-form deformation technique and present an adaptive method for volume deformation. In the following Section 3.2, the process of modifying NC programs is explained. Section 3.3 gives a short overview of the milling simulation which is used for the verification of the NC programs.

3.1. Free-form deformation

In order to modify CAM data with respect to a discrete deformation field, a continuous function for smooth space deformation is

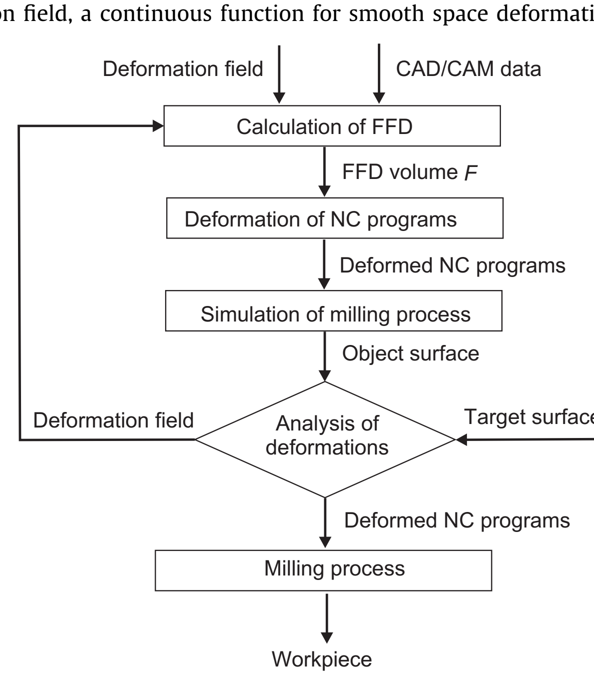

Fig. 1. Process of manufacturing the modified objects.