Advanced Welding Techniques
Advanced Welding Techniques
Holistic View with Design Perspectives
Preface

Welding technology has traversed through intense technological evolutions and transformations during the last four decades. The degree of revolution is gargantuan as its application is spreading to multiple co-ordinates of product developments. At present, it appears that welding technology is polarized into two streams: mechanical and metallurgy. The focus on design and power sources is in evanesce as observed from the perception of the welders, trainers and practitioners. Design defines the characteristics that a solution needs to meet the desired success. Design imparts the logical structure to the engineering products for its reliability and performance.

Our interactions with scholars, welding trainers, students and academicians participating in various programs from time to time during the process of preparation of this book has made us believe that there is an inadequacy with the knowledge of design although it is an integral component of welding. The expertise in the field of design for welding is sporadic while many engineers attending to technical glitches on welding of structures to offer solutions are facing conundrum. It is in this context, a need was felt to provide all the basic information on design for welding to the interested groups for their day to day teaching, learning, practicing and subsequent studies. Accordingly, a series of reference materials was initiated by espousing the simple to complex principle: starting with terminology introduction. The sequence of chapters is organized in such a way that the first chapter is conceptually interlinked to understand the second more effectively and so on.

The framework is reflected in the following sequence of production: Introduction to welding processes, design requirements, prominence of design, case studies presenting structural defacements due to inappropriate design, comprehensive surveys on welding processes selected from various process categories, design calculations to be adopted for specific applications and sample calculations. The following objectives were deliberated while initiating this volume: (i) disseminate information and promote in depth knowledge percolation on design vitalities for welding, (ii) awareness creation and motivation to learners to focus on unpolarized streams governing welding which are marginalized in recent times, (iii) to facilitate
idea convergence on wide range of experiences/circumstances/problems and topics with adequate insights into up-to-date knowledge.

Though encyclopaedic coverage of this type of work is non-viable in every facet, the provision for scope widening is guaranteed such that information’s reported in literatures till 2018 are accommodated for the benefit of learners irrespective of their discipline. A portion of descriptions encompassed, here, are mostly abstracted from the originals. Nevertheless, in few cases, they are acquired only from secondary sources as original were not immediately available. Complex experimental procedures and solutions are presented with minor alterations to complement the objectives or retained as it is to convey with the same technical flavour. Each entry made in this volume is scrutinized to ascertain the intent of benefiting the users to get an overall idea of the descriptions in a quick glance. This book will serve as a linchpin to all those involved in welding science by imparting ample insights to explore this magnificent terrain.

Bengaluru, India

Mukti Chaturvedi

S. Arungalai Vendan
Contents

1 Welding: An Overview ........................................ 1
   1.1 Welding Techniques—Classification ...................... 1
   1.2 Resistance Welding ........................................... 2
      1.2.1 Process Variations ........................................ 2
      1.2.2 Preferred Materials for RSW .......................... 4
      1.2.3 Design Considerations .................................. 5
      1.2.4 Typical Applications of Resistance Weld Variants ...... 5
   1.3 Solid-State Welding ........................................... 5
      1.3.1 Process Variations ........................................ 6
      1.3.2 Preferred Materials for Solid-State Welding .......... 7
      1.3.3 Design Considerations .................................. 8
      1.3.4 Typical Applications .................................... 8
   1.4 Arc Welding ................................................... 8
      1.4.1 Process Variations ........................................ 9
      1.4.2 Preferred Materials for Arc Welding .................. 10
      1.4.3 Design Considerations .................................. 10
      1.4.4 Typical Applications .................................... 11
   1.5 High-Energy Density Welding ............................... 11
      1.5.1 Process Variations ........................................ 11
      1.5.2 Preferred Materials for Laser Beam Welding ........... 13
      1.5.3 Design Considerations .................................. 13
      1.5.4 Typical Applications .................................... 14
   1.6 Conspectus of Welding Techniques ......................... 14
   References ....................................................... 15

2 Decision Making in Welding Design .......................... 17
   2.1 Introduction .................................................. 17
   2.2 Standards and Specifications ............................... 18
   2.3 Factors Affecting Design .................................... 18
   2.4 Expected Weld Characteristics ............................. 19
      2.4.1 Example: Design Requirements—For Spot Welding ...... 20
4.7 Sample Design Data, Process Parameters, and Design Calculations ........................................ 77
4.7.1 Welding Amperage Selection ........................................ 79
4.7.2 Sample Design Calculations ........................................ 80
4.7.3 Sample Data for Various Materials and Applications ........ 85
4.8 Conspectus of Design in Tungsten Inert Gas Welding ........ 87
References ........................................................................ 87

