

Welding Handbook

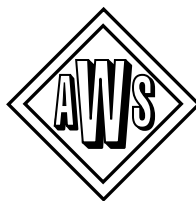
Ninth Edition

Volume 3

WELDING PROCESSES, PART 2

Prepared under the direction of the
Welding Handbook Committee

Annette O'Brien, Editor
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Library of Congress Control Number: 2001089999
ISBN: 978-0-87171-053-6

The *Welding Handbook* is the result of the collective effort of many volunteer technical specialists who provide information to assist with the design and application of welding and allied processes.

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DEDICATION

Dr. John M. Gerken

This book is dedicated to Dr. John M. Gerken in recognition of his distinguished work in the field of metallurgical engineering and the transfer of its technology, and for his steadfast commitment to the *Welding Handbook*. Dr. Gerken served on the Welding Handbook Committee beginning in 1992 during the preparation of the two Eighth Edition volumes of the *Welding Handbook, Materials and Applications, Part 1 and Materials and Applications, Part 2*. He served as the Chair of the Volume 1 Committee, which prepared Volume 1 of the Ninth Edition, *Welding Science and Technology* for publication in 2001. He is known nationally for his dedication to the welding industry and his service to the American Welding Society as a volunteer.

Dr. Gerken had a distinguished career with TRW, directing several welding research and engineering development programs involving the use of newly developed aerospace metals and requiring expertise in the major welding processes. After retiring from TRW, he extended his career at the Lincoln Electric Company as Manager of Technology Transfer, where he revised the *Welding Procedure Handbook*.

Dr. Gerken is a past president of the American Welding Society and served on the Board of Directors. In 1995 he was made a Fellow of the American Welding Society. He has been an active member of various national technical standards committees for AWS, currently including the Subcommittee on Nickel Alloys, the Committee on Joining Metals and Alloys, the U.S. Tag for ISO/TC 44/SC6, Resistance Welding; the Committee on Resistance Welding, and the Subcommittee on Stainless Steel Alloys.

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In addition to his public service, Dr. Gerken has privately served as a mentor to many in the welding community over the years. The Welding Handbook Committee is grateful for his guidance and friendship.

CONTENTS

ACKNOWLEDGMENTS	xii
PREFACE	xiii
REVIEWERS	xiv
CONTRIBUTORS	xv
CHAPTER 1—RESISTANCE SPOT AND SEAM WELDING	1
Introduction	2
Fundamentals	2
Equipment	11
Surface Preparation for Spot and Seam Welding	14
Resistance Spot Welding	15
Resistance Seam Welding	26
Metal Properties and Weldability	39
Economics of Resistance Welding	43
Safe Practices	43
Conclusion	45
Bibliography	45
CHAPTER 2—PROJECTION WELDING	49
Introduction	50
Equipment	52
Welding Variables	55
Welding Schedules	62
Metals Welded	63
Weld Quality	63
Cross Wire Welding	66
Economics	69
Safe Practices	69
Bibliography	71
CHAPTER 3—FLASH AND UPSET WELDING	73
Introduction	74
Flash Welding	74
Fundamentals	75
Applications	76
Equipment	77
Welding Procedures	79
Welding Machine Settings	92
Upset Welding	94
Fundamentals	94
Process Variations	94
Applications	94
Sheet, Strip, and Wire Welding	95
Continuous Upset Welding	98
Weld Quality	100
Examination and Testing	102
Economics	103
Safe Practices	103
Conclusion	104
Bibliography	105

CHAPTER 4—RESISTANCE WELDING EQUIPMENT	107
Introduction	108
Equipment Selection	108
Electrodes.....	123
Actuators	133
Power Conversion Equipment	135
Resistance Welding Controls	142
Quality Control Functions	152
Electric Service Equipment	153
Economics.....	154
Safe Practices.....	155
Conclusion.....	157
Bibliography.....	158
 CHAPTER 5—HIGH-FREQUENCY WELDING.....	 159
Introduction	160
Fundamentals.....	160
Applications	165
Induction Seam Welding of Pipe and Tubing	165
Contact Seam Welding of Pipe and Tubing.....	166
Welding Parameters.....	169
Equipment.....	169
Inspection and Quality Control.....	178
Economics.....	179
Safe Practices.....	180
Conclusion	180
Bibliography	181
 CHAPTER 6—FRICTION WELDING	 183
Introduction	184
Fundamentals.....	184
Welding Variables.....	191
Joint Design	197
Equipment.....	198
Welding Procedures.....	202
Applications	203
Weld Quality	203
Economics.....	205
Safe Practices.....	205
Conclusion	208
Bibliography.....	208
 CHAPTER 7—FRICTION STIR WELDING	 211
Introduction	212
Fundamentals.....	212
Equipment and Controls	214
Tool Design.....	217
Welding Parameters.....	219
Regions of a Friction Stir Weld.....	220
Factors Affecting Weldability	222
Heat Transfer	232
Material Flow	236
Applications	238

Mechanical Properties	239
Weld Quality	247
Economics	252
Safe Practices	253
Conclusion	253
Bibliography.....	253

CHAPTER 8—ULTRASONIC WELDING	263
Introduction	264
Fundamentals	264
Equipment	271
Welding Variables and Procedures	276
Metals Welded.....	280
Applications	283
Mechanisms of Ultrasonic Welding.....	285
Ultrasonic Microwelding	291
Weld Quality	295
Economics	300
Safe Practices	300
Conclusion	301
Bibliography.....	301

CHAPTER 9—EXPLOSION WELDING	303
Introduction	304
Fundamentals	304
Equipment and Facilities	308
Testing Equipment.....	312
Welding Variables.....	312
Materials	314
Applications	316
Cylinders	319
Transition Joints.....	320
Heat Exchangers	323
Weld Quality and Testing	324
Economics	327
Safe Practices	329
Conclusion	329
Bibliography.....	329

CHAPTER 10—ADHESIVE BONDING	333
Introduction	334
Fundamentals	334
Adhesives	341
Joint Design.....	347
Surface Preparation	353
Procedures.....	355
Equipment	358
Quality Control.....	358
Economics	360
Safe Practices	361
Conclusion	363
Bibliography.....	364

CHAPTER 11—THERMAL SPRAYING AND COLD SPRAYING	367
Introduction	368
Fundamentals	369
Process Variables	371
Process Variations	378
Equipment and Materials	387
Characteristics of Spray-Deposited Materials	396
Post-Spray Treatments	403
Applications	405
Quality Assurance	409
Economics	410
Safe Practices	412
Conclusion	417
Bibliography	418
 CHAPTER 12—DIFFUSION WELDING AND DIFFUSION BRAZING	 421
Introduction	422
Advantages and Limitations	422
Surface Preparation	423
Diffusion Welding	424
Fundamentals	424
Applications	426
Process Variables	426
Process Variations	428
Techniques	429
Equipment	430
Tooling	433
Metals Welded	433
Diffusion Brazing	437
Methods	438
Variables	439
Equipment and Tooling	441
Materials and Applications	442
Diffusion Soldering	445
Applications	446
Inspection of DFW and DFB Joints	446
Economics	447
Safe Practices	447
Conclusion	448
Bibliography	448
 CHAPTER 13—ELECTRON BEAM WELDING	 451
Introduction	452
Fundamentals	452
Equipment	468
Welding Procedures	484
Selection of Welding Variables	488
Applications	493
Weld Quality	494
Economics	499
Safe Practices	499
Conclusion	501
Bibliography	501

CHAPTER 14—LASER BEAM WELDING, CUTTING AND ASSOCIATED PROCESSES	503
Introduction	504
Fundamentals of Laser Beam Welding and Cutting	505
Laser Beam Welding	506
Laser Beam Systems	507
Welding Techniques	521
Applications	524
Joint Design	528
Laser Beam Cutting	530
Principles of Cutting and Drilling	531
Equipment	539
Materials	544
Process Variables	546
Quality	554
Economics of Laser Beam Welding and Cutting	554
Safe Practices	555
Conclusion	558
Bibliography	558
 CHAPTER 15—OTHER WELDING AND CUTTING PROCESSES	 561
Introduction	562
Forge Welding	562
Early Arc Welding	564
Hot Pressure Welding	566
Thermite Welding	573
Cold Welding	583
Magnetic Pulse Welding	592
Electro-Spark Deposition	598
Percussion Welding	602
Water Jet Cutting	607
Conclusion	613
Bibliography	613
 APPENDIX A—AMERICAN WELDING SOCIETY SAFETY AND HEALTH STANDARDS LIST	 617
 APPENDIX B—SAFETY CODES AND OTHER STANDARDS	 619
 APPENDIX C—CONVERSIONS FOR VARIOUS PRESSURE UNITS	 623
 MAJOR SUBJECT INDEX:	
Volumes 1, 2, and 3—Ninth Edition, and Volumes 3 and 4—Eighth Edition	625
 INDEX OF VOLUME 3, NINTH EDITION	 645

ACKNOWLEDGMENTS

The American Welding Society Welding Handbook Committee and the editors recognize the contributions of the volunteers listed below who have created, developed, and documented the technology of welding and shared it in past editions of the *Welding Handbook*, beginning with the first edition published in 1938. The enthusiasm and meticulous dedication of the authors and technologists reflected in the previous eight editions of the *Welding Handbook* are continued in this volume of the Ninth Edition.

This volume was compiled by the members the Welding Handbook Volume 3 Committee and the Chapter Committees, with oversight by the Welding Handbook Committee. Chapter committee chairs, chapter committee members, and oversight persons are recognized on the title pages of the chapters.

The Welding Handbook Committee and the editors recognize and appreciate the AWS technical committees who developed the consensus standards that pertain to this volume, and acknowledge the work of R. L. O'Brien, Editor of Volume 2, Eighth Edition. The Welding Handbook Committee is grateful to members of the AWS Technical Activities Committee and the AWS Safety and Health Committee for their reviews of the chapters. The Editors express their appreciation to the AWS Technical Division staff for their assistance during the preparation of this volume.

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PREFACE

This is Volume 3 of the *Welding Handbook*, the third of the five-volume series in the Ninth Edition. Following the publication of *Welding Handbook* Volume 1, *Welding Science and Technology*, the Welding Handbook Committee determined that one volume could no longer contain the process technology described in the 29 chapters of Volume 2, Eighth Edition; thus Volume 2 and Volume 3 of the Ninth Edition were designed to accommodate the expanded information. *Welding Processes, Part 1* presented updated information on arc welding and cutting, the gas processes, brazing, and soldering. This volume, *Welding Processes, Part 2* is devoted to information on resistance welding, solid state processes and other joining and cutting methods. Volumes 4 and 5 of the Ninth Edition of the *Welding Handbook* will address welding materials and applications.

Volume 3 contains updated resistance welding chapters: spot and seam welding, projection welding, flash and upset welding, high-frequency welding, and resistance welding equipment. The chapter on friction welding has been updated, and new in this edition, a separate chapter on the developing process variation, friction stir welding, has been added. Other chapters are ultrasonic welding, explosion welding, adhesive bonding, thermal spraying and cold spraying, diffusion welding and diffusion brazing. The chapters on electron beam welding and laser beam welding and cutting contain significantly expanded technology. The last chapter, Other Welding and Cutting Processes, contains information on two new or revitalized processes, magnetic pulse welding, and electro-spark depositing. New information is presented on water jet cutting, which is reappearing in many current applications as a modern, efficient process.

