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An information and simulation framework for increased quality in welded components

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ABSTRACT

The recent trend toward using simulation models with real-time data as digital twins is rapidly increasing in industry. In this paper, a digital framework supporting real-time geometrical quality control of welded components, is presented. The concept is based on a structured process model for all operations included in typical welding, strategies for selective assembly, automatic adjustment of fixtures and optimization of weld sequence. The concept utilizes recently developed algorithms for fast welding simulation and in-line scanning to be used in the optimization loop of an automated welding station—a digital twin for a welding cell.

1. Introduction

Simulation is today an important tool for design optimization and for shifting work, traditionally performed in late production phases, to earlier phases where cost for change is low. Last years' hype in digitalization and the trend toward using simulation models as digital twins, are rapidly increasing in industry. The concept was adopted by NASA for safety and reliability optimizations [1,2]. The vision of the digital twin refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information useful in the current and subsequent lifecycle phases [3,4]. Simulation and seamless transfer of data from one life cycle phase to the subsequent phase are central for the concept of the digital twin. Increased computer power, faster algorithms, and efficient optimization routines are critical for realizing the concept of a digital twin.

Geometry related problems usually constitute a significant part of the total cost for poor quality. Therefore, an effective and efficient digital geometry assurance process is important to drastically reduce costs and adjustments in production [5]. In the design phase, requirements are defined and broken down and concepts are analyzed and optimized to withstand manufacturing variation. In the pre-production phase inspection preparation and off-line programming of inspection devices are performed. In the production phase inspection data from parts and subassemblies are used to control production and to detect and correct errors.

Variation simulation and CAT tools are extensively used in the design phase to secure good geometrical quality in the final product. Geometry assurance activities typically include optimization of tolerances, locator positions, clamping and welding sequence etc [5]. Faster optimization algorithms, increased computer power and amount of available data, can allow simulation models to be used during production, as digital twins for real-time control and optimization of products and production systems. Including the effect of manufacturing variation is then important. In Ref. [6] functionality and data models necessary for real-time geometry assurance, and how this concept allows moving from mass production to more individualized production, are specified and discussed. In Ref. [7], a comprehensive reference model based on the concept of Skin Model Shapes, serving as a digital twin of the physical product, is proposed. In Ref. [8] the input data, feeding the digital twin for geometry assurance, is discussed.

During "fabrication", a number of small parts are manufactured and welded together to create a component or a product. The concept allows the use of scalable platforms to create variants. However, this introduces a number of quality issues, due to welding, that needs to be controlled during manufacturing.

1.1. Scope of the paper

To realize a digital twin for a welding line/cell, a number of issues related to variation need to be considered. This paper proposes such a framework. The concept offers a development platform supporting individualized mass production, increasing quality without tightening tolerances and increase machining cost. Chapter 2 presents the overall information model used to identify and keep track of all parameters influencing the final geometrical quality of the welded product. Chapter 3 presents the SCV-method for fast welding simulation that can be combined with variation simulation to improve the geometrical quality. Chapter 4 presents the concepts of selective assembly and virtual matching that further improve geometrical quality in a fabricated product. In Chapter 5, the information model, the welding simulation, the selective assembly and the virtual matching, presented in the following chapters, are combined to describe a digital twin setup for a welding line.

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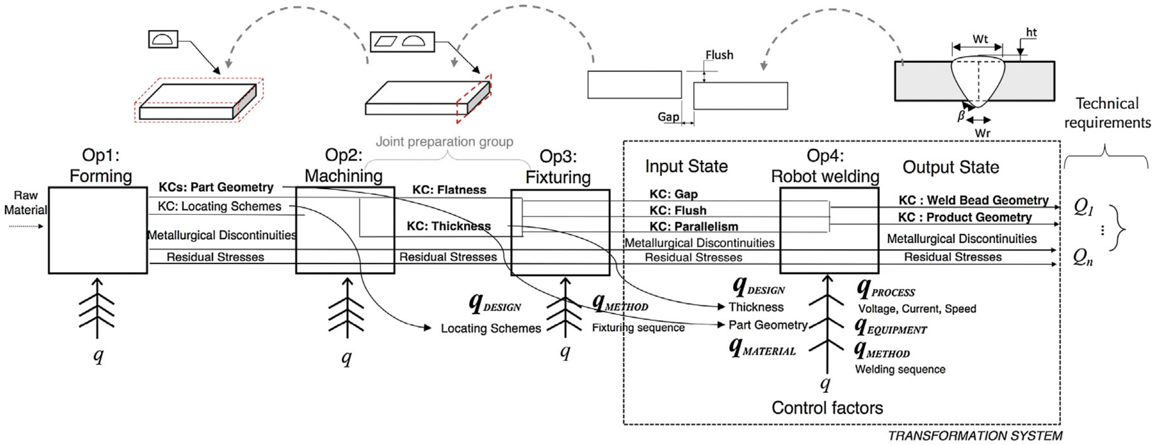

Fig. 1. Geometry assurance information model with KC flow down for welded structures.

