CHAPTER 8

CONCLUSIONS & RECOMMENDATIONS

Chapter's summary and conclusion is presented at the end of each chapter pertaining to particular studies conducted within the corresponding chapter. The seven chapters of this manuscript comprehensively dealt with the contemporary need of optimizing the welding process with the use of hybrid technique of experimental, simulation, analysis, optimization and artificial intelligence tools. Summarized concluding remarks of chapters are presented in the following to draw some recommendations and proposals for future research work.

The first chapter was of introductory nature and provided the basics of welding technology, arc welding, welding variables, weld induced residual stresses and distortions in thin walled structures, artificial intelligence, expert system, challenges in welding domain, scope and objectives of the research, research methodology and organization of this dissertation. Chapter 2 covered the literature review related to welding technology and issues, welding process and optimization, welding simulation (computational weld mechanics) including computational and experimental work pertaining to circumferential welding, measurement of residual stresses including hole drilling residual stress measurements, application of artificial intelligence to manufacturing and welding along with the AI tools limitations. Chapters 3 – 5 utilized the statistically and FEM powered experimental techniques of studying the TIG welding process. The main targets of the research have been the identification of influential parameters upon welding performance measures and the quantification of their effects. The chapter's summary detail is as:

Chapter 3 included the welding experiments for analyzing and optimizing the TIG welding variable parameters (welding current, welding voltage, welding speed and application of Ar trailing) and their effect and significant on response (weld strength, residual stresses and distortion) on thin plates of HSLA steel of thicknesses 3 to 5 mm by applying DOE, ANOVA and numerical optimization according to desirability statistical techniques by using Design-Expert® and MINITAB®. Chapter 4 presented the welding simulations containing analytical model, FE formulation, heat models, material model, simulation approach in ANSYS, details of welding induced residual (axial & hoop) stresses fields and distortions (axial & radial shrinkages) and covered the details of experiments performed for the FE models (thermal and structural) validation. Chapter 5 included the detail of virtual design of experiments (DOE) by utilizing the simulations and optimization of welding parameters for circumferential welding of thin walled shell structure of high strength low alloy steel of thicknesses 3 to 5 mm and covered the effects of welding process parameters (weld speed and heat input), geometric parameters (cylinder thickness), root opening and tack weld orientations on residual stresses. It also included the detail of analysis and optimization of process parameters for linear and circumferential welding comprising nine variables i.e. six input variables (welding current, welding voltage, welding speed, material thickness, trailing and weld type) and three output variables (weld strength, distortion and residual stresses).

Chapters 6 and 7 dealt with application of expert system tool, employing fuzzy reasoning mechanism, for finding the most suitable values of TIG welding parameters for accomplishment of the objectives of maximizing weld strength and minimizing residual stresses & distortion. The ES was also made capable of predicting the values of performance measures at different combinations of input parameters. Chapter 6 presented a static design of the expert system tool, with much emphasis upon its configuration, constituents, and procedure of operation. The expert system provided promising results and proved beneficial within its limited scope of application. Chapter 7 continued with these basics and presented high level automation for self-development of the expert system. The methodology of self-development included automatic generation of fuzzy sets, prediction rules, optimization rules, updating of interface, and more with two examples based on knowledge base levels.

Following two sections will provide the main conclusions drawn from the research work presented and the recommendations for its practical application at industrial level and also some directions for future research.

8.1 Conclusions

The conclusive points related to the welding of thin walled structures of high strength low alloy (HSLA) steel and optimization of the TIG welding process using expert system tool developed after performing experiments (actual and virtual DOE based on simulation) and statistical optimization, have been categorized under following sub-headings of welding induced stresses & distortion and weld strength, effect of welding process parameters, the expert system and the researcher's main contributions from the present research work:

8.1.1 Welding Induced Stresses & Distortions and Weld Strength

1. Weld strength increases with the reduction of residual stresses and distortion and decreases with the increase of residual stresses and distortion.
2. Weld strength increases with low values of welding current and voltage and high value of welding speed with the application of trailing according to the material thickness. Weld strength decreases above or below the optimal process parameters.
3. Residual stresses and distortion reduces with low values of welding current and voltage and high value of welding speed with the application of trailing according to the material thickness and increases with high values of welding current and voltage and low values of welding speed without the trailing application respectively.
4. From the comparison of responses (distortion and residual stresses), the results show that the low distorted samples give the low residual stresses and vice versa respectively.
5. In circumferential welding, high tensile and compressive axial residual stresses are observed on the thin walled cylinder inner and outer surfaces along and near the weld line respectively. Whereas, away from the weld line, compressive and tensile axial residual stresses observed on inner and outer surfaces respectively.
6. In circumferential welding near the weld line, the maximum axial and radial deflection is observed. Whereas, the axial shrinkage reduces continuously away from the weld line to a minimum or zero level. Similarly, in linear welding, the maximum deflection is observed along the weld line at about the centre of plate length and it reduces to minimum to the ends of plates both in longitudinal and axial direction.