A table of contents of each chapter is outlined on the cover page, and a subject index with cross-references appears at the end of the volume. A major subject index of this volume and previous editions of the *Welding Handbook* is included. Appendices A and B are lists of safety standards, and Appendix C presents a list of SI/inch-pound conversions of commonly used pressure units.

The chapters in this volume reflect the dramatic changes brought into welding processes over the past decade by the precise control of welding parameters made possible with digital controls and microprocessors as applied to new techniques and advanced materials. To meet the challenge of including this expanded technology, each chapter was prepared by a committee made up of highly qualified experts enthusiastic about the subject process, and headed by a chapter chair with an admirable dedication to the details of infusing state-of-the-art information into the basics of the processes. All committee members are volunteers who generously devoted countless hours of personal time to the chapters.

One hundred and ten American Welding Society volunteers contributed to this book, representing university, government, and private welding research and development institutions, manufacturers of welding equipment and materials, and manufacturers, fabricators, and welders who use this technology.

The Welding Handbook Committee welcomes your comments and suggestions. Please address them to the Editor, *Welding Handbook*, American Welding Society, 550 N. W. LeJeune Road, Miami, FL 33126.

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CHAPTER 1

RESISTANCE SPOT AND SEAM WELDING



Photograph courtesy of Soudronic Automotive AG

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Contents

Introduction	2
Fundamentals	2
Equipment	11
Surface Preparation	14
Resistance Spot Welding	15
Resistance Seam Welding	26
Metal Properties and Weldability	39
Economics	43
Safe Practices	43
Conclusion	45
Bibliography	45

CHAPTER 1

RESISTANCE SPOT AND SEAM WELDING

INTRODUCTION

Spot welding and seam welding are resistance welding processes. Resistance welding includes a group of processes that produce coalescence of the faying surfaces with the heat obtained from the resistance of the workpieces to the flow of the welding current in a circuit of which the workpieces are a part, and by the application of pressure.

A resistance spot weld is made between or on overlapping members (workpieces) in which coalescence may start and occur on the faying surfaces, or may proceed from the outer surface of one member. The weld cross section is approximately circular.

A seam weld is a continuous weld made between or on overlapping members, in which coalescence may start and occur on the faying surfaces, or may have proceeded from the outer surface of one member. The continuous weld may consist of a single weld bead or a series of overlapping spot welds.^{1,2}

Spot welding and seam welding adapt well to automation. They are mainstay processes in the automotive industry and in other industries that manufacture products involving the welding of similar thicknesses of the same metal. Examples include automobile fuel tanks, catalytic converters, mufflers, and roof joints. Seam welding is an important process for manufacturers of

cans and containers of all types. Other products of spot and seam welding are furnace heat exchangers and storage tanks.

This chapter covers the fundamental principles of these processes and their variations, equipment, and mechanical systems. The advantages and limitations of the processes are discussed, and welding conditions as applied to various metals are presented. Other topics include joint design, welding schedules, surface preparation, weld quality, and economics. The chapter concludes with a section on safe practices specific to the spot and seam welding processes.

FUNDAMENTALS

In resistance spot welding and seam welding, the coalescence of metals is produced by the heat generated in the workpieces due to resistance to the passage of electric current through each workpiece. Force, exerted on the joint through the electrodes, is always applied before, during, and after the application of current to confine the weld contact area at the faying surfaces and, in some applications, to forge the weld metal during postheating.

A resistance welding electrode is the part of a resistance welding machine through which the welding current and (in most cases) force are applied directly to the workpiece. The electrode may be in the form of a rotating wheel, rotating roll, bar, cylinder, plate, clamp, chuck, or a modification of one of these.

Figure 1.1 illustrates the mechanisms of the resistance welding processes.

1. Welding terms and definitions used throughout this chapter are from *Standard Welding Terms and Definitions*, AWS A3.0:2001, Miami: American Welding Society.

2. At the time of the preparation of this chapter, the referenced codes and other standards were valid. If a code or other standard is cited without a date of publication, it is understood that the latest edition of the document referred to applies. If a code or other standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

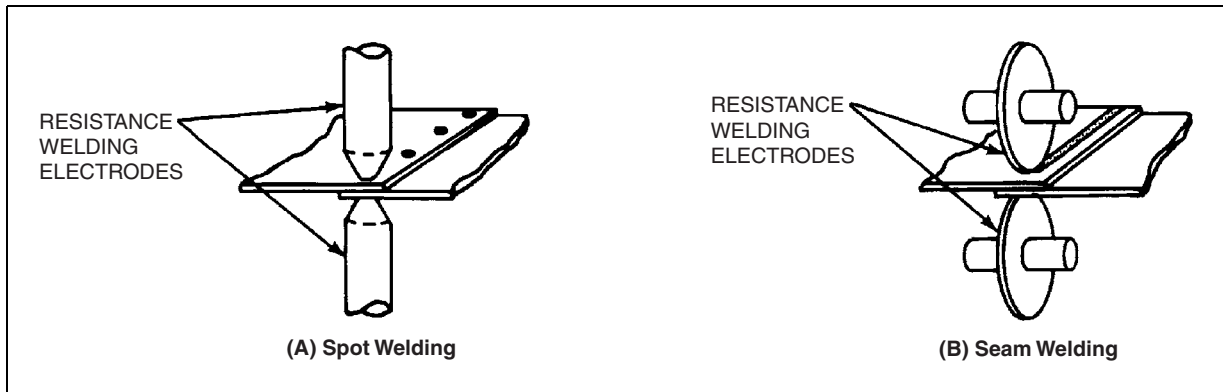


Figure 1.1—Simplified Diagrams of Basic Resistance Spot Welding (A), and Seam Welding (B)

In spot welding, a nugget (the weld metal that joins the workpieces) is produced at the electrode site, but two or more nuggets may be made simultaneously using multiple sets of electrodes. Seam welding is a variation of spot welding in which a series of overlapping nuggets are produced to obtain a continuous, leak-tight seam. One or both electrodes generally are in the form of wheels that rotate as the workpieces pass between them or between one wheel and a flat copper electrode. A seam weld can be produced with spot welding equipment, but the operation is much slower. A series of separate spot welds may be made with a seam welding machine and wheel electrodes by suitably adjusting the travel speed and the time between welds.

PRINCIPLES OF OPERATION

Spot and seam welding operations involve the coordinated application of electric current and mechanical pressure of sufficient magnitude and duration. The welding current must pass from the electrodes through the workpieces. The continuity of weld current is promoted by force applied to the electrodes. The first requirement in the sequence of operations is to develop sufficient heat to raise a confined volume of metal to the molten state. The fused metal is then allowed to cool while under pressure until it has adequate strength to hold the workpieces together. The current density and pressure must be high enough to form a nugget, but should not be so high that they cause molten metal to be expelled from the weld zone. The duration of weld current must be accurately timed to prevent excessive heating of the electrode faces that could fuse an electrode to a workpiece and greatly reduce the service life of the electrode.

As noted, heat in a resistance welding process is produced by electrical current flowing through the electrical resistance in the workpiece. Because metals have relatively low resistance, welding current must be relatively high to produce sufficient heat to develop welding temperatures at the desired location. Weld current also must exceed heat loss by thermal conduction in the workpiece and loss to the relatively cool electrodes in contact with the workpiece.

Heat Generation

The amount of heat generated in an electrical conductor depends on the following factors:

1. Amperage,
2. Resistance of the conductor (including interface resistance), and
3. Duration of current.

These three factors affect the heat generated, as expressed in the following equation:

$$Q = I^2 R t \quad (1.1)$$

where

- Q = Heat generated, joules (J);
 I = Current, amperes (A);
 R = Resistance of the workpieces, ohms (Ω); and
 t = Duration of current, seconds (s).

The heat generated is proportional to the square of the welding current and directly proportional to the resistance and the time. Some of the heat is used to form the weld and some is lost to the surrounding metal.

The welding current required to produce a given weld is an approximation inversely proportional to the square root of the time. Thus, if the time is extremely short, the current required will be high.

The secondary circuit of a resistance welding machine and the workpieces constitute a series electrical circuit. The total electrical impedance of the current path affects the current magnitude for a given applied voltage. The current in a series circuit will be the same in all parts of the circuit. The heat generated at any location in the circuit will be directly proportional to the resistance at that point.

A very important characteristic of resistance welding is the rapidity with which welding heat can be produced. The temperature distribution in the workpieces and electrodes in spot and seam welding is illustrated in Figure 1.2.

In effect, there are at least seven resistances connected in series that account for the temperature distribution in a weld. The resistances numbered from 1 through 7 shown in Figure 1.2 apply to a two-thickness joint. Numbers 1 and 7 denote the electrical resistance of the electrode material.

Numbers 2 and 6 represent the contact resistance between the electrode and the base metal. The magnitude of this resistance depends on the surface condition of the base metals and each electrode, the size and contour of each electrode face, and the electrode force. (Resistance is approximately inversely proportional to

the contacting force.) This is a point of high heat generation, but the surface of the base metal does not reach fusion temperature during the passage of current due to the high thermal conductivity of the electrodes (1 and 7) and the fact that they are usually water-cooled. For free-zinc galvanized steels (when zinc is in elemental form as opposed to zinc alloys such as zinc-nickel or zinc iron [galvanneal]), the contact and faying surface resistance is not significantly higher than the bulk resistance of the material. Therefore, bulk heating of the material contributes substantially to the development of the weld.

Planes 3 and 5 are locations of the total resistance of the base metal, which is directly proportional to its resistivity and thickness, and inversely proportional to the cross-sectional area of the current path.

Plane 4 is the location of the base metal interface resistance where the weld is to be formed. This is the point of highest resistance and therefore the point of greatest heat generation. Since heat is also generated at Points 2 and 6, the heat generated at Plane 4 is not readily lost to the electrodes.

Heat is generated at all of these locations, not at the base metal interface alone. The flow of heat to or from the base metal interface is governed by the temperature gradient established by the resistance heating of the various components in the circuit. This in turn assists or retards the creation of the proper localized welding heat.

