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Solid State Welding

(固相焊接技术)



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Preface

Welding technologies include fusion welding, brazing and soldering, and solid state welding (SSW). SSW processes produce coalescence of the faying surfaces at temperatures well below the melting point of the metal being joined. These processes rely either, on deformation, or, on atom diffusion with reduced deformation, as the mechanism to produce quality joints between similar and dissimilar material combinations alike. Therefore, they have found great potentials in advanced structural metallic materials, such as Mg alloys, Al alloys, Ti alloys, superalloys, and high-strength steels which are conventionally difficult-to-weld materials, especially the dissimilar material combinations.

“Solid State Welding” is one of the important courses in welding technology and engineering and as such has been included since 2009 in the syllabus of the “Materials Science and Engineering” and “Materials Forming and Control Engineering” undergraduate course of the Northwestern Polytechnical University, P. R. China. It can also be studied for the “Metallic Materials Engineering” major. The period of this textbook may be 32 credits.

This textbook has 14 chapters. Chapter 1 gives a brief introduction to welding, fusion welding and solid state welding. Chapter 2 provides a brief introduction to metal bond theory in term of energy. The rest of the book has 12 chapters which introduce different solid state welding processes, starting from the common cold welding, friction welding, diffusion bonding, explosion welding, ultrasonic welding and solid variants of resistance welding, to the new high-speed-impact based cold spraying, laser impact welding and magnetic pulse welding, and the filler-metal based soldering and brazing.

This textbook is addressed to students who are in the third or senior undergraduate year. It may be used by graduate students who are beginning to study “Materials Processing Engineering”, and anyone practicing welding engineer.

The authors would like to thank Science Press for agreeing to publish this work and for their kind support during the preparation stage. Acknowledgements are also due to graduates of the Department who did help during this past time.

Finally, it should be stated that we consider this textbook as work in progress as

welding is continuously expanding with newer processes. Feel free to send any questions, comments, corrections, and ideas for future versions of this textbook to liwy@nwpu.edu.cn or yangxiawei@nwpu.edu.cn.

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Contents

Preface

Chapter 1 Introduction to Solid State Welding	1
1.1 Terminology	1
1.2 Welding Technology	2
1.3 Classification of Welding	4
1.4 Fusion Welding	6
1.4.1 Gas Welding	6
1.4.2 Arc Welding	6
1.4.3 High-Energy Beam Welding	6
1.5 Heat Source	7
1.6 Solid State Welding	7
1.6.1 Classification of Solid State Welding	8
1.6.2 Advantages of Solid State Welding	9
1.6.3 Importance of Interface in Solid State Welding	9
Questions	10
References	10
Chapter 2 Fundamentals of Metal Adhesion and Cohesion	11
2.1 Terminology	11
2.2 Introduction	12
2.3 Surface Energy	12
2.4 Fracture Energy (Cohesion Energy)	12
2.5 Grain Boundary Energy	13
2.6 Interface Energy	14
2.7 Properties Influencing Adhesion	14
Questions	15
References	15

Chapter 3 Cold Welding	16
3.1 Terminology	16
3.2 Introduction	17
3.3 Bonding Mechanism	18
3.4 Variants of Cold Welding	20
3.4.1 Cold Pressure Lap Welding	20
3.4.2 Cold Pressure Butt Welding	21
3.5 Cold Welding in Drawing	23
3.6 Cold Welding in Extrusion	24
3.7 Cold Welding in Rolling	25
Questions	26
References	26
Chapter 4 Rotary Friction Welding	27
4.1 Terminology	27
4.2 Classification of Friction Welding	28
4.3 Principle of Rotary Friction Welding	28
4.4 Process Parameters	29
4.4.1 The Process of Continuous-Drive Friction Welding	29
4.4.2 The Process of Inertia Friction Welding (IFW)	31
4.5 Heat Generation during Rotary Friction Welding	32
4.6 Important Factors	34
4.7 Advantages and Limitations	34
4.8 Applications	35
Questions	35
References	36
Chapter 5 Linear Friction Welding	37
5.1 Terminology	37
5.2 Principle of Linear Friction Welding	39
5.3 Phases of Linear Friction Welding	40
5.3.1 Phase I : Initial Phase	40
5.3.2 Phase II : Transition Phase	40
5.3.3 Phase III: Equilibrium Phase	41
5.3.4 Phase IV: Deceleration Phase	41
5.4 Advantages and Limitations of Linear Friction Welding	41

