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Simulation-based numerical optimization of arc welding process for reduced distortion in welded structures

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ABSTRACT

This paper presents an effective numerical approach for welding process parameter optimization to minimize weld-induced distortion in structures. A numerical optimization framework based on coupled Genetic Algorithm (GA) and Finite Element Analysis (FEA) is developed and implemented for a low and a high fidelity model. Classical weakly coupled thermo-mechanical analysis with thermo-elasto-plastic assumptions is carried out for distortion prediction of numerical models. The search for optimum process parameters is executed by direct integration of numerical models and GA-based optimization technique. The developed framework automatically inserts the process parameters into the simulation models, executes the FE-based welding simulations and evaluates the required simulation output data for iterative evolutionary optimization. The optimization results show that the proposed approach can contribute substantially to enhance final welded product quality while facilitating and accelerating the product design and development.

1. Introduction

Arc welding is a major joining process used in automotive, shipbuilding, and other industries. It is prominent over other joining methods due to its competitive advantages such as reduced cost, enhanced joint strength, and wide range of applications. However, one of the major problems of welding is weld-induced distortion in the welded assembly. Distortion affects performance of welded structures in the form of reduced joint strength and dimensional accuracy. Despite tremendous development in arc welding technology over the years, weld-induced distortion is still one of the major obstacles for welding industry to ensure adequate reliability of welded structure's performance.

Correction of distortion often requires additional after-weld reworks, which are usually costly, time consuming, and practical only in the most crucial applications. The best practice to minimize or control distortion is proper welding process design through careful selection of various welding input parameters. Several process parameters influence welding distortion. Better control of these parameters will eliminate the conditions that promote distortion [1].

Control of distortion is mostly performed empirically using experiments [2]. A set of experiments is conducted in a defined range of conditions and the experimental results are used to determine the set of parameters that closely meets the joint requirements. However, this type of experimentally determined optimal criteria does not always guarantee the most ideal setting or applicability to the tested conditions.

In recent years, rapid growth in computing power and numerical algorithms has made it possible to model real-world welding processes through computer simulations. For more than three decades, finite element method (FEM) has been the most popular and powerful tool for simulating the thermomechanical behavior of a structure during welding process [3]. Several researchers investigated the problem of distortion during welding using FEM. Lindgren has provided an extensive review on finite element (FE) modeling for welding residual stress and distortion prediction [4–6]; the initial welding simulations were highly simplified based on two-dimensional (2D) approach and plane strain condition [4]. Although the 2D analysis gives indications of the welding residual stresses involved in quasi-static, plane strain conditions, it does not provide the total out-of-plane deformations [7]. Brown and Song [8] used both two 2D and three-dimensional (3D) models to investigate fixturing impact on large structures and concluded that full 3D models are essential in predicting welding distortion. Michaleris et al. [2,9] used two step numerical analysis approach that combines 2D welding simulation with 3D structural analysis for predicting buckling distortion; 2D welding simulation substantially reduces the computation time of their analysis. Tsai et al. [1]

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investigated distortion mechanism and the effect of welding sequence on panel distortion using FEM based on inherent shrinkage method. Jung and Tsai [10] developed a plasticity-based distortion analysis and applied it to investigate the relationship between cumulative plastic strains and angular distortion in a fillet welded T-joint. Camilleri et al. [7] proposed a method to improve the computational efficiency of generic FEM-based distortion prediction technique; they modified the full transient thermo-elasto-plastic analysis into an uncoupled thermal, elasto-plastic and structural treatment. More recently, Deng et al. [11–14] conducted substantial research on predicting welding distortion of welded structures. They have effectively used thermal elastic-plastic finite element analysis (FEA) to predict welding distortion in small or medium welded structures. However, the authors concluded this method is inapplicable to simulate the welding distortion for large welded structures because of the large amount of computational time [15]. They proposed an elastic FEM to predict welding distortion in large structures considering both local shrinkage and gap. Murakawa et al. [16] extended the application of inherent strain theory and interface element formulation to compute distortion in thin plate structures. They developed a practical distortion prediction system to compute the accumulated distortion during the welding assembly process based on inherent strain theory and interface element formulation. All these works have provided important and useful information about weld induced distortion phenomena. However, the advantage of knowledge associated with distortion mechanism can be augmented tremendously if FE-based welding simulations are integrated with numerical optimization techniques. The integration of numerical optimization and welding simulation makes it possible to find optimum process parameters computationally with less time and cost.

