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Evaluation of Critical MMAW Welding Defects Using Computer Simulation in Industrial Manufacturing Systems

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Abstract

Manufacturing is one of the key sectors of any countries GDP and welding is one of the prime manufacturing processes of the manufacturing sector. Welding has several notable advantages over mechanical joining techniques, including higher structural integrity, design flexibility, and cost and weight lowers. Welded products/structures are subjected to serious issues of residual stresses and distortions. The performance and sturdiness of the welded structures are severely impacted by weld remaining strain and deformation. Welding distortions introduce sever problems in assembling of the welded structures and reduce its quality. In some cases the higher values of the distortions make the products useless in shape. Whereas, the residual stresses cause the premature failures of the structures during the service life. Hence there is a need for suitable a methodology to control/minimize the residual stresses and distortions. Accordingly, this study has proposed three distinct methods, namely pre- setting, restraining and auxiliary side heating to control distortion in butt welds of MMAW process. Similarly auxiliary side heating is also proposed to control the residual stresses. For pre-setting the workpieces with known magnitudes of angular distortion in the opposite direction, a linear regression model based on five independent process parameters/factors (current, welding speed, electrode diameter, number of passes and plate thickness) is developed to predict the magnitude of angular distortion. The efficiency of linear regression model is tested through confirmation tests and it is found that a variation of the predicted angular distortion is within 10%. Similar to the regression model, use of Finite Element Analysis (FEA) is made for predicting angular distortion and residual stresses.

Keywords: Finite element analysis, MMAW process, submerged Arc welding, shielded metal Arc welding, WRSD

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INTRODUCTION

Manufacturing is one of the key sectors of any country"s GDP and welding is one of the prime manufacturing processes of the manufacturing sector. Welding has several noteworthy advantages over mechanical joining procedures, including increased quality of construction, cost and weight reductions, and flexibility for design. Industries like automotive, ship manufacturing, aeroplane, heavy structures used in chemical industries and nuclear energy use welding very extensively. Varieties of materials are welded by different welding processes. The welding can be performed in manual, semi- automatic and automatic manner. The defects in welding like slag inclusions, undercutting, porosity, toe cracks, incomplete fusion, residual stresses and distortions have created some serious issues in the reliability of welded structures [1-3].

Challenges In Welding Technology

When it comes to the large number of variables and aspects can contribute to the final product, welds is one of the most complicated manufacturing operations.

Based on the use of heat input, type of filler material, the pressure used, and the welding processes may be classified as (AWS Handbook Vol-1, 2005) [4-7],

Arc Welding

- Carbon Arc Welding
- Manual Metal Arc Welding (MMAW) /Shielded Metal Arc Welding (SMAW)
- Submerged Arc Welding (SAW)
- Metal Inert Gas Welding (MIG, GMAW)
- Tungsten Inert Gas Arc Welding (TIG, GTAW)
- Electroslag Welding (ESW)
- Plasma Arc Welding (PAW)

Resistance Welding (RW)

- Spot Welding (RSW)
- Flash Welding (FW)
- Resistance Butt Welding (UW)
- Seam Welding (RSEW)

Gas Welding (GW)

- Oxyacetylene Welding (OAW)
- Oxyhydrogen Welding (OHW)
- Pressure Gas Welding (PGW)

Solid State Welding (SSW)

- Forge Welding (FOW)
- Cold Welding (CW)
- Friction Welding (FRW)
- Explosive Welding (EXW)
- Diffusion Welding (DFW)
- Ultrasonic Welding (USW)

Thermit Welding (TW)

Electron Beam Welding (EBW)

Laser Welding (LW)

Based on the use of the processes in all types of welding works, Manual Metal Arc Welding (MMAW) / Shielded Metal Arc Welding (SMAW) contributes as 42% share. Also in the structural works, structural steel is the most commonly used material (AWS Welding Handbook, Vol.-II). Due to many factors involved and complexity in the process nature, the MMAW welded structures are subjected to the following typical defects [8].

i. Incomplete fusion
ii. Porosity
iii. Under bead cracks
iv. Undercut

v. Slag inclusion
vi. Hot Cracks
vii. Distortions
viii. Residual stresses

In recent years, a variety of surveys have been carried out for various welding organizations to evaluate the vital requirements for the sector. Distortion and residual stresses rank first or second among the steel a process of heat community's concerns in each and every poll that has been completed [9,10].