5.5	History and Applications of Linear Friction Welding	42
5.6	Microstructure and Properties of LFW Ti-6Al-4V	44
5.6.1	Microstructure	44
5.6.2	Mechanical Properties	46
5.7	Modeling of the Linear Friction Welding Process	47
5.7.1	Numerical Model	47
5.7.2	Typical Temperature and Axial Shortening Evolution	49
5.8	Heat Input	51
	Questions	52
	References	53
Chapter 6	Friction Stir Welding	54
6.1	Terminology	54
6.2	Principle of Friction Stir Welding	55
6.3	Benefits of Friction Stir Welding	57
6.4	Industrial Applications	58
6.5	Joint Microstructure	59
6.6	Joint Properties	60
6.7	FSW Tool Design	61
6.7.1	Tool Materials	61
6.7.2	Tool Geometry	61
6.7.3	Tool Wear and Failure	62
	Questions	63
	References	63
Chapter 7	Diffusion Bonding	65
7.1	Terminology	65
7.2	Introduction	67
7.3	Welding Mechanism	67
7.4	Important Factors Affecting Bonding	68
7.4.1	Surface Roughness	68
7.4.2	Surface Oxides	69
7.5	Effect of Interlayers	69
7.6	Diffusion Bonding of Stainless Steel with Titanium Alloy	70
7.7	Transient Liquid Phase Diffusion Bonding	70
	Questions	72

References	72
Chapter 8 Explosion Welding	73
8.1 Terminology	73
8.2 Introduction	74
8.3 The Process of Explosion Welding	74
8.4 Advantages and Disadvantages of Explosion Welding	75
8.4.1 Advantages	75
8.4.2 Disadvantages	75
8.5 Process Parameters	75
8.6 Examples	76
8.7 Formation Mechanism of Wavy Interface	77
Questions	78
References	78
Chapter 9 Ultrasonic Welding	79
9.1 Terminology	79
9.2 Introduction	79
9.3 The Process of USW	79
9.4 Process Parameters	81
9.5 Advantages and Disadvantages of USW	82
9.5.1 Advantages	82
9.5.2 Disadvantages	83
9.6 Microstructure and Mechanical Properties	83
Questions	84
References	84
Chapter 10 Cold Spraying	86
10.1 Terminology	86
10.2 Introduction	88
10.2.1 Surface Engineering	88
10.2.2 Thermal Spraying	89
10.3 Cold Spray Process	89
10.3.1 Principle of Cold Spraying	89
10.3.2 Main Advantages and Disadvantages of CS	90
10.4 Bonding Mechanisms in Cold Spraying	91
10.4.1 Bonding Hypothesis	91

10.4.2	Influencing Factors of Critical Velocity	92
10.5	Processing Parameters	92
10.5.1	Driving Gas	93
10.5.2	Nozzle Design	93
10.5.3	Powder Property	94
10.6	Applications	94
10.6.1	Protective Coatings	94
10.6.2	Functional Coatings	96
10.6.3	Repair and Restoration	96
10.6.4	Additive Manufacturing/Spray Forming	97
	Questions	97
	References	97
Chapter 11	Laser Impact Welding	99
11.1	Terminology	99
11.2	The Process of Laser Impact Welding	99
11.3	Process Parameters	100
	Questions	101
	References	101
Chapter 12	Magnetic Pulse Welding	103
12.1	Terminology	103
12.2	The Process of Magnetic Pulse Welding	103
12.3	Process Parameters	104
12.3.1	Impact Energy Level	104
12.3.2	Standoff Distance	104
12.3.3	Coil Geometry	105
12.3.4	Overlap Width	105
	Questions	105
	References	106
Chapter 13	Soldering and Brazing	107
13.1	Terminology	107
13.2	Introduction	109
13.3	Wettability and Solderability	109
13.4	Process Characteristics and Parameters	110
13.4.1	Important Features	110