5 Laser Beam Welding and Design ........................................ 89
5.1 Introduction ..................................................................... 89
5.2 Process Applications ..................................................... 92
5.3 Compatible Materials .................................................... 92
5.4 Fundamentals of Laser Beam Weld Process ....................... 94
5.5 Laser Welding Machine Details ....................................... 94
5.6 Literature Survey ........................................................... 97
5.7 Sample Design Data, Process Parameters, and Design Calculations ........................................ 102
5.7.1 Design Sequence in Welding ....................................... 103
5.7.2 Approach I: Heat Affected Zone Considerations .......... 104
5.7.3 Approach II: Thermal Gradients with Varying Thickness ......................................................... 106
5.7.4 Approach III: Use of Energy-Based Model for Weld Depth Determination ..................................... 109
5.7.5 Approach IV: Use of Process Optimization Techniques ......................................................... 113
5.7.6 Sample Parameter Values ........................................... 115
5.7.7 Case Study for Selection of Laser Source .................... 119
5.7.8 Laser Welding Parameters .......................................... 122
5.7.9 Power Supply for Laser Machine ............................... 125
5.8 Conspectus of Design Studies in Laser Beam Welding ....... 129
References ........................................................................ 130

6 Friction Stir Welding and Design ........................................ 133
6.1 Introduction ..................................................................... 133
6.2 Process Applications ..................................................... 137
6.3 Compatible Materials .................................................... 138
6.4 Fundamentals of Friction Stir Weld Process ....................... 138
6.4.1 Heat Generation Analysis ........................................ 139
6.5 Friction Stir Welding Machine Details ............................. 142
6.6 Literature Survey ........................................................... 147
6.7 Sample Design Data, Process Parameters & Design Calculations ........................................ 153
6.7.1 Sample Data I .......................................................... 154
6.7.2 Design Calculations– Case Study .............................. 157
6.8 Conspectus of Design Studies in Friction Stir Welding ....... 164
References ........................................................................ 164
7 Magnetic Pulse Welding and Design .................................................. 167
  7.1 Introduction ........................................................................ 167
  7.2 Process Applications ............................................................ 170
  7.3 Compatible Materials ............................................................. 170
  7.4 Fundamentals of Magnetic Pulse Weld Process ......................... 170
  7.5 Magnetic Pulse Welding Machine Details .................................. 173
  7.6 Literature Survey ............................................................... 175
  7.7 Sample Design Data, Process Parameters, and Design Calculations .................................................. 180
    7.7.1 Design Calculations I ..................................................... 181
    7.7.2 Design Calculations II ................................................... 185
    7.7.3 Design Case Study III .................................................. 187
    7.7.4 Design Case Study IV ................................................... 189
    7.7.5 Design Calculations—Weldability Curve .......................... 191
    7.7.6 MPW: Electrical Model ................................................. 193
  7.8 Conspectus of Design Studies in Magnetic Pulse Welding .......... 196
References ................................................................................. 196
About the Authors

Mukti Chaturvedi is Assistant Professor in the School of Engineering at Dayananda Sagar University. She graduated with electrical engineering and did postgraduation in VLSI and Embedded Systems. During her graduation, she cultivated interest in power electronics and control system. She instituted various projects pertinent to power electronics, control system and electrical drives. Relentless efforts resulted in technical acquaintance with several concepts from versatile fields encompassing manufacturing, especially welding. With the opportunity to work in various industries, she has got the exposure to different domains of work. The current role as a faculty member provided ample scope for reading, learning, teaching and performing interesting experimentations on different subjects moulding her to acquire multifaceted outlook. This led her to identify welding technology to be her area for Ph.D. which constitutes power source design, configurations and process understanding, automations through programming for control and converter modules.

S. Arungalai Vendan is presently Associate Professor in the School of Engineering at Dayananda Sagar University, Bangalore. Previously, he was a faculty member in Industrial Automation and Instrumentation Division at VIT Vellore. He undertook research on advanced welding processes since 2006. He received his Ph.D. from the National Institute of Technology, Tiruchirappalli, India, in 2010. He has received several fellowships and awards for his technical contributions from various government and private organizations. He has successfully completed numerous government-funded research projects and industrial consultancy tasks and has published more than 80 research papers in reputed international journals and conference proceedings. He has associations with top manufacturing industries and research and development centres under various capacities. His research interest mainly focuses on the interdisciplinary science underlying welding which includes the confluence of terminologies from electrical/mechanical/metallurgical materials and magnetic streams.
List of Figures