8.1.2 Effect of Welding Process Parameters

1. Heat input per unit volume (i.e. welding current, welding voltage and welding speed) to the welded structures is the main influential parameter for the occurrence and control of residual stress & distortion levels. Increase in the value directly enhances the residual stress and distortion levels resulting reduction in the weld strength.
2. In parametric studies, the welding current with large parametric range is the most influential parameter with respect to thickness of sheets/cylinders besides other parameters.
3. Generally, plate thickness and cylinder wall thickness has negative effects on the magnitude of residual stress and distortion fields. Increased wall thickness results in reduction of distortion and residual stresses.
4. The increase in plate thickness from 30% to 65% (i.e. 3-5 mm thickness) result decrease in distortion about 15% to 30% and 20% to 25% in residual stresses respectively. The range of increase in weld strength is 10-15% (i.e. 690-790 MPa) only whereas the reduction in distortion is three times (2.2 - 7.2 mm) and two times in residual stresses (335 – 608 MPa) respectively.
5. Similarly, the increase in cylinder thickness from 30% to 65% (i.e. 3-5 mm thickness) result decrease in distortion about 25% to 45% and 30% to 35% in residual stresses respectively. Whereas, the reduction in distortion is three times (1.2 – 3.9 mm) and in residual stresses (268 – 577 MPa) is two times respectively.
6. The application of Ar trailing has negative effects on the magnitude of residual stress & distortion levels and positive effects on weld strength. Application of trailing results in reduction up to 15% of residual stresses and distortion accordingly.
7. The residual stresses and distortion of TIG welding are lower in circumferential welds than in linear welds at same parameters for same thicknesses of HSLA steel thin walled structures.

8.1.3 The Expert System

1. In this research work, expert system tool has been successfully applied for optimization of parameters and prediction of performance measures related to TIG welding process of thin walled HSLA steel structures domain. The optimization of parameters is performed based upon objective(s) of maximization and/or minimization of certain combination of performance measures. At the completion of optimization process the finalized settings of input variables are used to predict the values of the performance measures. This expert system tool possesses high potentials for reducing production cost, cutting down lead-time, and improving the product quality at expense of few seconds that the expert system would take to process.

2. The uncertainty and vagueness in relationship between inputs and outputs of the welding process can be effectively tackled by utilization of fuzzy logic. In this way, the knowledge related to the welding process can be represented by sets of fuzzy rules. The fuzzy rule-base can be optimized for maximum accuracy by applying simulated annealing algorithm.

3. The important feature of this research work is the success in imparting self-developing abilities to the fuzzy expert system for welding process optimization. The presented expert system is capable of auto-managing data, self-developing fuzzy sets, self-generating rule-base, automatically updating expert system interface, and providing conflict resolution among contradictory rules. These abilities make the expert system exceedingly adaptable to continuously changing high-tech industrial environments, without need of human intervention in the field of welding of thin walled structures.

4. A data structure, named as doubly linked list, was introduced for handling the data related to rules for process decision making. This linked list provides efficient way of managing the storage and the processing of data along with allocation of just minute portion of memory.

5. Simulation and optimization of the welding process is becoming an efficient and effective approach to achieve high quality weld products with reduced residual stress and distortion. An expert system, EXWeldHSLASteel, based on experiments for linear welding as well as virtual experiments by performing FEA and simulation of welding process with experimental validation for circumferential welding, has developed to predict welding distortion and residual stress in thin walled structures. Due to its accuracy, computation speed and time, EXWeldHSLASteel can be applied in welding process and product design by engineers on shop floor very easily with minimum know-how.

6. Optimization using expert system, on the other hand, allows engineer to reach optimized process parameters much more efficiently and without hazardous impact to the environment by using the simulation results in real welding process of thin walled cylinders with the quality concept of “do it right at first time”. By using developed ES, the time to have optimized parameters for required response has reduced with cost avoidance and eliminates associated waste, rework, reduced cost of operation, reduced scrap and consumables and energy, as well as fumes and emissions.

