Wenya Li (李文亚)
Xiawei Yang (杨夏炜)
Achillefs Vairis

Solid State Welding

(固相焊接技术)

科学出版社

Solid State Welding

(固相焊接技术)

Wenya Li (李文亚) Xiawei Yang (杨夏炜) Achillefs Vairis

Science Press
Beijing

Responsible Editor: Jie Zhu, Dan Yang

Published by Science Press
16 Donghuangchenggen North Street
Beijing 100717, P. R. China

Printed in Beijing

ISBN 978-7-03-053372-2

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.

Wenya Li（李文亚）
Xiawei Yang（杨夏炜）
Achillefs Vairis
Oct. 2016

Contents

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.

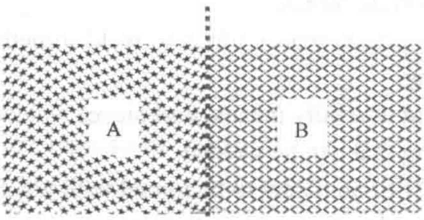


Figure 1-1 Welding between Materials A and B

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.

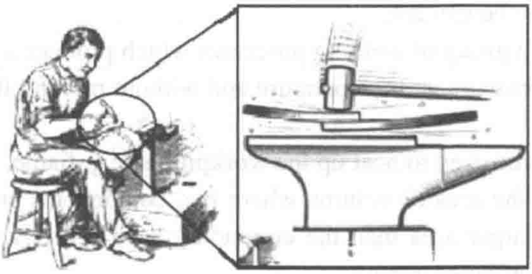
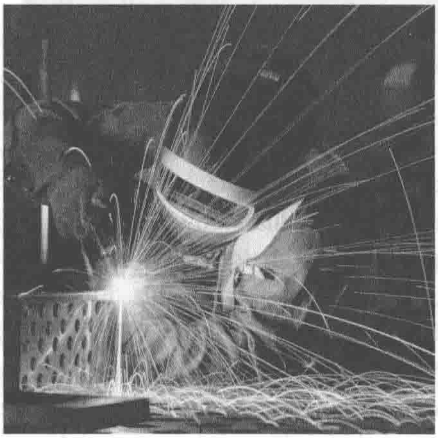
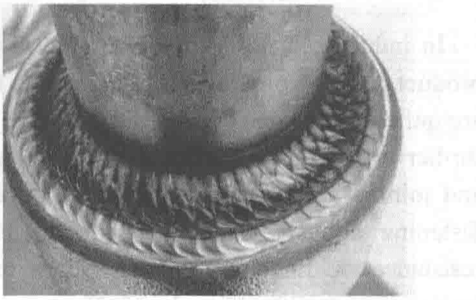


Figure 1-2 Welding Performed in the Old Times by a Blacksmith

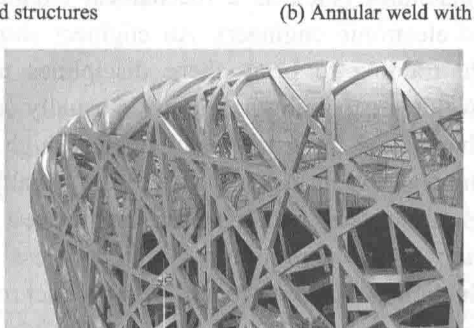
Figure 1-3 shows a typical modern welding process, arc welding, and typical welded structures. Manual arc welding is one of the most widely used welding processes in fabricating steel structures (e.g. "Bird Nest" Olympic stadium in Beijing), where an arc is established between a stick-like covered electrode 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