Fig. 1.1 Classification of welding processes ....................... 2
Fig. 1.2 Schematic and weld schedule of RSW .................... 3
Fig. 1.3 Types of Resistance Welding Methods .................... 3
Fig. 1.4 Process variations of solid-state weld ..................... 6
Fig. 1.5 Schematic of arc welding .............................. 9
Fig. 1.6 Schematic of non-consumable electrode arc welding ...... 10
Fig. 1.7 Schematic of laser beam welding ........................ 12
Fig. 1.8 Components of Nd:YAG Laser .......................... 12
Fig. 1.9 a Fiber laser mechanism, b fiber ......................... 13
Fig. 2.1 Plates of different thickness ................................ 20
Fig. 2.2 Schematic showing distance of form to the center of spot weld ........................................ 21
Fig. 2.3 Schematic for overlap region in spot weld ................. 21
Fig. 2.4 Part of lorry having weld defect .......................... 28
Fig. 2.5 Weld joint between carbon steel piping and oil tank ......... 29
Fig. 2.6 Arrangement of the core of Chernobyl unit 4 ............... 31
Fig. 2.7 Annulurs in an aircraft engine ........................... 32
Fig. 3.1 Schematic of RSW circuit .............................. 36
Fig. 3.2 Cross section of RSW nugget .............................. 37
Fig. 3.3 Effect of voltage on load bearing capacity .................. 38
Fig. 3.4 Spot weld lobe curve ..................................... 38
Fig. 3.5 Various resistances and theoretical dynamic resistance curve .......................... 41
Fig. 3.6 Machine and control link .............................. 43
Fig. 3.7 Schematic of a capacitive discharge welder ................. 43
Fig. 3.8 AC RSW supply ..................................... 44
Fig. 3.9 HFDC power supply circuit ............................ 45
Fig. 3.10 Welding current for different power supply mechanism .... 45
Fig. 3.11 Sites of failure initiation ............................... 46
Fig. 3.12 Dependence of tensile–shear force on weld time and welding force .......................... 47
Fig. 3.13 Schematic for electrode tip voltage measurement circuit .......................... 48
Fig. 5.9  a Weld dimensions versus incident angle, b weld pool volume versus incident angle ........................................... 99
Fig. 5.10 Joining speeds as function of used laser power for various optical setups and spot diameter ................................. 100
Fig. 5.11 Experimental and ANN estimated values for different experimental conditions .............................................. 101
Fig. 5.12 Hybrid laser arc welding ........................................ 101
Fig. 5.13 Weld cross section and assumed molten pool volume .... 104
Fig. 5.14 Structural areas of HAZ ........................................ 105
Fig. 5.15 Two-dimensional conduction mode laser beam .............. 106
Fig. 5.16 Temperature distribution for thin plate ....................... 107
Fig. 5.17 Temperature distribution for thin plate ....................... 108
Fig. 5.18 Cooling rates with variation in plate thickness ............... 109
Fig. 5.19 Reinforcement form factor versus energy density ........... 112
Fig. 5.20 Variation of penetration size factor with energy density ... 113
Fig. 5.21 Plots showing effect of process parameters on UTS and hardness ................................................................. 116
Fig. 5.22 Relation between DOP, pulse off time, and duty cycle ...... 118
Fig. 5.23 Laser beam focused on the weld metal ....................... 121
Fig. 5.24 Cross section of pulsed laser seam weld ...................... 122
Fig. 5.25 Calibration curve of laser machine ............................ 124
Fig. 5.26 Pulse shape of the flashlamp current ........................ 126
Fig. 5.27 Circuit for flashlamp power supply ............................ 126
Fig. 5.28 Charging circuit ............................................... 127
Fig. 5.29 Overvoltage circuit ............................................ 128
Fig. 5.30 Flashlamp RLC circuit ....................................... 129
Fig. 5.31 Response of critically damped circuit ........................ 129
Fig. 6.1 Schematic of friction stir weld process ......................... 134
Fig. 6.2 FSW tool shape ............................................... 135
Fig. 6.3 Tool and workpiece tilted with respect to each other ........ 136
Fig. 6.4 Forces acting in FSW and exit hole ........................... 136
Fig. 6.5 Variation of stress with temperature .......................... 137
Fig. 6.6 Possible configurations, a T-joint, b corner joint ............ 138
Fig. 6.7 Schematic of FSW tool ....................................... 139
Fig. 6.8 Schematic of surface orientations and infinitesimal segment areas, a concave shoulder, b pin side, c pin tip .............. 140
Fig. 6.9 Conventional FSW fixture requirements ....................... 142
Fig. 6.10 Bobbin FSW tool ............................................ 143
Fig. 6.11 Self-reacting Bobbin tool ..................................... 143
Fig. 6.12 Fixed gap Bobbin tool ....................................... 144
Fig. 6.13 Microstructural classification for FSW product ............. 146
Fig. 6.14 Effect of PID gains on temperature response ............... 148
Fig. 6.15 Torque, spindle speed power, and temperature response to step changes in desired temperature ....................... 148
Fig. 6.16 Variation of energy and torque requirement with welding speed and rotational speed. Dashed line—experimental values reported and the solid line—numerically calculated values.