Over the time, several efforts have been made to eliminate the welding defects like lack of fusion, porosity, bead cracks, undercuts, hydrogen inclusion etc. But, critical defects such as welding residual stresses and distortions are still posing challenges to design and welding engineers. Welding Residual Stresses and Distortions (WRSD) changes with type of welding processes, the geometry of the weld joint, type of material used and the welding processes parameters. Hence one universal solution cannot be found which will be applicable to all combinations of materials and welding processes. The extremely localized temperature variations produced during the welding process result in high [11] extensive deformation or distortion of the structures to be welded, as well as residual stresses on the order of elasticity of the material within and outside the weld site.

Residual deformations introduce sever problems in assembling of the welded structures and reduce its quality. In some cases, the higher values of the distortion make the products useless in shape. Whereas, the residual stresses cause the premature failures of the structures during the service life. The welding induced distortions and residual stresses have become the critical issue in the welding industry and needs to be tackled effectively. Also the literature doesn"t support the studies carried out in the area of residual stresses and distortions using SMAW/MMAW process [12-15].

Therefore, it was felt that there is a need for assessing weld induced residual stresses and deformations especially in case of MMAW. Also development of some mitigation techniques for residual stresses and deformations will be helpful to design and welding engineers. Such mitigation techniques will ensure intended in-service use of the welded structures with improved dimensional accuracy and structural reliability.

Welding Residual Stresses and Distortions

The stresses that a body would come across if all external loads and constraints were eliminated are known as stresses that remain. Internal stress, original stress, intrinsic stress, response stress, and locked-in stress are some of the technical words used in research to describe residual stress. At certain stages of their life cycle, mechanical gadgets experience residual stresses, which are often undesirable. The majority of residual stresses in engineering designs are created during their manufacturing stage, which includes the techniques of casting, forging, shaping, and welding the metal sheet [16].

Local plastic deformations brought about by a local temperatures history that consists of a quick heating and cooling phase result in welding residual stresses in a structure. The weld component is fused locally and heated significantly more than the surrounding area during the welding process. Fire causes the material to expand. Thermal pressures result from the adjacent colder area limiting this expansion. The elasticity limit, which is reduced at higher temperatures, is partially exceeded via thermal stresses.

As a result, the region of welding is hot-compressed plastically. It creates tensile residual stress after cooling out too short, too narrow, or too tiny in comparison to the surrounding region, whereas adjacent regions experience compressive residual stresses to preserve the state of equilibrium [17].

High longitudinal strains are created in the core of the plate as a result of the heating and cooling cycles as well as restraints from the surrounding materials. The longitudinal stress progressively reduces with farther distance from the weld center. According to the equilibrium condition of the residual stresses, the longitudinal stress decreases to zero along the longitudinal direction while changing to compressive along the transverse path [18-20]. Likewise, transverse residual stress is seen with a lesser amplitude and slight shifts in the longitudinal stress concentration (Figure 1).