13.4.2	Process Parameters	111
13.5	Advantages and Limitations	113
13.6	Techniques Available	113
13.6.1	Torch Brazing and Soldering	113
13.6.2	Furnace Brazing and Soldering	113
13.6.3	Induction Brazing and Soldering	114
13.6.4	Dip Brazing and Soldering	114
13.6.5	Vacuum Brazing	115
13.6.6	Resistance Soldering	115
13.6.7	Hot Gas Soldering	115
13.7	Joint Designs	115
	Questions	116
	References	117
Chapter 14	Solid State Variants of Resistance Welding	118
14.1	Terminology	118
14.2	Introduction	118
14.3	Flash Welding	119
14.3.1	History and Applications	119
14.3.2	Advantages and Limits	120
14.3.3	Process Parameters	121
14.4	Upset Welding	121
14.4.1	Welding Cycle	122
14.4.2	Weldable Metals and Applications	122
14.5	Projection Welding	123
14.5.1	Process Parameters	123
14.5.2	Projection Design	124
14.5.3	Advantages and Limits	124
	Questions	125
	References	125

Chapter 1

Introduction to Solid State Welding

1.1 Terminology

Weld (vt./n.): to join components together permanently; a weld means the welded seam.

Welding (n.): a method to weld things.

Welder (n.): a welder is a person whose job is to weld something, or a machine that is used to weld something.

Weldment (n.): a weldment normally means workpieces welded or being/to be welded.

Weldable (adj.): something that can be welded.

Weldability (n.): the ability of an object to be joined with welding.

Joining (n.): the process used to bring separate parts or components together to produce a unified whole assembly or structural entity; similar to but having a larger meaning than welding.

Bonding (n.): similar to welding, but has a larger meaning than welding and joining by having materials together through all kinds of methods. Among the welding processes only “diffusion bonding” uses this term. “Adhesive bonding” is a term for a joining process. Generally, all three terms welding, joining and bonding are used to the same effect.

Fusion welding: a group of welding processes which produce a weld by melting part of the components to be welded.

Solid state welding: a group of welding processes which produce a weld with a suitable combination of pressure and temperature and without melting the components to be welded.

Heat source: the source used to heat up the workpieces, e.g. flame, arc, and laser.

Joint (n.): a joint is the area or volume where two components are fastened or joined together. It is a larger area than the commonly used center zone, or “weld”, as it includes the heat affected zone.

Similar joint/weld: a joint/weld of components which are of the same material

Dissimilar joint/weld: a joint/weld of components which are of different materials

Laser (*n.*): an acronym for Light Amplification by Stimulated Emission of Radiation. A laser is a narrow beam of concentrated light produced by a special machine. It is used for cutting very hard materials, and in many technical fields such as surgery and telecommunications. An optical device produces an intense monochromatic beam of coherent light.

1.2 Welding Technology

Welding is a process where two parts, as shown in Figure 1-1, of the same or different materials, are joined permanently through localized coalescence at an interface, which is the result of a suitable combination of temperature, pressure and metallurgical conditions. Depending on the combination of temperature and pressure, ranging from high temperature under no pressure condition to high pressure at a lower temperature, a wide range of welding processes have been developed.