Fig. 6.17 FOPDT model.

Fig. 6.18 Tool–workpiece thermocouple method.

Fig. 6.19 A typical monitoring architecture.

Fig. 6.20 Offline control mechanism for design and material parameters.

Fig. 6.21 Transverse view and detail of the parameters.

Fig. 6.22 Comparison curve of temperature with and without assisted heating.

Fig. 6.23 Effect of process parameters on various forces.

Fig. 6.24 Specific weld energy versus weld speed curve.

Fig. 6.25 Tool geometry.

Fig. 6.26 Friction power versus contact pressure.

Fig. 6.27 Plastic deformation energy as a function of welding speed for different shear stress values.

Fig. 6.28 Effect of welding speed on power Sources generated during FSW.

Fig. 6.29 Comparison of power versus weld speed at melting temperature and recrystallisation temperature.

Fig. 6.30 Variation of power with weld speed at Tm for different weld widths.

Fig. 6.31 Power versus radius ratio.

Fig. 7.1 Schematic of current discharge circuit, middle section close up.

Fig. 7.2 MPW arrangement showing electromagnetic effects.

Fig. 7.3 MPW schematic.

Fig. 7.4 Discharge current and magnetic pressure variation with time.

Fig. 7.5 Sample showing center of welding joint.

Fig. 7.6 Variation of shear strength with standoff distance.

Fig. 7.7 Skin depth and resistivity relation.

Fig. 7.8 MPW system.

Fig. 7.9 MPW setup for tubes.

Fig. 7.10 Current waveform in an underdamped circuit.

Fig. 7.11 Effect of coil width on magnetic pressure.

Fig. 7.12 Experimental results for various axial positions and variation of time.

Fig. 7.13 Effect of varying influencing parameters on the impacting conditions.

Fig. 7.14 Variation of skin depth with frequency.
List of Figures

Fig. 7.15 CAD model for the working coil with tubular workpieces ...... 179
Fig. 7.16 Simulation results for Al-SS workpieces with Cu coil ........... 180
Fig. 7.17 Dependence of field shaper function on length of working zone ........................................ 182
Fig. 7.18 Influence of applied voltage, plate thickness, and standoff distance on impact velocity ......................... 186
Fig. 7.19 Schematic of MPW discharge circuit .......................... 187
Fig. 7.20 3D model of the coil ........................................ 188
Fig. 7.21 Current waveform at 9 kJ discharge energy ..................... 188
Fig. 7.22 Interface between Al and Fe/Ti/Mg ........................... 189
Fig. 7.23 Variation of welded surface-to-contact surface ratio ........... 190
Fig. 7.24 Bonding interface ........................................... 190
Fig. 7.25 Weldability window for 6061 T0 Al alloy ....................... 191
Fig. 7.26 Schematic of analytical process ................................ 193
Fig. 7.27 Electrical model ............................................. 194
List of Tables

Table 2.1 Preferred weld method for different weld specifications ........ 22
Table 3.1 Material properties of AISI 316L and DSS 2205 ............... 56
Table 4.1 Properties and choice of AC/DC power source for TIG welding ................................................. 70
Table 4.2 Parameter values for manual TIG welding of AL using HF AC supply .................................................. 80
Table 4.3 Parameter values for manual TIG welding of MS using DC supply ......................................................... 81
Table 4.4 Observation table for input parameters and the resulting bead width .......................................................... 86
Table 5.1 Materials and their properties for the weld process ........... 93
Table 5.2 Sample calculations for the use of optimization techniques ... 115
Table 5.3 Optimum values of the variable parameters .................... 116
Table 5.4 UTS and Brinell hardness for given parameter values .......... 116
Table 5.5 Process parameters chosen for SET II: laser welding of Austenitic 304L stainless steel sheet ....................... 117
Table 5.6 Mechanical properties of DP1000 ................................ 123
Table 5.7 Properties of laser system: SISMA SWA 300 .................. 123
Table 6.1 Design features and effects of the FSW tool .................. 145
Table 6.2 Weld zones and their characteristics ............................ 146
Table 6.3 Mechanical properties of Al2014-T3 ............................ 157
Chapter 1
Welding: An Overview

Welding involves binding of two materials to form a single component. The materials to be joined are subjected to heat or pressure or combination of both. The material prior to welding needs to be qualified as weldable which indicates that welds of sufficient size and strength can be obtained for the material when welded with standard welding equipment and procedures.