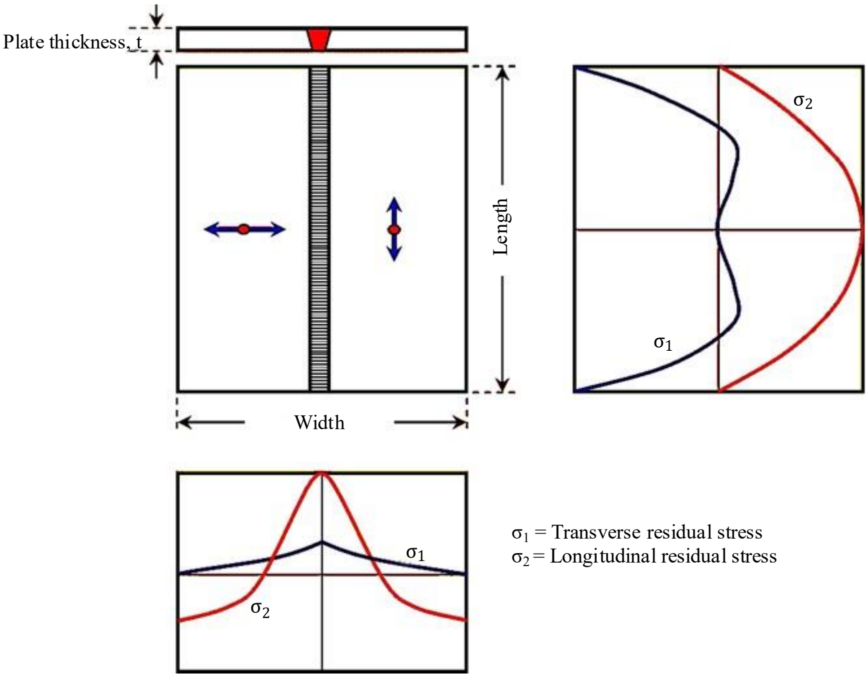

Figure 1. Schematic view of residual stresses in welded rectangular plate.

LITERATURE SURVEY

The end of the last century was characterized by the formation of a powerful arsenal of welding technologies for producing permanent joints in almost any structural (metallic, non-metallic, composite and organic) materials with the thickness in the range from micrometres to meters in the conditions of the earth's atmosphere, space vacuum and zero gravity, and also water (underwater). Fusion welding is one of the most versatile and widely used manufacturing processes for the fabrication of complex, built-up and metallic structures (AWS Weld Handbook, Vol-II,) Road, rail, and marine vehicles, together with fluid storage applications, benefit particularly from the design opportunity to fabricate continuously connected lightweight structures from sheet, plate, and section stock. The design threat in using welding is that structures tend to distort from their planned size and shape and also acquire high magnitude residual stress fields. These are problematic in a fatigue-loaded context and may also induce buckling behaviour. In order to maximize the stiffness-to-weight ratio with such constructions, these issues worsen since material thickness is decreased and joint frequency is addressed [21-25].

An excellent overview of the formulation of residual stresses and weld distortions has been presented in earlier studies. Other research has highlighted the adverse effects of welding distortion and residual stresses on structural performance. This fact is revealed by a large number of papers in the literature also. The residual stresses and bends in welding are controlled in a number of ways. In order to reduce angular distortions in single-pass deep arc welded (SAW) butt joints.

As a part of the present research, literature review covering 187 articles published is carried out. This review helped a great deal to understand the status of Welding Residual Stresses and Distortions (WRSD) better, to classify the literature according to topical areas and to identify and figure out a number of modelling issues. It also gives an insight into predicting and controlling issues of WRSD, the major contributions and the limitations of the past research. The major part of this paper caters to identification of the various issues that may be of interest to various researchers working on WRSD. An attempt is made in this paper to present the silent features of various research studies carried out on WRSD so far [26].

This is how the paper is designed. A synopsis of the evolution of welding technology can be read in section 2.2.

A classification scheme devised for encapsulating the literature on welding process modelling and WRSD is described in the next section, along with an overview of the literature pertaining to each category in the following sections. Section 2.7 presents the limitations of the previous research and the potential research areas for the future pursuit, followed by a brief conclusion in the last section [27-30].

Historical Development

As early as 1000 BC, forge welding was being employed to create weapons, marking the beginning of welding expertise. The electric fusion procedure was first reported to be used in Germany in 1782. Nevertheless, the majority of the texts indicate that the electric arc welding method begun in late nineteenth century. A brief history of the development in welding processes is depicted in Figure 2.