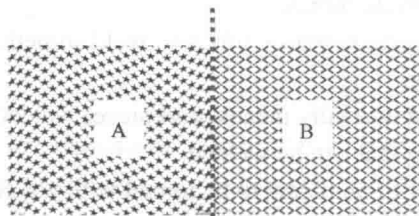


Figure 1-1 Welding between Materials A and B

Here are some examples of welding processes. Figure 1-2 shows a blacksmith (the welding engineer of old times) using forge welding (FOW) to join metal parts together. Forge welding produces a joint by heating the materials to welding temperature, which is below the melting point, and then applying pressure (as a hammer blows the parts or a steady pressure is applied) to effect the weld. Possibly dating back to circa 4000 B.C., forge welding is the oldest known welding process.

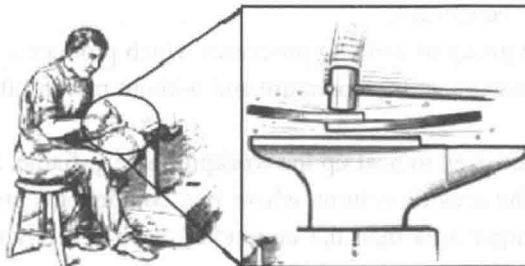
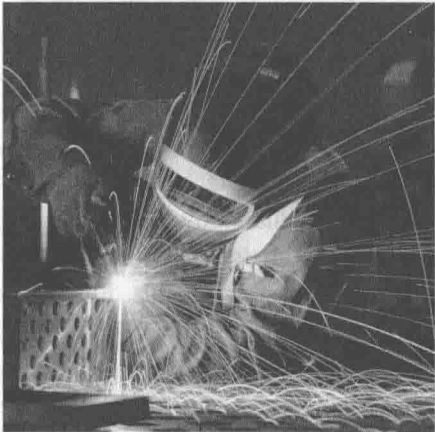
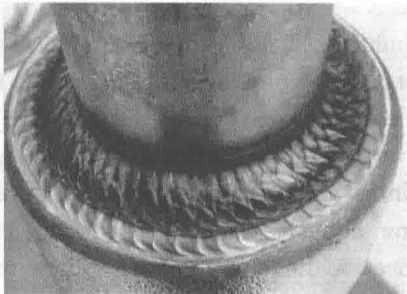


Figure 1-2 Welding Performed in the Old Times by a Blacksmith

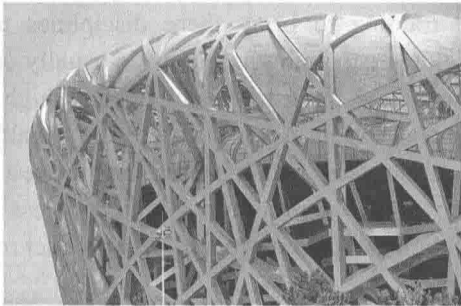
Figure 1-3 shows a typical modern welding process, arc welding, and typical welded structures. Manual arc welding is one of the most widely used welding processes in fabricating steel structures (e.g. “Bird Nest” Olympic stadium in Beijing), where an arc is established between a stick-like covered electrode and components. The electrode holder is electrically connected through a welding cable to one terminal of the power source and the workpiece is connected through a second cable to the other terminal of the power source to complete the circuit. During welding, a low and safe voltage at high currents are typical features of the power supply. The welder looks like an armored warrior. The spatter and weld can have nice colors because of metal oxidation.



(a) Welded structures



(b) Annular weld with fish-scale patterns



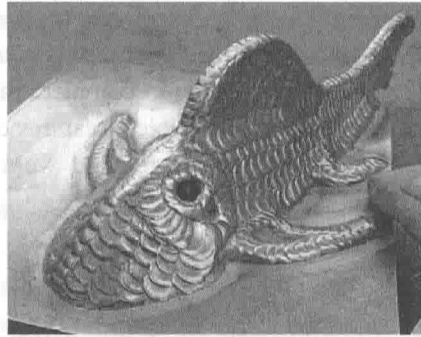
(c) “Bird Nest” Olympic stadium in Beijing

Figure 1-3 Arc Welding Process

Therefore, welding can create art, not only structures with specific uses, as shown in Figure 1-4. For more on this aspect of welding see <https://www.pinterest.com/explore/welding-art>.