7. Usually, an actual welding experiment sample of HSLA steel sheet of 3x260x500 mm (sheet cutting, preparation and welding) including testing (weld strength samples or residual stresses measurement and distortion) related to thin walled structures consume time 3-4 days with use of a good experimental setup and cost of $200 whereas in case of circumferential welding (3 x Ø300 x 300 mm), the cost would be two times. However, in optimization following DOE, the number of experiments required depends upon the number of factors and their levels. The sixteen experiments are required for only four factors with two levels for a full factorial design and time & cost would be sixteen times as mentioned above for only one material thickness. Whereas each simulation time (based on the element topology, thermal & structural boundary conditions, material model, time of load-steps and the corresponding sub-steps etc) required after developing three dimensional FE models is 7-8 hrs for plate and 20-24 hrs for circumferential welding for both thermal and structural analysis with the use of an IBM compatible PENTIUM-IV 2.4 GHz

computing machine with 6 GB RAM on a 64 bit platform for computational and data storage with extra hard disks whereas the size of one result file is 108 GB. The developed tool for optimization of welding process parameters and prediction of responses consumes only few seconds to give desired solution before the start of process on shop floor and this may be used in shipbuilding, aerospace and nuclear industries, oil and gas engineering and in other areas before the manufacturing of structural elements.

8.1.4 Researcher's Main Contributions from the present Research Work

1. A fuzzy expert sytem (EXWeldHSLASteel) development for the optimization and prediction of TIG welding process (linear and circumferrential welding) of thin walled HSLA steel strucures.

2. Imparting self-developing capabilities for self-learning, self-correcting and self-expanding to the developed expert system (EXWeldHSLASteel) for the optimization and prediction of TIG welding process of thin walled HSLA steel strucures.

3. Development of 3D fully parametric FE model with experimental validation for circumferrential welding of thin walled HSLA steel.

4. Development of empirical models for TIG welding process both for linear and circumferrential welds of HSLA steel for maximization of weld strength and minimization of distortions/residual stresses or as per desireability.

8.2 The Recommendations

The previous section outlines important conclusions that provide the directives for increasing the viability of thin walled structure welding process with optimized parameters at industrial level. The major area of concern in welding domain is the optimization of welding process of thin walled shell structure of high strength low alloy steel to minimize the residual stresses and distortion for improvement of weld mechanical properties and production rate by using expert system. This research work has considerably contributed towards this requirement, related to TIG welding process of thin walled steel structure for linear and circumferential welding using hybrid technique as experimental and simulation with experimental validation with statistical analysis for numerical optimization and developing expert system. The vital recommendation, in this regard, is to use the parameters of welding resulting low input heat (low current, low voltage and high speed) with application of trailing with respect to material thicknesses for the maximum weld strength and minimum residual stresses and distortion in thin walled structures of HSLA steel for linear and circumferential welding.

It is strongly recommended to utilize the presented expert system for deciding the values of important welding parameters as per objective before the start of actual welding process on shop floor. The user should be absolutely clear about the nature and requirements of any given TIG welding process, e.g., the setting parameters, fixed parameters, geometric parameters, structural boundary conditions etc. Finalize the set of objectives with corresponding values of weight-age and input this information to expert system along with the data related to the fixed conditions. For the best possible simultaneous achievement of these requirements, the expert system will provide the suggestions of most suitable values for the parameters or response predictions under control of the user. Presently, the ES covers the six input parameters and three responses with the capability of automatic enhancement of the scope upon feeding the experimental data after further experimentation at any stage.

Today, knowledge management is an emerging area which is gaining interest and importance by both industry and public sectors. For knowledge organizations, knowledge management will play a key role towards the success of transforming individual (expert) knowledge into organizational knowledge. Artificial intelligence is one of the key fields for developing and advancing the field of knowledge management and many knowledge management practitioners and theorists are overlooking this field [241]. This research work related to artificial intelligence by developing expert system in the domain of welding for optimizing welding process of thin walled structure will also serve the newly emerging field of knowledge management.

8.2.1 Proposals for Future Research

1. The comprehensive investigation and optimization of welding process can also be targeted utilizing other welding techniques like EBW, Laser, Plasma or hybrid. The various performance measures can then be compared with those achieved.

2. The developed FE model for TIG welding can also be applied to other welding processes as MIG, Plasma, EBW, or Laser etc. The model will require to be amended according to the nature and requirements of the process and further be used for virtual DOE and optimization.

3. The self-developing expert system can also be applied to other welding processes as well, like EBW, Laser, Plasma or Hybrid etc. The algorithm will require to be modified according to the nature and requirements of the process.

4. The scope and utilization of self-developing expert system for welding process can be extended to other materials, thicknesses and sizes of plates and cylinders etc. The algorithm, FE model and DOE for ANOVA results will require to be modified according to the nature and requirements of the process.

5. The self-developing expert system can also be applied to other manufacturing processes for thin walled structures as well, like heat treatment process, spinning, grinding, and metal forming etc. The algorithm will require to be modified according to the nature and requirements of the process.

6. The optimization of any manufacturing process can also be explored using Hybrid AI systems, for example the combination of expert system and artificial neural networks or FEM simulation with development of auto interfacing to each other as well as online optimization of process.