(1801)
Discovery of electric arc by Sir Humphrey Devy

↓

(1860-1865)
Wilde first intentionally joined me a by electric welding in early 1860 and was granted a patent in 1865 for his work

↓

(1885)
De Meritens obtained patent of electric arc welding process in England using carbon electrode

↓

(1886)
E. Thomson obtained a patent on resistance welding

↓

(1887)
Benardos, a Russian scientist, got first patent of electric arc welding for slightly different equipment then by De Meritens

↓

(1891)
Another Russian N. Slavianoff replaced carbon electrode with a metal electrode and obtained a patent on metal welding

↓

(1908)
Kjellberg, a Swedish, got a patent for coated welding electrode

↓

(1908-1940)
Development in joining process continued and major welding process including oxyacetylene, MMAW (manual metal arc welding), and GMAW (gas metal arc welding) processes were successfully implemented

↓

(1960)
Advanced welding types such as electron Beam, Laser and Ultrasonic welding were developed between 1950-1960

↓

(2000)
Most recent development is magnetic pulse

Figure 2. Brief history of development phases in welding processes.

METHODOLOGY

In this paper a brief introduction is given to the various tools and techniques, such as regression analysis based on statistical design of experiments (DoE) and Finite element modelling used to model the welding process. The paper is divided into two parts, first part gives the detailed steps of DoE and whereas procedure used for element modelling is provided in part two.

Statistical Regression Analysis

The study of the relationship involving two or more variables is known as statistical regression analysis, and employs the least squares approach to build the empirical equation involving input-output parameters. It is also the most widely used statistical modeling method that was created compared to experimental data. Since the two-level fully factorial design is one of the most often used experimental designs, it is utilized as well in the current investigation. The following are the various methods used for analysis.

1. Determining the top and bottom limits of the critical process oversight variables.
2. Creating the design array (experimental statistical research).
3. Recording the response data and carrying out the trials in keeping with the concept matrix.
4. Creating the models or figuring out the pair of regression coefficients.
5. Verifying the gear's suitability.
6. Determining the ultimate models and testing the accuracy of the coefficients.
7. Outlining its direct and indirect implications.
8. Analysis of Results.

Process Modeling for Finite Element Analysis

In this section the detailed FE modelling of process is described. The thermo mechanical analysis is performed for predicting temperature distributions and distortions are presented in the two subsequent sections.

During welding, the weld pool melts and solidifies within a short period of time. The heat transfer to the work piece is transient in nature and the corresponding structural effect is nonlinear. With the advancement of computational power, the finite element methods have become popular for simulating the welding process. While performing welding simulation for predicting temperature distributions, residual stresses and distortions, the complex weld pool fluid dynamics is not generally considered. Instead, while doing finite element analysis of welding process the heat transfer is considered to be governed by Fourier‟s conduction equation and the temperature history attained by each node is provided as an input in structural analysis with appropriate material model for predicting residual stresses and distortions.

In the present work, for predicting the temperature distributions, thermal stresses and distortions, transient thermal analysis have been carried out using three-dimensional finite element method.

REGRESSION MODELING FOR ANGULAR DISTORTION

The experimental investigations provide valuable insights into the process of the arc welding. Furthermore, traditional trial and error approach based on costly and time- consuming welding exercise may not result in sound welds due to the large number of welding process parameters. Extending the application to the arc welding process to the shop floor level with dependability, cost effectiveness, and compatible control approaches is essential for setting the process parameters. One helpful tool for managing manufacturing processes is the Design of Experiments (DoE). When doing an experiment in DOE, we actively alter a process variable or factor while maintaining the same values for the other variables to see how the change affects one or more response variables (s). A designed execution of viable experiments under several naturally varying variables is known as statistical design of investigation.