2. Geometry assurance model for welded structures

A producability model [9,10] can be used to represent the product quality creation during the fabrication process of welded components. This model constitutes the framework for a digital twin for welded structures. The model, illustrated in Fig. 1, represents the manufacturing operation chain, composed of four main operations to form a welded component: (1) Net shape forming processes are employed to produce part shapes. (2) The machining operation prepares the joint edges for good alignment conditions. (3) Parts are placed into a fixture to be locked and aligned in optimal positions. (4) The robot welding operation performs the weld. After the robot welding, the product ought to contain certain product characteristics and properties that fulfill performance quality requirements.

Besides product geometrical integrity to fulfill aerodynamics and structural requirements, KCs (Key Characteristics) like weld bead geometries, metallurgical discontinues such as cracks and pores and residual stresses also need to be kept within certain tolerance limits. All these aspects constitute the weld quality [11]. However, weld quality depends not only on the welding operation but also on the transformations that the product has undergone in previous operations [12,13]. To represent the variation propagation in an assembled product, a hierarchical KC flow down [14] has been adopted in the producability model. In the proposed model, see Fig. 1, top product level KCs, derived from technical requirements, are broken down into KCs at the different subsystem product levels and aligned to the outcome of each operation. For example the KC “Weld bead geometry” (output of Op4:Robot welding) can be broken down into KCs “Gap”, “Flush” and “Parallelism” (output of Op3:Fixturing), which in turn are broken down into the KCs “Flatness” and “Thickness” (output of Op2:Machining), which ultimately lead to the KC “Part geometry” (output of a Op1:Forming). In this way, variation propagation from initial until the last operation can be represented. Furthermore, each operation is modeled as an isolated transformation system, according to the Theory of Technical Systems (TTS) by Ref. [15]. In the model, KCs are described as operands that are transformed from an input state to a desired output state. An Ishikawa diagram, inspired from Ref. [16], is added to the model to represent variation sources that act as control factors at each operation. In this way, the technical systems that control and execute the transformation process are represented. The control factors q_{DESIGN} and q_{MATERIAL} refer to product geometry and material characteristics selected by the designers, thus belong to the product system. For example, during fixturing operation, the design of the locating schemes will affect the quality of the alignment, thus affecting gap and flush KCs [16]. During welding, the q_{DESIGN} part geometry will have an effect on the welding output quality [9]. The other control factors, q_{METHOD}, $q_{\mathrm{EQUIPMENT}}$ and q_{PROCESS}, relate to the manufacturing system as they refer to manufacturing equipment aspects, manufacturing process variables (welding current, voltage or speed) and process methods, such as welding or fixturing sequences, which can also be controlled and optimized to improve the output quality [17,18]. The model in Fig. 1 carries the information related to quality control of welded structures. To predict and control the effect of welding in real-time, fast welding simulation is needed.

3. The SCV-method for fast welding simulation

A number of the KCs described in Fig. 1 have a great effect on the welding process and how welding affects the final geometry. In order to assure the quality of the welding process and the resulting geometry and stress after welding, computational welding mechanics (CWM) is often used.

During welding, the local heating causes large thermal gradients which lead to plastic strain and residual stress. Furthermore, surrounding the melted zone is the heat affected zone where the microstructure of the metal is changed. The microstructural composition in every time step is affecting the material properties of the metal. To capture all these physical phenomena in CWM a transient simulation of the complete thermal-, microstructure-, and structural history needs to be performed. However, the relation between thermal-, microstructural- and structural dynamics is typically assumed to be weakly coupled so that in one time step first the thermal field is updated, based on this update, the microstructure is updated and lastly, based on these fields, the structural state is updated [19,20].

The movement of the heat source and the high gradients involved in welding put high requirements on the size of the time steps and of the size of the finite elements close to the weld in simulation. This leads to long simulation time. For industrial cases, simulation times of several hours for a single weld are not unusual.

Because of long simulation times in CWM, approximate methods have been developed for the weld induced deformation. Ueda and Yuan proposed the method of inherent strain [21]. Here, a smaller segment of the weld path is welded using transient simulation. An inverse formula is then used to obtain what is called the *inherent strain* which is applied along the complete weld path. A more direct strategy where welding deformation is related to the thermal contraction of melted volume has been shown to give reasonable results [22,23].

Today welding simulation is typically done using nominal geometries. However, studies have shown that, in order to accurately capture the effects from welding on distortion and stress, geometrical deviation and variation prior to joining need to be included [13,24]. This drastically increases the need for fast welding simulation. Therefore, to combine variation simulation for welded assemblies in early phases the SCV-method (Steady state-Convex hull-Volumetric Shrinkage-method) was developed by Lorin et al. [25]. The method consists of three steps, see Fig. 2 (left). Step 1 is a steady state simulation to obtain the steady state temperature distribution surrounding the weld gun during welding. For weld paths that are not straight or if the geometry surrounding the weld path is subject to change, this step needs to

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