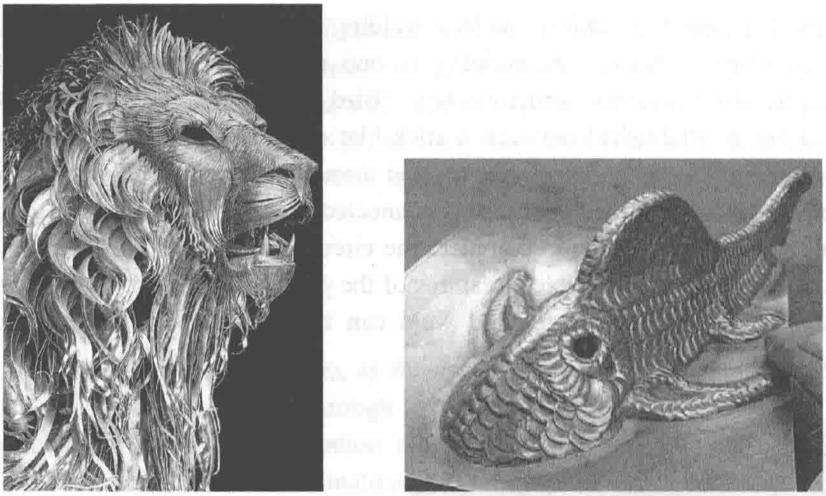
(b) Annular weld with fish-scale patterns



(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.

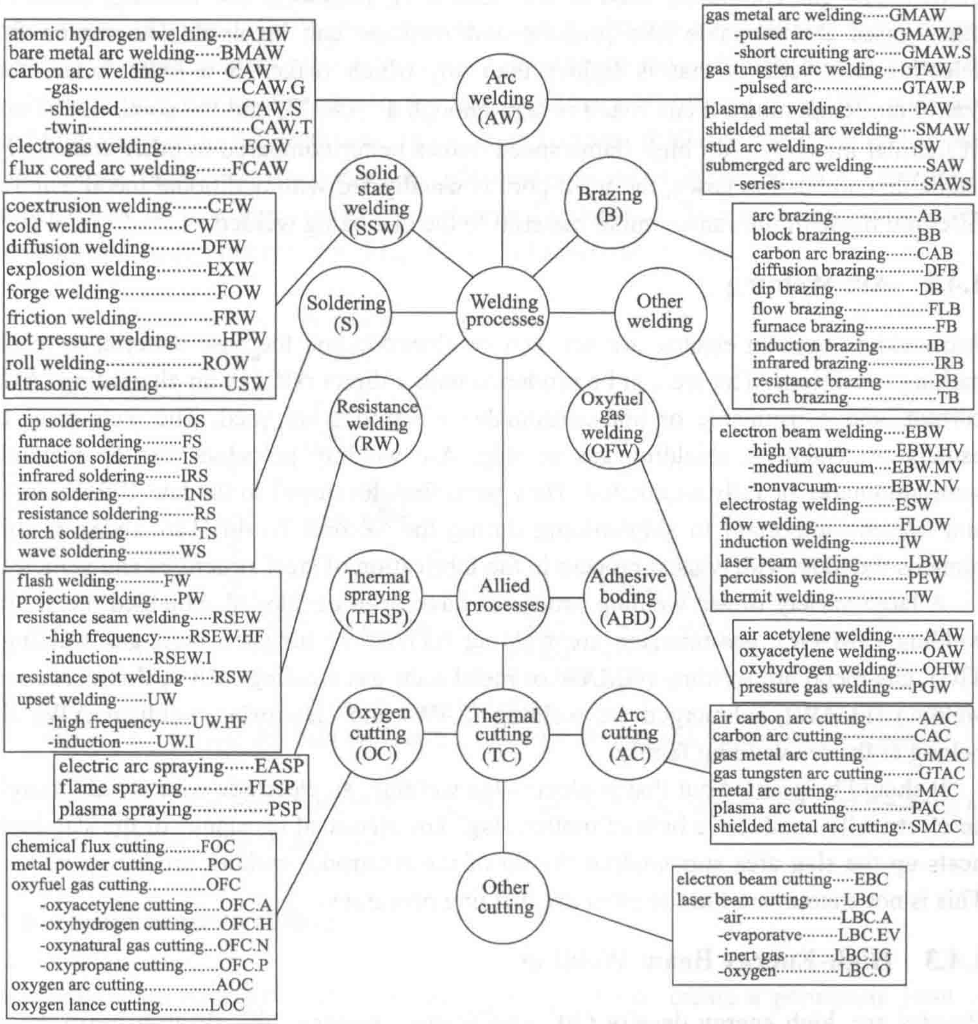


Figure 1-5 Classification of Welding Processes according to AWS

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℃, 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