Advent of versatile materials catering to the twenty-first century industrial requirements attributed to the evolution of advanced welding technologies that relies on complex phenomena.

A portion of this book covers the design procedures for selecting optimal ranges of process parameters in the different techniques of welding. Attainment of optimal ranges for these parameters is imperative to yield a weld with good quality and strength.

1.1 Welding Techniques—Classification

Fig. 1.1 shows the classification of the welding techniques based on the type of heat source. Different techniques are thus governed by various process parameters depending upon the material properties and the application of the weld product. Based on the type of heat source, the operating principles need to be well understood for working in any stage of the weld process. The following section describes the operating principles of various welding categories covering the multidisciplinary aspects of each process and the involved design parameters in brief.

Each process has been covered to the complete detail in the following chapters. The techniques have been chosen from the categories of resistance, arc, solid state and high-energy density welding processes. These processes allow for better control and also can be optimized with possible automation.
1.2 Resistance Welding

This process involves joining of two metals with the help of resistance offered to the flow of current in a material. The joule heating at the common surface of the weld materials causes the metals to undergo localized heating and consequent melting, and thus, they join together. This heat generation is affected by the resistance at any point in the circuit. Current level, electrode force, and materials being welded are the variables expected to cause significant variation in the shape of the weld. The current flow duration and the electrode pressure need to be controlled for achieving the weld characteristics. Applying optimal force consistently improves the material joining as it reduces the path resistance and also eliminates the oxide layer in the surface [1].

The basic weld schedule and schematic for resistance welding are shown in Fig. 1.2. The weld schedule describes the stages involved in the RSW process described as: holding the elements (squeeze time), heating (weld time), and the hold time. The electrode force acts on the materials throughout the process.

1.2.1 Process Variations

Resistance welding techniques are widely used in automatic pressure welding machines on factory automation sites. Figure 1.3 below describes the types of resistance welding techniques [2].
1.2 Resistance Welding

Fig. 1.2 Schematic and weld schedule of RSW

Fig. 1.3 Types of Resistance Welding Methods [2]. Source https://www.welding-machine-dahching.com/about-welding.html
Resistance Spot Welding (RSW): This method of welding uses the concept of heat generation due to the resistance offered to the current flow in a material and is suitable for thin sheet welding. This heat melts the workpieces in a spot of a particular size depending upon the dimensions of the electrode tip. Control mechanism associated with the electrode guides the weld formation. The melted spot causes the two workpieces to coalesce and takes the form of a nugget when the workpieces cool down.

Resistance Seam Welding (RSEW): RSW with rapid pulses of current results in a series of overlapping spot welds. These overlapping welds appear to be like a seam weld. This method is suitable for airtight welding.

Resistance Projection Welding (RPW): Localized RSW with welding intended at projections on the component and the sheet metal which are clamped between current carrying plates. Electrodes used in this welding must retain the hardness value during normal temperature.

Flash Welding (FW): RSW with voltage of around 5 V applied at the clamps and the high spots at the contact area are removed by deoxidizing the joint which is called flashing. Pressure is then applied to forge the weld on to the thick workpieces such as anchor chain, rails, and pipes.

Electroslag welding (ESW): A consumable electrode and welding flux are used in this process of welding [3]. The joule heating caused by the arc between the electrode and the weld metal causes the flux to melt, and it changes its form to a molten slag, which maintains this state due to the heat produced by the electric current. The molten slag at 3500 °F melts the consumable electrode and the workpiece and causes a bond between the two.

1.2.2 Preferred Materials for RSW

Low-carbon steels and aluminum alloys can be welded using RSW. Higher-carbon steels and alloy steels, if welded using this technique, may result in a brittle weld. Steel and specifically low-carbon steel have low thermal conductivity and higher electrical resistance and thus is the preferred material for spot welding. Current requirement in zinc-coated galvanized steel is larger than uncoated steels. Quality of weld surface is degraded if copper electrode is used with zinc alloys.

Nickel and super austenitic alloys can also be used in limited cases because of the tendency to crack due to absence of ferrite in these alloys. Special consideration should be taken in the form of wider joint angles, lower heat input, and flat bead shapes.