(a) Lion



(b) Fish

Figure 1-4 Welding Art

In industry, welding processes are essential to the manufacture of virtually every product as they join various components to form a product. However, these processes are quite often expensive and form a large part of a product's cost while they may limit further production capabilities. There is a variety of reasons for this. Firstly, welding and joining are complex operations, because of their sheer number of variants (e.g. fastening, adhesive bonding, soldering, brazing, arc welding, diffusion bonding, and resistance welding) and the disciplines required to work together to design, develop and operate welding machines (such as a mechanical engineer, materials scientist, physicist, chemist, and electronic engineer). An engineer should have an unusually broad, while in depth, training to bring these disciplines together and use them effectively. Secondly, welding or joining problems do usually occur during production, where the relative value of the parts to be scrapped is high. Thirdly, a very large number of product failures do occur at joints as they are usually located in parts of an assembly with the highest stresses, making them the weakest parts of the assembly. Finally, careful selection of the appropriate joining process can reap considerable economies during production and provide remarkable product reliability.

1.3 Classification of Welding

According to the American Welding Society (AWS), welding can be narrowly classified as gas welding, arc welding, resistance welding, solid state welding, soldering, brazing, and other processes, e.g. electron beam welding and laser beam welding.

Figure 1-5 shows in detail this classification. It is clear that welding processes could

additionally similar processes, like thermal spraying and adhesive bonding, or even thermal cutting which use similar heat input sources to welding.

However, according to the Chinese classification, welding is narrowly defined as fusion welding, pressure welding, brazing and soldering. Pressure welding requires pressure to be applied on the workpieces during welding irrespective of whether they melt or not, which is different from solid state welding. Actually some pressure welding processes, like resistance spot welding and resistance seam welding, where a melted nugget is formed, belong to fusion welding. The majority of the other pressure welding processes can be classified as solid state welding, e.g. friction welding, diffusion bonding and explosion welding.