Heat will be generated in each of the seven locations shown in Figure 1.2 in proportion to the resistance of

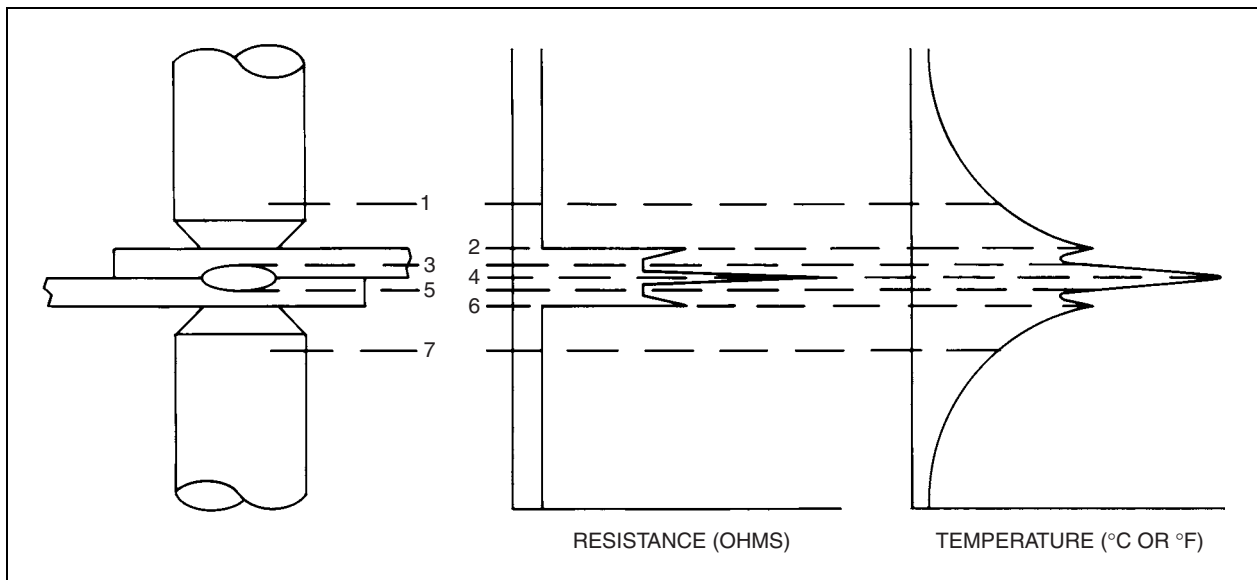


Figure 1.2—Relationship of Resistance and Temperature as a Function of Location in the Diagrammed Circuit



each. However, welding heat is required only at the base metal interface, and the heat generated at all other locations should be minimized. Since the greatest resistance is located at Plane 4, heat is most rapidly developed at that location. Points of next-lower resistance are Planes 2 and 6. The temperature rises rapidly at these points also, but not as fast as at Plane 4. After about 20% of the weld time has elapsed, the heat gradient may conform to the profile shown in Figure 1.2. Heat generated at Planes 2 and 6 is rapidly dissipated into the adjacent water-cooled electrodes at Planes 1 and 7. The heat at Plane 4 is dissipated much more slowly into the base metal. Therefore, while the welding current continues, the rate of temperature rise at Plane 4 will be much more rapid than at Planes 2 and 6. The welding temperature is indicated on the chart at the right in Figure 1.2 by the number of short horizontal lines within the drawing that lead to the matching curve. In a well-controlled weld, the welding temperature is first reached at numerous contact points at the weld interface; then melting occurs, and with time, the contact points quickly grow into a nugget.

The following factors affect the amount of heat generated in the weld joint by a given current for a unit of weld time:

1. The electrical resistances within the workpieces and the electrodes,
2. The contact resistances between the workpieces and between the electrodes and the workpieces, and
3. The heat lost to the workpieces and the electrodes.

Effect of Welding Current

In the formula, $Q = I^2Rt$, current has a greater effect on the generation of heat than either resistance or time. Therefore, it is an important variable to be controlled. Two factors that cause variation in welding current with alternating current (ac) welding machines are fluctuations in power-line voltage and variations in the impedance of the secondary circuit. Impedance variations are caused by changes in circuit geometry or by the introduction of varying masses of magnetic metals into the secondary loop of the machine.

In addition to variations in the magnitude of welding current, current density may vary at the weld interface. This change in current density can result from the shunting of current through preceding welds and contact points other than those at the weld. An increase in electrode face area will decrease current density and welding heat. This may cause a measurable decrease in weld size. Minimum current density for a finite time is required to produce fusion at the interface. Sufficient heat must be generated to overcome the losses to the adjacent base metal and the electrodes.

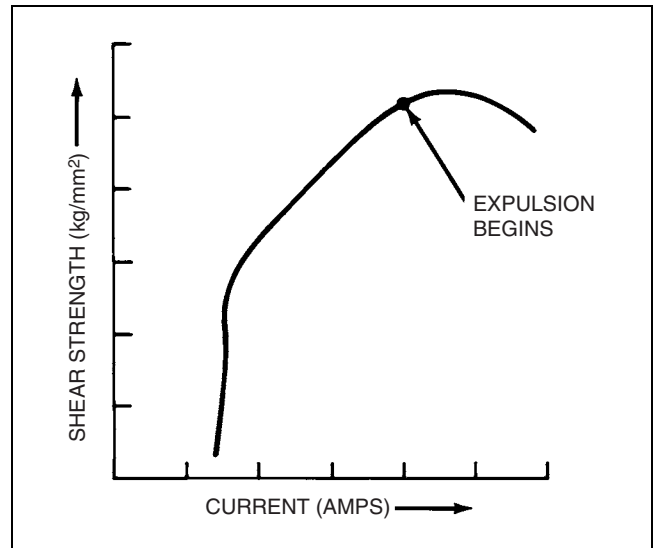


Figure 1.3—Effect of Welding Current on Shear Strength of Spot Welds

Weld nugget size and strength increase rapidly with increasing current density. Excessive current density will cause molten metal expulsion (resulting in internal voids), weld cracking, and lower mechanical strength properties. Typical variations in the shear strength of spot welds as a function of current magnitude are shown in Figure 1.3. In spot and seam welding, excessive current overheats the base metal and results in deep indentations in the workpieces and will cause overheating and rapid deterioration of the electrodes.

Effect of Weld Time

The rate of heat generation must be adjusted so welds with adequate strength will be produced without excessive heating and rapid deterioration of the electrode. The total heat developed is proportional to weld time. Essentially, heat is lost by conduction into the surrounding base metal and the electrodes; a very small amount is lost by radiation. These losses increase in proportion to weld time and metal temperature.

Given suitable current density, some minimum time is required to reach melting temperature during a spot welding operation. If current is continued, the temperature at Plane 4 (refer to Figure 1.2) in the weld nugget will far exceed the melting temperature, and the internal pressure may expel molten metal from the joint. Generated gases or metal vapor and molten particles may be expelled. If the work piece surfaces are scaly

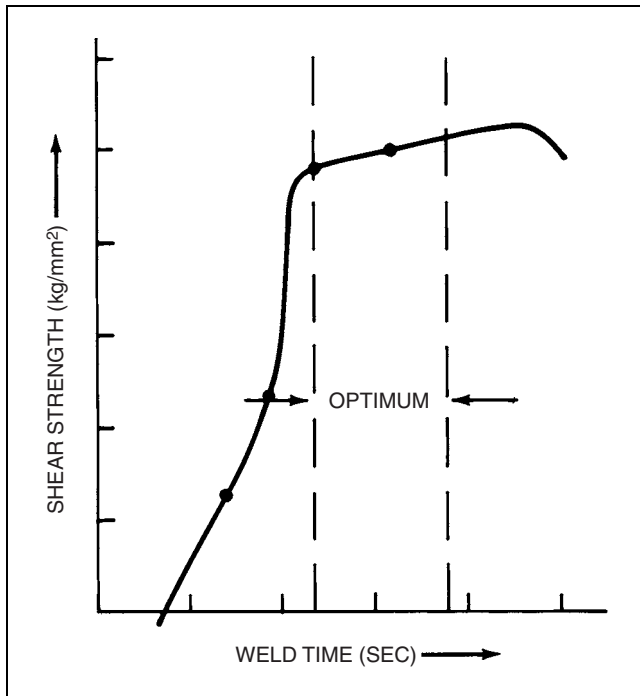


Figure 1.4—Tensile Shear Strength as a Function of Weld Time

or pitted, gases and particles also may be expelled at Planes 2 and 6.

In most cases, at some point during an extended welding interval the heat losses will equal the heat input and temperatures will stabilize. An example of the relationship between weld time and spot weld shear strength is shown in Figure 1.4, assuming all other conditions remain constant.

To a limited extent, weld time and amperage may be complementary. The total heat may be changed by adjusting either the amperage or the weld time. Attempts to speed up the process by increasing current and reducing weld time eventually will produce a runaway thermal condition at the faying surface accompanied by severe expulsion. The heat must be applied long enough for the faying surface heat to be conducted into the surrounding metal to grow the nugget and produce the desired weld size.

When spot-welding heavy plate, welding current commonly is applied in several relatively short impulses without removal of electrode force. The purpose of pulsing the current is to gradually build up the heat between the workpieces at the weld interface. The amperage needed to accomplish welding can rapidly melt the metal if the heat pulse time is too long, resulting in expulsion.

Effect of Welding Pressure

The resistance R in the heat formula (Equation 1.1) is influenced by welding pressure through its effect on contact resistance at the weld interface. Welding pressure is produced by the force exerted on the joint by the electrodes. Electrode force is considered to be the net dynamic force of the electrodes on the workpieces, and it is the pressure produced by this force that affects the contact resistance.

Workpieces to be spot or seam welded must be clamped tightly together at the weld location to facilitate passage of the current. For a given set of parameters, including welding circuit, welding equipment, electrode geometry, and workpiece surface condition, the amperage will rise to some limiting value as the electrode force or welding pressure is increased. The effect on the total heat generated in the workpiece, however, may be the reverse. As the pressure is increased, the contact resistance and the heat generated at the interface will decrease. To increase the heat to the previous level, amperage or weld time must be increased to compensate for the reduced resistance.

On a microscopic scale, the surfaces of metal components are a series of peaks and valleys. When they are subjected to light pressure, the actual metal-to-metal contact will be only at the contacting peaks, which is a small percentage of the area. Thus, with light pressure on the workpieces, contact resistance will be high. As the pressure is increased, the high spots are depressed and the actual metal-to-metal contact area will be increased, causing a decrease in the contact resistance. In most applications, the electrode material is softer than the workpieces; consequently, the application of a suitable electrode force will produce lower contact resistance at the electrode-to-workpiece interfaces than at the interface between the workpieces.

Of the variables in the resistance welding process, surface resistance may be the most difficult to control. Increasing the weld force frequently will reduce this resistance and cause the process to be more dependent on the bulk material resistance, which is generally consistent. This reduces process variation at the expense of higher current, increased wear and tear on the machine, and other negative factors associated with higher force.

Influence of Electrodes

Electrodes perform a vital function in the generation of heat because they conduct the welding current to the workpieces. In spot and seam welding, the electrode contact area largely controls the welding current density and the resulting weld size. Electrodes must have good electrical conductivity, but they also must have adequate strength and hardness to resist deformation caused by repeated applications of high electrode force.

Deformation or “mushrooming” of the electrode face increases the contact area and decreases both current density and welding pressure. Weld quality deteriorates as deformation of the electrode face proceeds; therefore, the electrodes must be reshaped or replaced at intervals to maintain adequate heat generation for acceptable weld properties. A similar increase in the electrode contact area is caused by erosion and pitting of the electrodes when welding coated materials.

When the electrodes are slow in following a sudden decrease in total thickness of the workpieces, a momentary reduction in pressure occurs. If this happens while the welding current is on, interface contact resistance at Locations 2, 4, and 6 (refer to Figure 1.2) and the rate of heat generation will increase. An excessive heating rate at the three contacting surfaces tends to cause overheating and violent expulsion of molten metal. Molten metal is retained at each interface by a ring of unfused metal surrounding the weld nugget. A momentary reduction in electrode force permits the internal metal pressure to rupture this surrounding ring of metal that is not fused. Internal voids or excessive electrode indentation may result. Weld properties may fall below acceptable levels, and electrode wear will be greater than normal.