Optimization of welding process to minimize weld-induced distortion in final structure has been an active research area for several decades. Two optimization approaches (i.e., experimental and computational) can be implemented to determine the optimum welding conditions. The first approach, where actual welding experiments are used, still dominates the published literature. An extensive review of experimental optimization of welding process can be found in Refs. [17,18]. In experimental optimization, DOE, Taguchi method, Evolutionary Algorithms and Artificial Neural Networks are the most frequently used methods.

In numerical optimization, computational models replace the expensive experimental evaluations. As such, design optimization can be conducted using computers rather than real experiments [19] for determining optimum structural sizing, shape and topology parameters in automotive and aerospace industry [20]. In welding industry, this approach is yet to be adopted in full scale. Very few research works have been conducted in the domain of welding optimization via integration of welding simulation and optimization algorithm. Kadivar et al. [21] linked Genetic Algorithms (GA) with a transient 2D FE model to determine optimum welding sequence of a circular pipe for minimization of distortion. Song et al. [22,23] investigated sensitivity of thermo-mechanical responses of welded joints to variation in material properties and optimized quasi-static weakly coupled thermo-elasto-plastic FE process for side heater design. Zhang et al. [24] and Ertas et al. [25] conducted FE based design optimization of spot welded structures under maximum fatigue life considerations.

Furthermore, most of the research conducted in this domain is devoted to investigate the influence of specific parameter variation on welding distortion and residual stress. Teng et al. [26] performed thermo-elasto-plastic analysis using FEM to evaluate residual stress and angular distortion in T-joint fillet welds and analyzed the effect of flange thickness, welding penetration depth and restraint condition on angular distortion. Gannon et al. [27] used FEM to study the influence of welding sequences on the distribution of residual stress and distortion generated when welding a flat-bar stiffener to a steel plate. Schnk et al. [28,29] studied the influence of the clamping time, the release time and the influence of clamp preheating on welding distortion.

It is believed that numerical design optimization has the potential to improve not only the manufacturing side of welding process but also the design side as well. The present study focuses on this topic. Specifically, the objective of this paper is to investigate the implication of numerical approach for design and optimization of industrial welding processes to minimize weld induced distortion in welded structures. The proposed computational approach is to employ a global optimization method through GA in conjunction with FEM for welding process design.

In this paper, a coupled thermo-elastic-plastic FE modeling approach is adopted for welding simulation. Two 3D FE models are developed for a plate lap joint specimen and an automotive structure specimen. The developed models are analyzed through FE-based thermo-mechanical welding simulations. The simulation results are presented for the temperature time history and distortion pattern of the structures. Since the ultimate objective of this paper is distortion minimization through numerical optimization, discussion of residual stress generation is beyond the scope of current study. Next, the models are integrated with optimization algorithm to establish an automated and iterative optimization system. The system is subsequently implemented to perform numerical optimization of the two test problems. Weld-induced distortion is set as objective function (that will be minimized) and minimum weld quality requirement in the form of sufficient weld fusion or melting is set as design constraint. The important parameters including welding speed, input current, arc voltage and welding direction or sequence, etc. are treated as design variables during the analysis and bounded by upper and lower limits. The optimization results are presented and discussed.

2. Numerical optimization framework

The proposed numerical design optimization system consists of four computer programs: (1) an optimization program, (2) a simulation input generation program, (3) a welding simulation program and (4) a simulation output evaluation program. The structure of the system is illustrated in Fig. 1. The four programs are integrated sequentially in a closed loop to establish the automatic and iterative optimization system.

The optimization program is the main controlling program of the system. It executes GA as optimization solver. It also takes important decisions of triggering other three programs when required and stopping the analysis by checking the stopping criteria in each iteration. Furthermore, it also keeps records of results, model information and constraint violations. MATLAB® GA solver is used as the optimization tool. A customized GA variant is developed by varying different default solver properties to meet the problem-specific requirements.

Welding simulation program is a commercial FE-based welding simulation program named simufact.welding©. It executes the welding simulation based on input file and stores the desired output results. It has the ability to simulate welding process models with multiple welding robots working at the same time or different times, flexibility to define or modify welding parameters, paths, directions and simple automatic batch running option useful for simulation-based numerical optimization.

In numerical optimization, the objective function and constraints are evaluated by numerical methods such as FEA. In such cases, the mapping from design variables to objective function and constraints is strictly implicit. Therefore, conversion of the original simulation model and its responses into standard mathematic function values recognizable by the optimization algorithm is