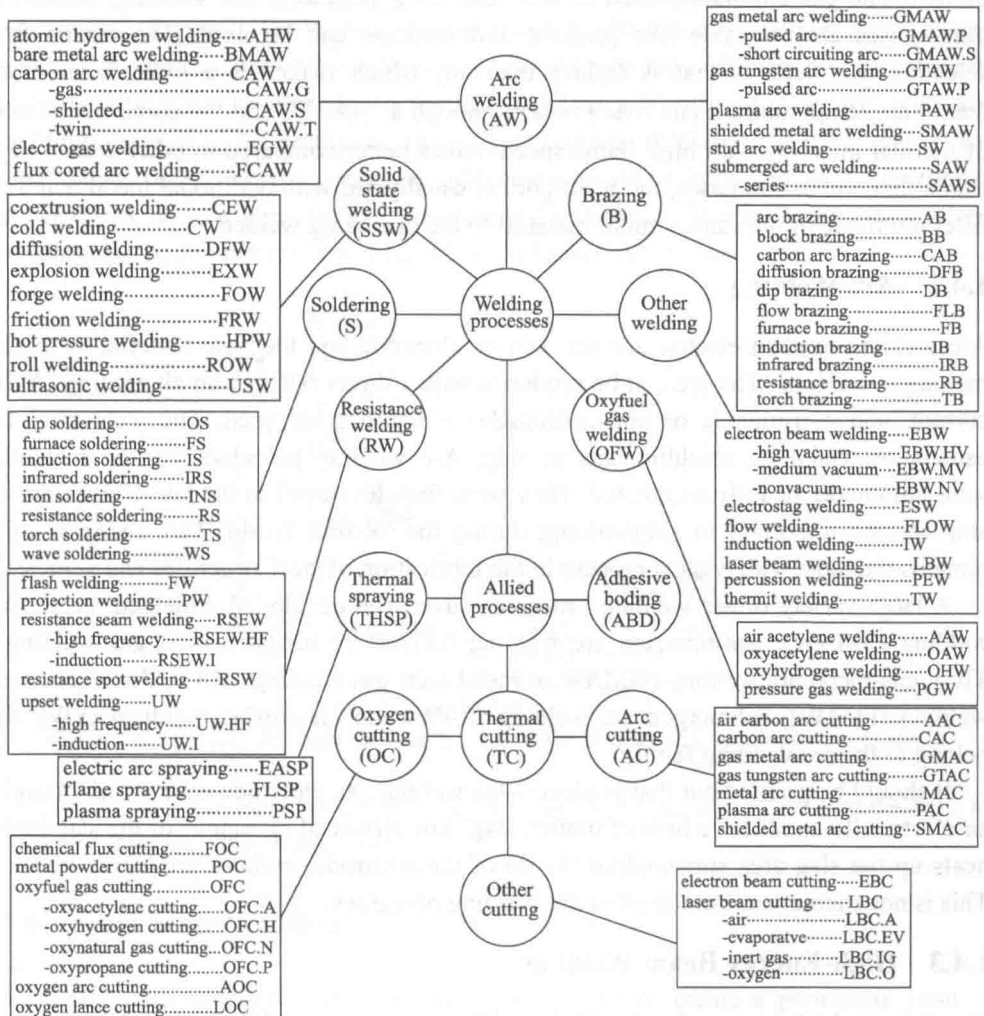


Figure 1-5 Classification of Welding Processes according to AWS

1.4 Fusion Welding

In fusion welding, the temperature reached during the process is higher than the melting point of the materials being joined. Bonding is achieved at the interface due to the high mobility atoms in the molten material pool, and sound joints are produced following cooling. There are three major types of fusion welding.

1.4.1 Gas Welding

Chemical energy stored in gases is converted to heat through combustion. Therefore, gas welding is a process that uses the flame when a mixture of fuel gas and oxygen is burned. The gas commonly used is acetylene C_2H_2 (oxyacetylene welding) although other gases are available like propane and methane can be used. The reason for selecting acetylene is that is lighter than air, which makes it a safe choice, the maximum temperature it can reach is high enough at $3087^\circ C$, and the combined effect of thermal intensity with high flame speed makes better compared to other commonly available combustion gases, the weld pool is usually fed with additional metal using a filler rod made of the same/similar material to the one being welded.

1.4.2 Arc Welding

Arc welding uses an electric arc between an electrode and the base material to reach melting conditions. The arc can be produced with a direct (DC) or an alternating (AC) current, and consumable or non-consumable electrodes are used. The weld pool is usually protected by shielding gas or slag. Arc welding processes can be manual, semi-automatic, or fully automated. They were first developed in the late 19th century, and became important to shipbuilding during the Second World War. Today it still remains the most widely used process in the fabrication of steel structures and vehicles.

A large variety of arc welding processes have been developed. Shielded metal arc welding (SMAW), gas-tungsten arc welding (GTAW or tungsten inert gas welding: TIG), gas-metal arc welding (GMAW or metal inert gas welding: MIG), flux-cored arc welding (FCAW), submerged arc welding (SAW) and electroslag welding (ESW) all belong to the arc welding family.

It should be pointed out that in electroslag welding, an electrode wire is fed through an electrically conductive bath of molten slag. The electrical resistance of the slag bath heats up the slag area surrounding the tip of the electrode, without producing an arc. This is not encountered in the other arc welding processes.

1.4.3 High-Energy Beam Welding

Besides arc, high energy density ($10^5 \sim 10^9 W/cm^2$) sources, like electron beam, laser