Influence of Surface Condition

The surface condition of the workpieces influences heat generation because contact resistance is affected by oxides, dirt, oil, and other foreign matter on the surfaces. The most uniform weld properties are obtained when the surfaces are clean.

The welding of workpieces with an irregular coating of oxides, scale, or other contamination causes variations in contact resistance. This produces inconsistencies in heat generation. Heavy scale on the work surfaces also may become embedded in the electrode faces, causing rapid deterioration of the electrode. Oil and grease on the surface may pick up dirt that will contribute to electrode deterioration.

Influence of Metal Composition

The electrical resistivity of a metal directly influences resistance heating during welding. In high-conductivity metals such as silver and copper, little heat is developed even under high current densities. The small amount of heat generated is rapidly conducted into the surrounding workpiece and the electrodes.

The composition of a metal determines its specific heat, melting temperature, latent heat of fusion, and thermal conductivity. These properties govern the amount of heat required to melt the metal and produce a weld. However, the amount of heat necessary to raise a unit-mass of most commercial metals to the fusion

temperature is very nearly the same. For example, stainless steel and aluminum require the same number of energy units to reach fusion temperature, even though they widely differ in spot welding characteristics. As a result, the electrical and thermal conductivities become dominant. The conductivities of aluminum are about ten times greater than those of stainless steel. Consequently, the heat lost in the electrodes and surrounding metal is greater with aluminum. Accordingly, the welding current used for aluminum must be considerably greater than that used for stainless steel.

Heat Balance

Heat balance occurs when the depth of fusion (penetration) in the two workpieces is approximately the same. The majority of spot and seam welding applications involves the welding of similar thicknesses of the same metal, with electrodes of the same alloy, shape, and size. In these cases, heat balance is automatic. The heat generated in the workpiece is unbalanced, however, for applications in which welding is performed on different gauges and grades of materials.

Heat balance may be affected by the following conditions:

1. Relative electrical and thermal conductivity of the workpieces,
2. Relative geometry of the workpieces at the joint,
3. Thermal and electrical conductivity of the electrodes, and
4. Geometry of the electrodes.

It should be noted that if dissimilar electrodes are used in high-volume production operations, the design must be error-proofed by using electrode (tip) designs that cannot be interchanged. The use of the incorrect electrode tends to cause an unbalanced heat condition leading to discrepant welds.

Heating will be unbalanced when workpieces have significantly different composition or different thickness, or both. The imbalance can be minimized in many cases by the design of the workpiece or the design and material of the electrode. Heat balance also can be improved by using the shortest weld time and lowest current that will produce acceptable welds.

Heat Dissipation. During welding, heat is lost by conduction into the adjacent base metal and the electrodes, as shown in Figure 1.5. This heat dissipation continues at varying rates during the application of current and afterward until the weld has cooled to room temperature. It may be divided into two time phases: during the time of current application and after the cessation of current. The extent of the loss depends on the composition and mass of the workpieces, the

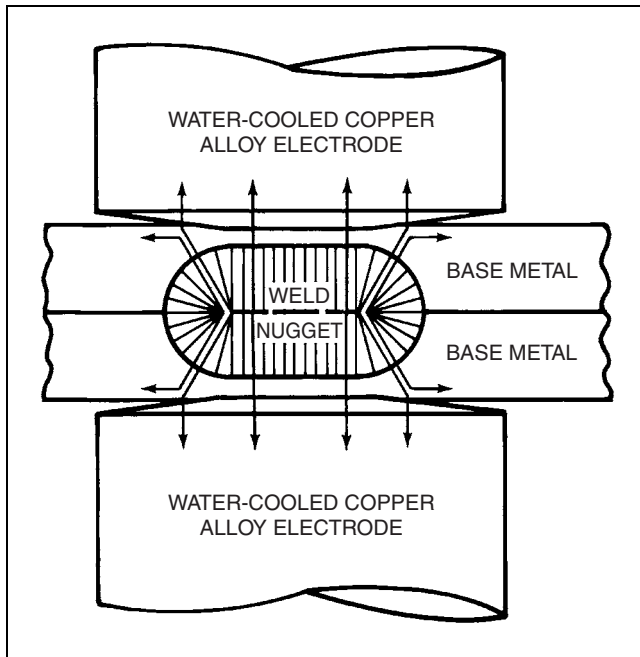


Figure 1.5—Heat Dissipation into Surrounding Base Metal and Electrodes During Resistance Welding

welding time, and the means of external cooling. The composition and mass of the workpieces are determined by the design. External cooling depends on the welding setup and the welding cycle.

The heat generated by the welding current is inversely proportional to the electrical conductivity of the base metal. The thermal conductivity and temperature of the base metal determine the rate at which heat is dissipated or conducted from the weld zone.³ In most cases, the thermal and electrical conductivities of a metal are similar. In a high-conductivity metal, such as copper or silver, high amperage is needed to produce a weld and compensate for the heat that is dissipated rapidly into the adjacent base metal and the electrodes. Spot and seam welding of these metals is difficult.

If the electrodes remain in contact with the workpieces after weld current ceases, they rapidly cool the weld nugget. The rate of cooling decreases with longer welding times because a larger volume of base metal would have been heated. This reduces the temperature

gradient between the surrounding base metal and the weld nugget. The cooling rates are slower for thick sheets of metal that generally require long welding times than for thin sheets and short weld times.

Problems may result if the electrodes are removed from the weld too quickly after the welding current is turned off. This action may cause excessive warping when welding thin sheets. With thick sheets, adequate time is needed to cool and solidify the large weld nugget while under pressure. On coated materials, such as galvanized steel containing zinc, the removal of the electrodes too soon may allow the surface temperature to increase to the level that zinc penetration into the grain boundaries of the steel may occur. Zinc penetration can reduce weld strength and performance. It usually is best, therefore, to maintain the electrodes in contact with the workpieces until the weld cools to a temperature that is strong enough to sustain any loading that will be imposed when the pressure is released.

The cooling time for a seam weld nugget is short when the electrodes are rotated continuously. Therefore, welding is commonly done with water flowing over the workpieces to remove the heat as rapidly as possible. The flowing water develops a steam bubble over the hot area, and more effective cooling is achieved by directing a stream of water from a nozzle at the point where the welded material exits from under the resistance welding electrode. It is not always good practice to cool the weld zone rapidly. When welding quench-hardenable steel alloys, it usually is best to retract the electrodes as quickly as possible to minimize heat dissipation to the electrodes, and thus reduce the cooling rate of the weld.

WELDING CYCLE

The welding cycle for spot and seam welding consists of the four basic phases: squeeze time, weld time, hold time, and off time. Off time generally is used only for manually initiated repetitive welding cycles. The phases of the welding cycle are described as follows:

1. *Squeeze time*—the time interval between initiating the timer and the first application of current; the time interval added to ensure that the electrodes contact the workpieces and establish the desired electrode force before welding current is applied;
2. *Weld time*—the time that welding current is applied to the workpieces in making a weld in single-impulse welding;
3. *Hold time*—the time during which force is maintained on the workpieces after the last impulse of current ends, allowing the weld to cool, solidify and cool until it has adequate strength; and

3. For additional information, see "Heat Flow in Welding," Chapter 3 in American Welding Society (AWS) Welding Handbook Committee, Jenney, C. L., and A. O'Brien, Eds., 2001, *Welding Science and Technology*, Vol. 1, *Welding Handbook*, 9th ed., Miami: American Welding Society.

4. *Off time*—the time during which the electrodes are off the workpiece and the workpiece is moved to the next weld location. The term is generally applied when the welding cycle is repetitive.

Figure 1.6 shows a basic welding cycle. One or more of the following features may be added to this basic cycle to improve the physical and mechanical properties of the weld zone:

1. Precompression force to seat the electrodes and workpieces together,
2. Preheat to reduce the thermal gradient in the metal at the start of weld time,
3. Forging force to consolidate the weld nugget,
4. Quench and temper times to produce the desired weld strength properties in hardenable alloy steels,
5. Postheat to refine the weld grain size in steels, and
6. Current decay to retard cooling in aluminum.

In some applications, the welding current is supplied intermittently during a weld interval time; it is on during heating time and ceases during cooling time. Figure 1.7 shows the sequence of operations in a more complex welding cycle than the basic cycle.

WELDING CURRENT

Alternating current (ac) or direct current (dc) can be used to produce spot and seam welds. The transformer in the welding machine transforms high-voltage line power to low-voltage, high-amperage welding power. Many applications use single-phase ac of the same frequency as the power line, usually 60 hertz (Hz). Direct current is used for applications that require very high welding current. Direct current is preferred for these applications because the load power can be drawn from a three-phase power line. The use of dc welding current also reduces power losses in the secondary circuit. Direct current may be essentially constant for a timed period or may be in the form of a high-peaked pulse. The latter normally is produced from stored electrical energy.

PROGRAMMING THE CURRENT

Welding current used to produce the heat in the workpiece can be manipulated by electronic control systems. Wave forms can be alternating current, direct current, and combinations of these. In addition, current can be obtained from the power lines and stored for later use. When a stored-energy machine is used, the demand from the power lines is reduced. Power is