Such experiments can provide data that will enable the manufacturers to identify the causes of performance and to improve the product quality. Properly designed and executed experiments will generate precise data, while using substantially a fewer experimental runs compared to the alternative approaches. They will lead to the results that can be interpreted using relatively simple statistical techniques. Factorial design allows varying all the factors at once, in which experiments are conducted for all combinations of levels, for all the factors. Testing will show the consequences of one variable when the other elements change in such a research. The biggest benefit of DoE is that it offers a rigorous mathematical framework for concurrently tweaking all relevant elements in a limited number of experimental run.

Two-level design is one of the most popular experimental designs, which is used in this study to precisely predict the stress fields and distortion patterns (transient and residual), which is of critical importance to ensure the in-service structural integrity of the welded structures.

Process Modeling

During experimentation, some (but not all) of the distinct and/or continuous input elements that make up a process can be changed or manipulated. It is necessary to represent what happens (output) as a function of the input variables. In most cases, it is assumed that the output response is continuous. Once an experimental design has been completed and the investigation has been carried out, the experimental data is utilized to determine what aspects have the greatest impact on the outcome and to develop an empirical (approximation) model connecting the output and inputs. Fitting a polynomial model to the data is usually used to do this.

From the literature, five independent parameters affecting the angular distortion are considered for modelling the SMAW process. The parameters considered are, welding current, and the number of passes, plate thickness, and weld speed and electrode diameter.

Data Collection for Process Modeling

Input/output data related to SMAW welding process is collected according to the planning of full factorial design of experiments, using standard SMAW welding set up.

Determining the value of the key process control components

Both inputs and outputs are taken into consideration in the identification of significant process components.

For example, factors and response. After consulting relevant literature, the list of all welding process components, including their upper and lower levels of settings, is first determined by real trial. Each of the elements on the list was thoroughly examined to see whether or not its components were independent.

Table 1. Factors and their levels –SMAW process

S.N.	Factor	Notation	Unit	Level	Value
1	Current	A	Amp	-1 +1	110 150
2	Number of Passes	B	--	-1 +1	3 7
3	Welding Speed	C	mm/sec	-1 +1	1.5 3
4	Electrode Diameter	D	mm	-1 +1	3.15 4
5	Plate Thickness	E	mm	-1 +1	12 16

Then it is confirmed that, angular distortion depends on a number of process parameters- welding speed, welding current, welding electrode diameter, plate thickness, and number of weld passes. Before planning the experiment, two levels (maximum and minimum values) for each independent process parameters have been identified as shown in Table 1.

CONCLUSION

A large number of manufacturing industries worldwide use various types of welding processes. In today‟s highly competitive market, the traditional ways of producing weld structures are no longer seen as an attractive proposition by the manufactures in search of some innovative techniques to improve their responsiveness. The Welding Residual Stresses and Distortions (WRSD) has become a critical issue to produce safe and strong weld structures. Complete removal of WRSD from weld structures is practically impossible. However, they can be reduced in magnitudes by using proper controlling methods. The current study looked into some of the techniques used to deal with WRSD. This document comprises a short that summarizes the study which has been done.

More specifically, the purpose of this paper is to accomplish the following:
1. To summarise the details of the research work carried out and present it in a consolidated form.
2. To highlight the contributions and important findings of the present research.
3. To provide an overview of the possible limitations of the present work.
4. To suggest potential problems/extensions for further research.

It provides the introduction to various welding defects and their effects on the weld structures. Development of „WRSD‟ concept and their criticality to weld structures has been highlighted. The motivation for the present research related to„WRSD‟ and the scope of the research has been outlined in this paper.

It provides an account of the literature on WRSD published in last 20 years. A brief introduction to the historical development of welding technology has been provided and the literature has been classified according to the different issues related to WRSD. This includes literature on general perspectives of WRSD, basics of WRSD, process modelling of welding process, various methods used for controlling of WRSD. These methods include preventive methods, in-process controlling methods and post weld methods.

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