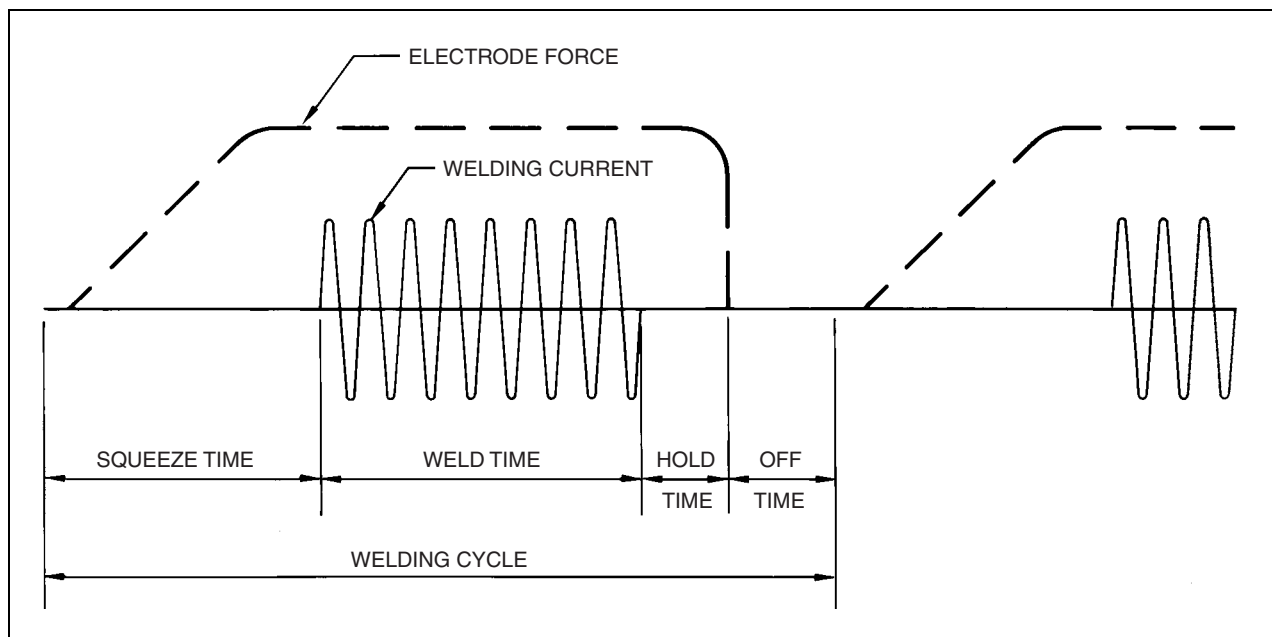


Figure 1.6—Basic Single-Impulse Welding Cycle for Spot Welding

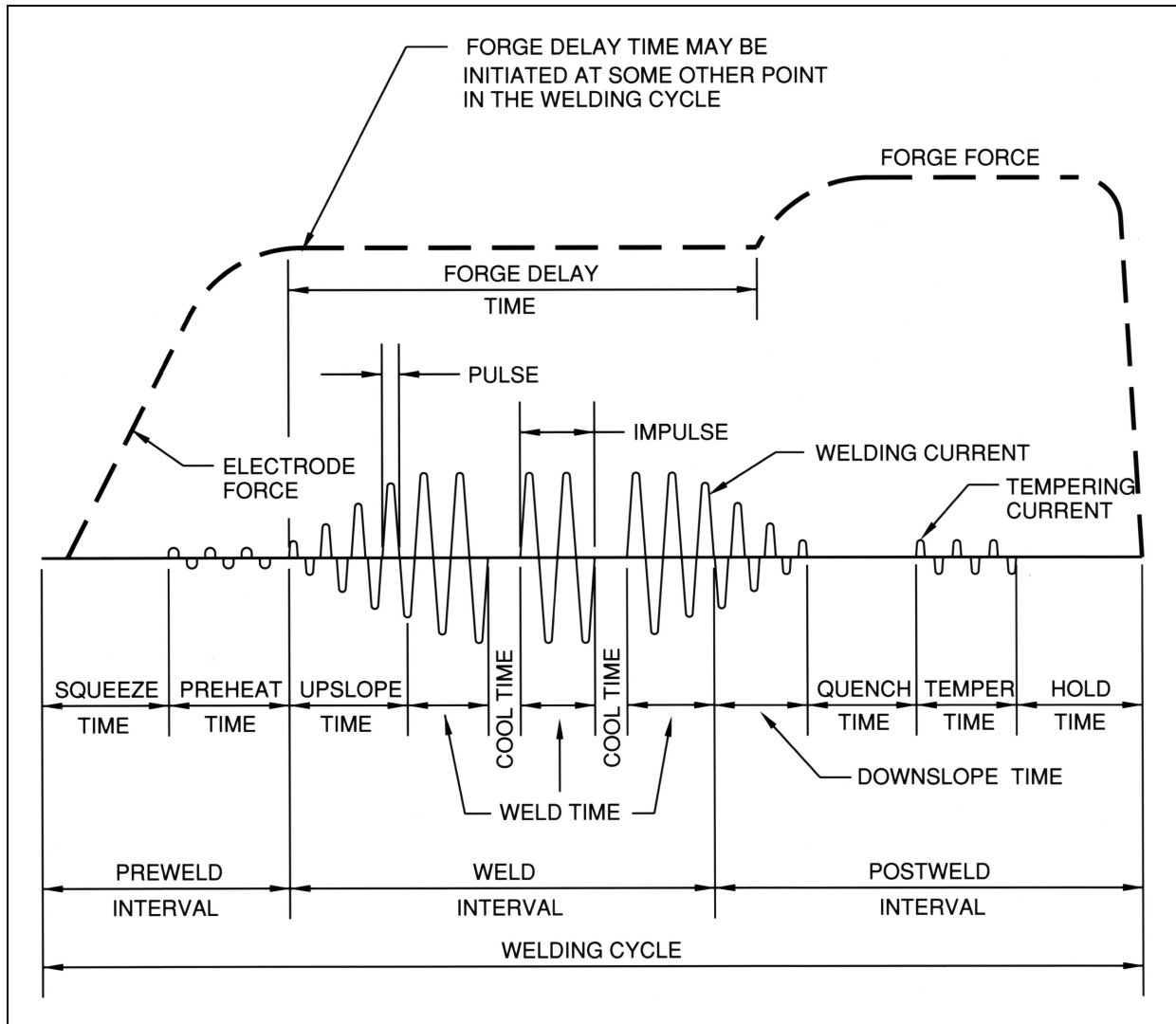


Figure 1.7—Enhanced Welding Cycle with Preheat, Upslope, Downslope, Quench and Temper Times, and Hold Time at Forging Force (Alternating Current)

acquired over longer periods of time than it takes to make a weld. When the primary power source is not capable of delivering sufficient power, stored-energy systems may offer the only way to make some resistance welds. The next section describes some of the systems in common use for controlling welding current.

Direct-Energy and Stored-Energy Welding Machines

The term *direct-energy welding machine*, as applied in this instance, refers to a machine that obtains energy

directly from the utility line supply as the weld is being made. A stored-energy machine obtains and stores the energy from the utility before the weld is made and then discharges the stored energy into the weld system. Typically the weld time of a stored-energy machine is fixed by the physical characteristics of the system and only the magnitude of the current can be adjusted.

The rate of current rise and fall can be programmed when using direct-energy welding machines. The period during which the current continuously rises or increases is called *upslope time*. The period during which the current continuously falls or decreases is called *downslope time*. These cycles are illustrated in Figure 1.7. These

features are available on machines equipped with electronic control systems.

Upslope generally is used to avoid overheating and expulsion of metal at the beginning of weld time, when the base metal interface resistance is high. Downslope is used to control weld nugget solidification, to avoid cracking in metals that are quench-hardenable or subject to hot tearing.

Prior to welding, the base metal can be preheated using a low current. Following the formation of the weld nugget, the current can be reduced to some lower value for postheating of the weld zone. This may be the downslope interval, as shown in Figure 1.7, or a separate application of current following a period of quench time.

WELD TIME

Weld time is the duration of the flow of welding current through the workpieces while making a weld. The time of applied current for machines other than stored-energy power sources is controlled by electronic, mechanical, manual, or pneumatic means. Weld times commonly range from one-half cycle (1/120 s) for very thin sheet metal to several seconds for thick plate metal. For the capacitor or magnetic type of stored-energy welding machines, the weld time is determined by the electrical constant of the system.

Single-Impulse Welding

The use of one continuous application of current to make an individual weld is called *single-impulse welding* (refer to Figure 1.6). Upslope or downslope current may be included in the time period.

Multiple-Impulse Welding

Multiple-impulse welding uses two or more pulses of current separated by a preset cooling time, as shown in Figure 1.7. This sequence is used to control the rate of heating at the interface while spot welding relatively thick steel sheet.

ELECTRODE FORCE

Completion of the electrical circuit through the electrodes and the workpieces is accomplished by applying electrode force. This force is produced by hydraulic, pneumatic, magnetic, or mechanical devices. The pressure developed at the interfaces depends on the area of the electrode faces in contact with the workpieces. This force, or pressure, performs the following functions:

1. Brings the various interfaces into intimate contact,
2. Reduces initial contact resistance at the interfaces,
3. Suppresses the expulsion of molten weld metal from the joint, and
4. Consolidates the weld nugget.

Forces may be applied during the welding cycle to accomplish the following:

1. Maintain a constant weld force;
2. Regulate precompression and weld forces to supply a high initial level to reduce initial contact resistance and bring the workpieces into intimate contact, followed by a lower level for welding;
3. Supply precompression at several levels of weld force and forging force at the first two levels as described in No. 2, followed by a forging force near the end of the weld time; and
4. Apply required weld and forging forces, the latter used to reduce porosity and hot cracking in the weld nugget.

EQUIPMENT

Spot and seam welding equipment consists of three basic elements: an electrical circuit, the control equipment, and a mechanical system.⁴

ELECTRICAL CIRCUIT

The electrical circuit is comprised of a welding transformer, a primary power control system, and a secondary circuit. The secondary circuit is made up of the electrodes that conduct the welding current to the workpiece, and includes the workpieces as part of the circuit. In some cases, a means of storing electrical energy is also included in the circuit. Either alternating current or direct current can be used. The welding machine converts 60-Hz line power to low-voltage, high-amperage power in the secondary circuit of the welding machine.

Alternating-Current Machines

Some resistance welding machines produce single-phase alternating current of the same frequency as the power line, usually 60 Hz. These machines contain a single-phase transformer that provides the high welding currents required at low voltage. Depending on the thickness and type of material to be welded, currents

4. Chapter 4 of this volume, "Resistance Welding Equipment," provides more detailed information on welding controls.

may range from 1000 amperes (A) to 100 000 A. A typical electrical circuit designed for this type of machine is shown in Figure 1.8.

Direct-Current Machines

Welding machines may produce direct current of continuous polarity, pulses of current of alternating polarity (frequency-converter machines), or high-peak pulses of current. The high-peak pulses are produced by stored electrical energy.

Rectifier Machines

Rectifier machines are direct-energy types, in which ac power from the electric utility plant distribution system (line power) passes through a welding transformer and is then rectified to dc power. Silicon-diode rectifiers are widely used in secondary circuits because of their inherent reliability and efficiency. The system can be single phase; however, one of the advantages of direct-current systems is the capability of using a three-phase transformer to feed the rectifier system in the secondary circuit. This makes it possible to use balanced three-phase line power.

Frequency-Converter Machines

Frequency-converter machines have a special welding transformer with a three-phase primary and a single-

phase secondary. The primary current is controlled by ignitron tubes or silicon-controlled rectifiers. Half-cycles of three-phase power, either positive or negative, are conducted to the transformer for a timed period that depends on the transformer design. The transformer output is a pulse of direct current. By switching the polarity of the primary half-cycles, the polarity of the secondary current is reversed. A weld may be made with one or more dc pulses.

Stored-Energy Machines. Stored-energy machines are electrostatic designs. They draw power from a single-phase system, store it, and then discharge it in a very short pulse period to make the weld. These machines draw power from the supply line over a relatively long time between welds, accumulating power to deliver to the electrodes during a short weld time.

The equipment for electrostatic stored-energy welding consists primarily of a bank of capacitors, a circuit for charging the capacitors to a predetermined voltage, and a system for discharging the capacitors through a suitable welding transformer. High-voltage capacitors generally are used, the most common varying from 1500 volts (V) to 3000 V.

ELECTRODES

Resistance welding electrodes perform the following functions:

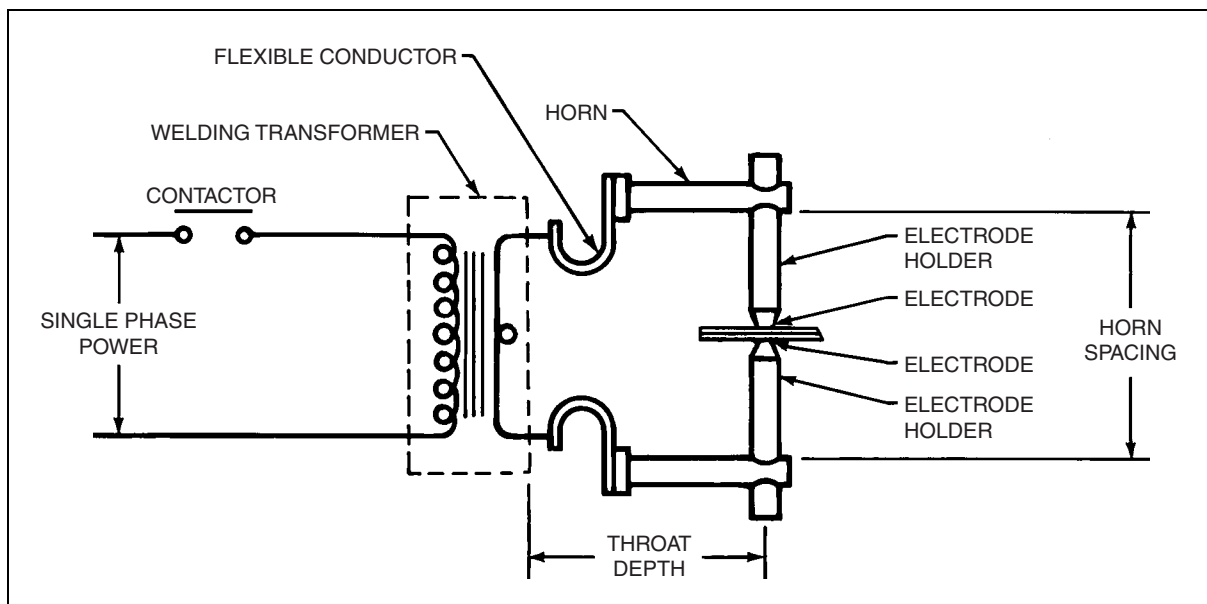


Figure 1.8—Typical Single-Phase Spot Welding Circuit

1. Conduct the welding current to the workpieces, and for spot or seam welding, provide stable electrical contact area at the weld zone;
2. Transmit a force to the workpieces;
3. Dissipate part of the heat from the weld zone; and
4. Maintain relative alignment and position of the workpieces.⁵

If the application of pressure were not involved, electrode material could be selected almost entirely on the basis of electrical and thermal conductivity. However, since the electrodes are often subjected to forces of considerable magnitude, they must be capable of withstanding the imposed stresses at elevated temperatures without excessive deformation. Proper electrode shape is important because the current must be confined to a fixed area to achieve the needed current density.

When only one spot or seam weld is to be made at a time, only one pair of electrodes is required. In this case, the force and current are applied to each weld by shaped electrodes.

Electrodes made from copper alloys with satisfactory physical and mechanical properties are available commercially. Generally, the harder the alloy, the lower are its electrical and thermal conductivities. The choice of a suitable alloy for any application is based on a compromise between its electrical and thermal properties and its mechanical qualities. Electrodes selected for aluminum welding, for instance, should have high conductivity at the expense of high compressive strength to minimize the sticking or fusing of electrodes to the workpieces. Conversely, electrodes for welding stainless steel should sacrifice high conductivity to obtain enough compressive strength to withstand the required electrode force.

Resistance of the electrode to deformation or mushrooming depends on the proportional limit and hardness of the electrode alloy. Hardness is established by heat treatment or cold working during the forming process. The temperature of the electrode face is a major factor in electrode service life because this is where softening takes place. The sizes and shapes of electrodes usually are determined by the type and thickness of the metal sheet to be welded.

CONTROL EQUIPMENT

Welding controls usually provide one or more of the following principal functions:

1. Initiate and terminate current to the welding transformer,

2. Control the magnitude of the current, and
3. Actuate and release the electrode force mechanism at the proper times.

Welding controls are divided into three functional groups: welding contactors, timing and sequencing controls, and other current controls and regulators.

A welding contactor, often simply referred to as a *weld timer*, connects and disconnects the primary power and the welding transformer. Electronic contactors using phase-shift heat control may use silicon-controlled rectifiers, ignitron tubes, thyatron tubes, power transistors or saturable reactors to regulate the primary current. The majority of weld controls use solid-state devices for regulating the weld current.

Adjustments to the timing and sequence control establish the welding sequence and the duration of each function of the sequence. This includes the application of electrode force and current, and the timing of intervals following each function.

The welding current output of a machine is controlled by transformer taps or an electronic heat control, or both. An electronic heat control is used to regulate the current conduction in power-switching devices. It controls current by delaying the conduction of the power switches (in the case of phase-shift heat control) during each half-cycle (1/120 s for 60 Hz power). Varying the firing delay time can be used to gradually increase or decrease the effective primary voltage. This provides control of upslope and downslope welding current.

Transformer taps are used to change the number of primary turns connected across the ac power line. This changes the turns ratio of the transformer, and produces an increase or decrease in open-circuit secondary voltage. Decreasing the turns ratio will increase the open-circuit secondary voltage, the primary current, and the welding current.

MECHANICAL SYSTEMS

Resistance spot welding and seam welding machines essentially have the same types of mechanical operation. The electrodes approach and retract from the workpieces at controlled times and rates. Electrode force is applied by hydraulic, pneumatic, magnetic, or mechanical means. The rate of electrode approach must be rapid, but controlled, so that the electrode faces are not deformed from repeated impact with the workpieces. The locally heated weld metal expands and contracts rapidly during the welding cycle and the electrodes must follow this movement to maintain welding pressure and electrical contact. The ability of the machine to follow motion is influenced by the moving mass of the machines force control system and its friction.

5. Resistance welding electrodes are discussed in more detail in Chapter 4, Resistance Welding Equipment.

If the pressure between the electrodes and workpieces drops rapidly during weld time, the contact surfaces of the electrodes and workpieces may overheat and result in the burning or pitting of the electrode faces. The electrodes may stick to the workpieces, and in some instances, the surfaces of the workpieces may vaporize from the very high energy concentration.

The electrode force used during the melting of the weld nugget may not be adequate to consolidate the weld metal and to prevent internal porosity or cracking. Multiple-level force machines may be employed to provide a high forging pressure during weld solidification. The magnitude of this pressure should be appropriate to the composition and thickness of the metal and the geometry of the workpieces. The forging pressure applied often is two to three times greater than the welding pressure. Since the weld cools from the periphery inward, the forging pressure must be applied at or close to the time the current terminates.

SURFACE PREPARATION

For all types of resistance welding, the condition of the surfaces of the workpieces largely controls how consistent weld quality will be. The contact resistance of the faying surfaces has a significant influence on the amount of welding heat generated; hence, the electrical resistance of these surfaces must be highly uniform for consistent results. They must be free of high-resistance materials such as paint, scale, thick oxides, and heavy oil and grease. If it is necessary to use a primer paint on the faying surfaces prior to welding, as is sometimes the case, the welding operation must be performed immediately after applying the primer, or special conducting primers must be used. For best results, the primer should be applied as thinly as possible so that the electrode force will displace it and allow metal-to-metal contact.

Paint should never be applied to outside base metal surfaces before welding because the paint will result in poor surface appearance and reduced electrode life. Heavy scale should be removed by mechanical or chemical methods. Light oil on steel is not harmful unless it has picked up dust or grit. Remnants of drawing compounds containing mineral fillers should be removed before welding.

Some seam welding and special processes that use continuously fed foil or wire between the electrode and workpiece can be used for welding coated materials. This is discussed in more detail in the seam welding section.

PREPARATION METHODS

The methods of preparing surfaces for resistance welding differ for various metals and alloys. The manufacturer of the alloy should be consulted for recommendations on preparing the surfaces for welding. The use of surface preparation processes or compounds may involve materials that present specific risks to the user. Procedures for the safe use of the cleaning materials recommended by the suppliers of the cleaners, solvents, and etchants should be carefully and consistently followed.

Some base metals may be prepared for welding by the metal supplier and shipped with protective coating or wrapping to preserve the clean surface required for good weldability. This service may be available to high-volume users.

Aluminum

The chemical affinity of aluminum for oxygen causes the aluminum to become coated with a thin film of oxide when it is exposed to air. The thin oxide film that forms on a freshly cleaned aluminum surface does not cause sufficient resistance to be troublesome for resistance welding. The permissible holding period, or elapsed time between cleaning and welding, may vary from 8 hours to 48 hours or more, depending on the cleaning process used, the cleanliness of the shop, the alloy, and the application. Heavy oxide, which is an excellent electrical insulator, and resulting hydrated surface compounds that form on aluminum alloys prevent the successful welding of aluminum that has been stored over long periods of time.

An aluminum surface may be mechanically cleaned for resistance welding using a fine grade of abrasive cloth, fine steel wool, or a fine wire brush. Clad aluminum also may be cleaned by mechanical means, but damage to the cladding must be carefully avoided. Numerous commercial chemical cleaners are available for aluminum. Chemical cleaning usually is preferred for large-volume production for reasons of economy as well as for uniformity and control.

Magnesium

The cleaning of magnesium alloys is particularly important because they readily alloy with copper at elevated temperatures. The contact resistance between the electrode and the workpiece must be kept as low as possible. Manufacturers of magnesium alloys supply the material with a coating of oil, or the alloys are chrome-pickled to protect them from oxidation during shipment and storage. The protective coating must be removed to facilitate the removal of oxidation and magnesium oxide to obtain sound and consistent welds.

Copper

The proper cleaning of copper alloys is important. The beryllium-coppers and aluminum-bronzes are particularly difficult to clean by chemical means. Mechanical means are preferred. In some instances, a flash coating of tin is applied to produce a uniformly higher surface resistance than that of pure copper.

Nickel

Nickel and nickel alloys demand high standards of cleanliness for successful resistance welding. The presence of grease, dirt, oil, and paint increases the probability of sulfur embrittlement during welding and will result in defective welds. Oxide removal is necessary if heavy oxides are present from prior thermal treatments. Machining, grinding, blasting, or pickling may be employed. Wire brushing does not produce a satisfactory surface.

Titanium

The surfaces of titanium workpieces should be scrupulously clean before welding. Contaminants such as oil, grease, dirt, oxides and paint can adversely affect both weld consistency and chemical composition. Titanium and titanium alloys react with many elements and compounds at welding temperatures. Contamination by oxygen, hydrogen, nitrogen and carbon, which enter the microstructure interstitially, can significantly reduce weld ductility and toughness. Scale-free surfaces may be welded either after degreasing or after degreasing and acid pickling. The surfaces may be degreased with acetone, methylethylketone, or a dilute solution of sodium hydroxide. Chlorinated solvents should not be used. Titanium and titanium alloys are susceptible to stress corrosion. Pickling may be used to remove light oxide scale before welding.

Steel

Plain carbon steels and low-alloy steels have relatively low resistance to corrosion in ordinary atmosphere; hence, these metals usually are protected by a thin film of oil during shipment, storage, and processing. This oil film has no harmful effects on the weld, provided the oily surfaces are not contaminated with shop dirt or other poorly conductive or dielectric materials.

Steels are supplied with various surface finishes. Some of the more common finishes are the following:

1. Hot-rolled;
2. Hot-rolled, pickled, and oiled; and
3. Cold-rolled with or without annealing.

Hot-rolled steel must be pickled or mechanically cleaned prior to welding. Hot-rolled pickled steel is weldable in the as-received condition, possibly needing only wiping to remove loose dirt. Cold-rolled steel presents the best welding surface and, if properly protected by oil, requires no cleaning prior to welding other than wiping to remove loose dirt.

High-alloy steels and stainless steels are noncorrosive and usually require only minimum cleaning before resistance welding. When exposed to elevated temperatures, stainless steels acquire an oxide film; the thickness of the oxide depends on the temperature and the length of time of exposure. The film is an oxide of chromium, which is effectively removed by pickling. Oil and grease should be removed with solvents or by vapor degreasing prior to welding.

Coated Steels. The various coatings and types of plating applied to carbon steel sheet metal to provide corrosion resistance or to enhance appearance lend themselves satisfactorily to welding with resistance welding processes, with few exceptions. In general, good results may be obtained without special cleaning processes. However, the surfaces of aluminized steel should be wire brushed before welding to minimize expulsion and electrode pickup.

Phosphate coatings can increase the electrical resistance of the surfaces to a degree that welding current cannot pass through the sheets with low welding pressures. Higher pressures will produce welds, but slight variations in coating thickness may prevent welding.

SURFACE PREPARATION CONTROL

Surface preparation control can be maintained by periodically measuring the room temperature contact resistance of the workpieces immediately following cleaning. The measurement is most readily taken tip-to-tip between two resistance welding electrodes through two or more thicknesses of metal. The unit surface resistance varies inversely with pressure, temperature, and area of contact. To make the measurements significant in the control of surface cleanliness, the test conditions must be specified.

RESISTANCE SPOT WELDING

Resistance spot welding (RSW) produces a weld at the faying surfaces of a joint by the heat obtained from resistance to the flow of welding current through the workpieces from electrodes that serve to concentrate the welding current and pressure at the weld area. Figure 1.9



Photograph courtesy of KUKA Flexible Production Systems

Figure 1.9—Resistance Spot Welding Machine

shows a robotically controlled resistance spot welding system, used for manufacturing automotive underbodies.

APPLICATIONS

Resistance spot welding is used to fabricate sheet metal assemblies up to about 3.2 mm (0.125 in.) in thickness when the design permits the use of lap joints and leak-tight seams are not required. Occasionally the process is used to join steel plates 6.35 mm (1/4 in.) or more in thickness; however, the loading of such joints is limited and the joint overlap adds weight and cost to the assembly when compared to the cost of an arc-welded butt joint.

Stainless steel, aluminum, and copper alloys are commonly used metals in commercial spot welding. The process is used extensively for joining low-carbon steel sheet metal components for automobiles, cabinets, furniture, and similar products.

Resistance spot welding is used in preference to mechanical fastening, such as riveting or screwing, when disassembly for maintenance is not required. It is much faster and more economical because separate fasteners and additional filler materials are not needed for assembly.

ADVANTAGES AND LIMITATIONS

The major advantages of resistance spot welding are its high speed and adaptability for automation in the

high-rate production of sheet metal assemblies. Spot welding is also economical in many job shop operations because it is faster than arc welding or brazing and requires less skill to perform.

Some of the limitations of the process are the following:

1. Disassembly for maintenance or repair is very difficult;
2. A lap joint adds weight and material cost to the product compared to a butt joint;
3. The equipment costs generally are higher than the costs of most arc welding equipment;
4. The short time, high current, and high power requirements produce unfavorable line power demands, particularly with single-phase machines; and
5. Heat produced by the spot weld tends to develop in the center of a stack of sheets; therefore, welding a thin outside sheet to two thick sheets becomes difficult and is not recommended where gauge ratios exceed 2:1.

SPOT WELDING VARIATIONS

Variations in the methods of performing resistance spot welds include direct and indirect welding, series welding, and parallel welding. The methods differ in the application of welding current and pressure, and in the arrangement of the secondary circuit.

Direct and Indirect Welding

Direct welding involves a resistance welding secondary circuit variation in which welding current and electrode force are applied to the workpieces by directly opposed electrodes, wheels, or conductor bars for spot or seam welding.

Arrangements for direct single spot welds are shown schematically in Figure 1.10(A), (B), and (C). In Figure 1.10(A), direct welding uses electrodes with similar geometry. In Figure 1.10(B), a larger electrode against one workpiece provides an increased contact surface area for applications requiring welding heat balance, or to reduce the indentation on the lower sheet by the electrodes. Figure 1.10(C) is similar to 1.10(B) except individual spot welds can be produced by sequenced weld guns.

Indirect welding involves a resistance spot or seam welding secondary circuit variation in which the welding current flows through the workpieces in locations away from, as well as at the point of welding.

Figures 1.10(D) through 1.10(G) represent indirect resistance welding arrangements. A backing plate

arrangement in Figure 1.10(D) provides a current path and pressure when the backing plate is made of a conducting material. If the backing plate is non-conductive, it provides support for only the welding force, and the current path will be from the top electrode, through the faying surface location, along the lower workpiece to the return connection further down the joint. Figure 1.10(E) is similar to (D) except that the electrode that does not exert pressure is away from the lap joint. The current path may be through a conducting backing plate between the electrodes, or through the base material between the electrodes. Figures 1.10(F) and (G) are similar to the joints in (D) and (E), but are for the spot welding of high-resistance materials that require higher voltages. The two secondary circuits are in series, and are connected to two transformers. The primary circuits may be connected either in series or in parallel. The two secondary circuits provide the sum of their respective voltages at the spot welds. This transformer and electrode arrangement is commonly called “push-pull,” or “over-under” and typically is used when welds are needed in the center of large workpieces. With this arrangement there is no need for a circuit to wrap around the workpiece.

Parallel and Series Welding

Parallel welding and series welding are secondary-circuit variations of resistance welding used for multiple spot welding applications. In parallel welding, the secondary current is divided and conducted through the workpieces and electrodes in parallel electrical paths, simultaneously forming multiple spot welds. Examples of parallel welding are shown schematically in Figure 1.11(A) and (B); series welding arrangements are shown in Figure 1.11(C) and (D).

In Figure 1.11(A), the welding current is from a single transformer with multiple electrodes in the secondary circuit in parallel. Figure 1.11(B) represents a parallel welding system operating with a three-phase primary. This particular system is limited to three workstations.

In series welding, Figures 1.11(C) and (D) show that the secondary circuit current is conducted through the workpieces and the electrodes in a series electrical path, simultaneously forming multiple spot welds at the electrode locations. A series-welding arrangement requires equal resistance values at the faying surfaces to obtain uniform heating at each spot weld. When spot welding with two electrodes in series, a portion of the current travels through the adjacent area of the workpiece from one electrode to the other, bypassing the faying surfaces. This shunted current does not contribute to the spot weld, and this must be taken into account when developing a procedure for series spot welding. It should be noted that on galvanized steel, this current raises the

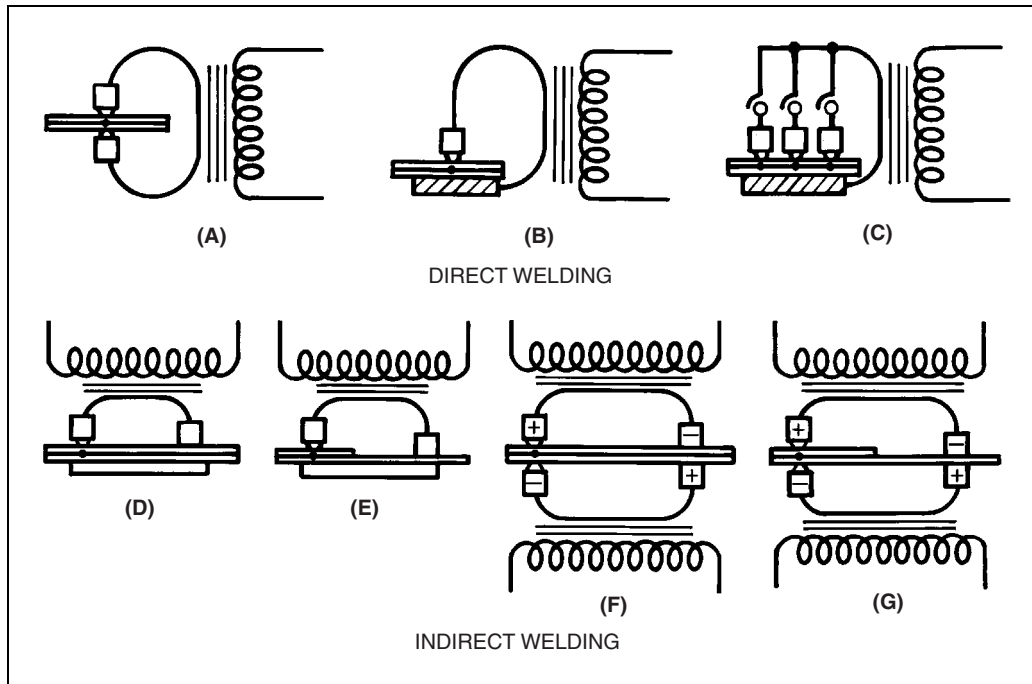


Figure 1.10—Typical Arrangements for Single Spot Welds

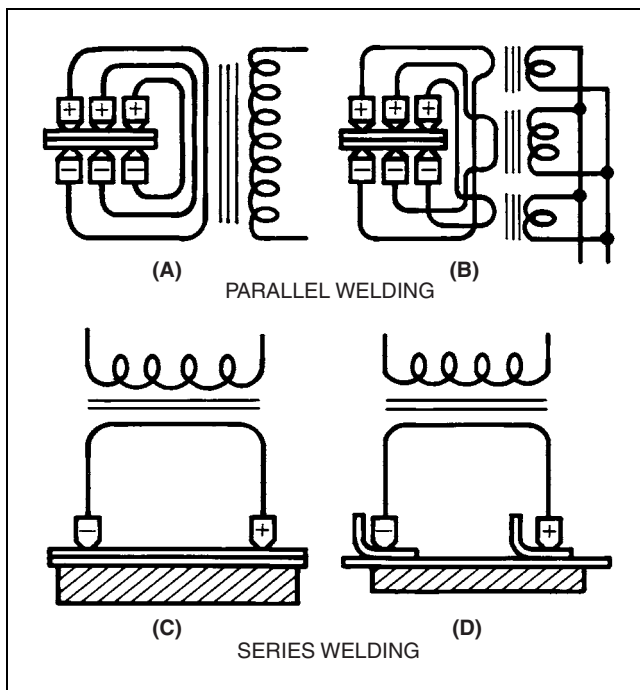


Figure 1.11—Typical Secondary Arrangements for Direct Multiple-Spot Welding

temperature of the steel surrounding the weld to the level at which zinc penetrates into the grain structure of the steel and may substantially reduce strength. Therefore, series welding should be not be used on galvanized steel.

HEAT BALANCE

Heat balance in a spot weld occurs when the depths of fusion in the two workpieces are approximately the same. Problems with heat balance arise when joints are made between metals of different thickness, different electrical conductivity, or a combination of both. Variations in electrode configurations and compositions can be used to overcome unbalanced heating to some extent, as shown in Figure 1.12. This sketch illustrates general methods for overcoming improper joint heating involving base metals with different electrical conductivity.

In Figure 1.12(A), an electrode with a smaller face area is used on the metal with the higher conductivity. The smaller contact area increases the current density in the higher conducting metal. Less heat is conducted away from the joint by the base metal and the electrode. More heat is generated in the workpiece, and the fusion area shifts from the less conductive metal to the metal with higher conductivity. An alternative would be

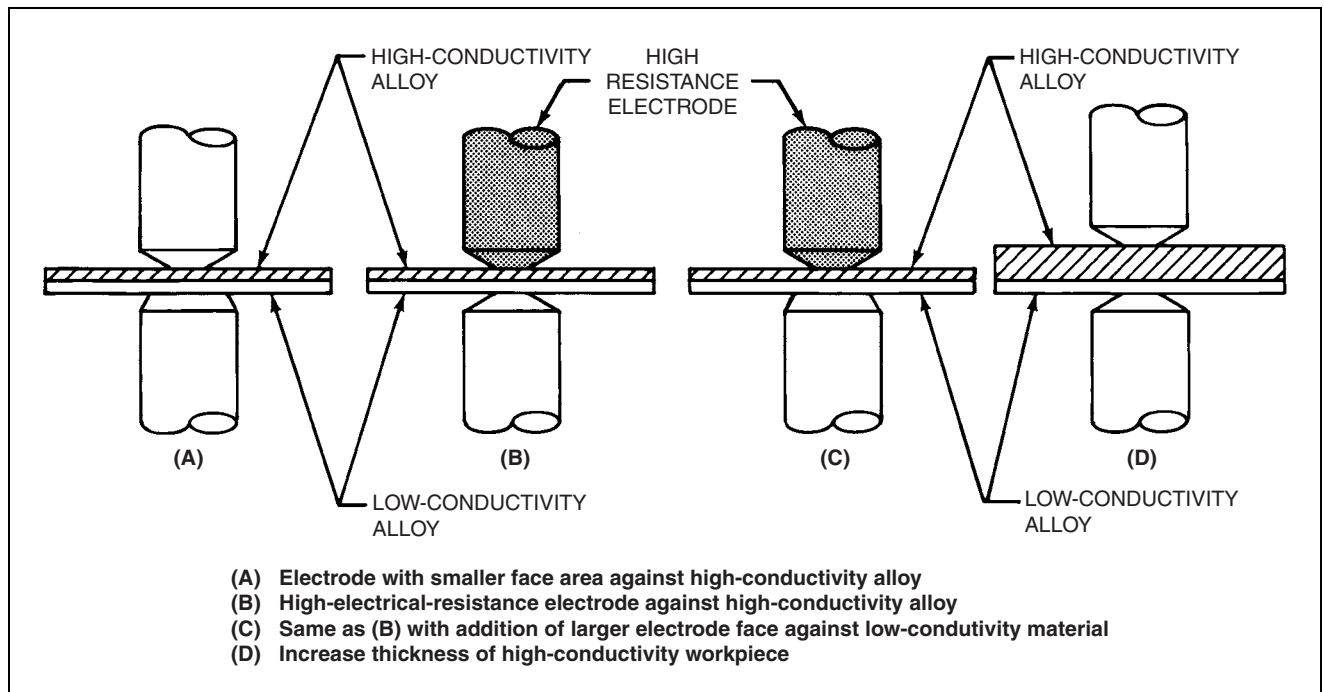


Figure 1.12—Typical Techniques for Improving Joint Heat Balance When Spot Welding Metals with Different Electrical Conductivities

to apply an electrode with higher resistance against the metal with higher conductivity to limit the heat loss through that electrode, as shown in Figure 1.12(B). Figure 1.12(C) shows the combination of a higher-resistance electrode and a smaller electrode face area applied to the more conductive metal. Better heat balance also can be obtained by increasing the thickness of the more conductive metal, as shown in Figure 1.12(D). This results in an increase in the effective resistance of the sheet.

The spot welding of metals with similar electrical characteristics but differing thickness also will result in uneven joint heating. The thicker workpiece will exhibit a higher resistance (lower conductivity) than the thinner sheet, resulting in deeper penetration into the thicker sheet. The heat balance can be improved by decreasing the current density in the thicker sheet, by decreasing the heat loss from the thinner sheet, or by a combination of both. Applying a large-diameter electrode on the thicker sheet will concentrate the current density into the thinner metal, shifting the nugget penetration deeper into the thinner sheet. It should be noted that when dissimilar electrodes are used to achieve heat balance, the design should include an error-proofing function that prevents the use of incorrect electrodes.

In order to effectively make spot welds in two or more dissimilar thicknesses of the same metal, a maximum section-thickness ratio of the outer sheets is suggested. For carbon steels, the suggested maximum section-thickness ratio is 4 to 1. (If the same electrodes are used on both sides, the ratio must not exceed 3 to 1.) To join three different thicknesses of carbon steel using Type A or E electrodes (classified by the Resistance Welding Manufacturing Alliance [RWMA]),⁶ an outer sheet thickness ratio of 2.5 to 1 is suggested. Zinc-coated materials require a reduced ratio of about 2 to 1. To accommodate joints with higher thickness ratios, altering the electrode face diameter and the electrode composition are important methods of balancing the heat produced in each member of the joint.

In multiple layers of dissimilar thickness, a long weld time permits more uniform distribution of heat in the asymmetrical resistance path between the electrodes. Correct heat balance may be obtained by using multiple-impulse (pulsed) welding, or a single impulse of continuous current for an equivalent time.

6. Resistance Welding Manufacturing Alliance, a standing committee of the American Welding Society, 550 N.W. 11th Ave., Miami, Florida 33126. www.rwma.org.

LAP JOINT DESIGN

The joint design in all applications of spot welding consists of a lap joint. One or more of the welded members may be flanges, or formed sections such as angles and channels. The use of standard resistance welding machines, portable welding guns, and special-purpose machines must be considered when designing the lap joint configuration. The joint design for direct welding must allow access to both sides of the joint by the electrodes.

Design Requirements

Factors that should be considered when designing for spot welding include:

1. Edge distance,
2. Joint overlap,
3. Fitup,
4. Weld spacing,
5. Joint accessibility,
6. Surface marking, and
7. Weld strength.

Edge Distance. The edge distance is measured from the center of the weld nugget to the edge of the sheet. The location of the spot weld must ensure that enough base metal is available to resist the expulsion of molten metal from the joint. Spot welds made too close to the edge of one or both workpieces will cause the base metal at the edge of the workpiece to overheat and upset outward, as shown in Figure 1.13. The restraint by the base metal at the edge of the molten nugget is reduced and expulsion of molten metal may occur due to the high internal pressure in the nugget. The weld nugget may be unsound, the electrode indentation excessive, and the weld strength low. The required minimum edge distance is a function of base metal composition and strength, section thicknesses, electrode face contour, and the welding cycle.

Joint Overlap. The minimum permissible joint overlap in sheet metal is calculated at two times the minimum edge distance. The overlap must include the base metal requirement for avoiding edge overheating and expulsion for both sheet metal workpieces. Other factors, such as electrode clearance, positioning tolerance of the weld tip and the workpieces, may require a larger overlap to provide for consistent weld quality. If the overlap is too small, the edge distance will automatically be insufficient, as sketched in Figure 1.13.

Fitup. The faying surfaces of the workpieces should fit together along the joint with little or no gap between them. Any force required to overcome gaps in the joint

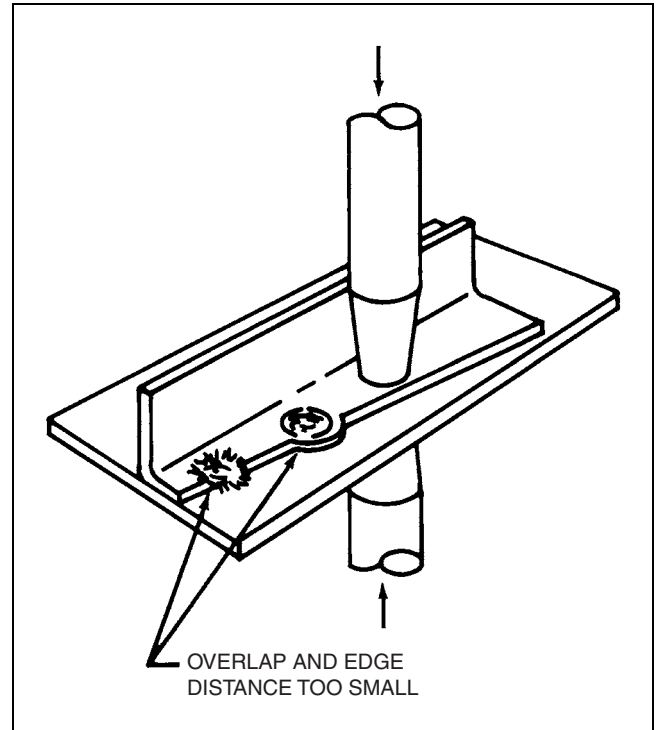


Figure 1.13—The Effect of Improper Overlap and Edge Distance

will reduce the effective welding force. The force required to close the joint may vary as welding progresses, and consequently may change the actual welding force. The ultimate result may be significant variations in the strength of the individual welds.

Weld Spacing. When numerous spot welds are made successively along a joint, a portion of the secondary current shunts through the adjacent welds. This shunting of the current must be considered when establishing the distance between adjacent spot welds and when establishing the welding machine settings. Typical weld current and minimum spacing shown in general welding charts do not provide compensation for this shunt effect. Some welding machines are capable of providing a different weld schedule for the second weld when spacing would be less than the recommended minimum. If this is the case, spacing can be somewhat below the minimum, but greater electrode wear and surface marking can be expected because of the higher current required to make the weld. The effect of shunting current also can be influenced by presence of sealants, fluxes, and other coatings at the faying surfaces.

The division of current depends primarily on the ratio of the resistances of the two paths, one through the adjacent welds and the other across the interface between the sheet metal workpieces. If the path length through the adjacent weld is longer than the thickness of the joint, the resistance will be high compared to the resistance of the joint, and the shunting effect will be negligible.

The minimum spacing between spot welds is related to the conductivity and thickness of the base metal, the diameter of the weld nugget, and the cleanliness of the faying surfaces. For example, thick sections or metals with high conductivity will require greater spacing between spot welds. The suggested minimum spacing between adjacent spot welds is increased when joining three or more sheets. The spot spacing for a weld joining three thicknesses is generally 30% greater than the spacing required for welding two sections of the thicker outer sheet. Current levels may be increased in order to provide more current to the weld and thus offset the shunting effects; however, the higher heat inputs may cause expulsion if applied to the first spot weld, which is not shunted. An auxiliary weld timer or current control may be provided to produce the first spot weld using lower heat input. Modern electronic welding controls frequently provide several different welding schedules that can be selected in this situation. This is not a recommended practice when using a manual welding gun with a standard control, because the operator will be required to select alternate triggers to get the alternate weld schedule. Even the most conscientious worker sometimes may select the incorrect one. Most weld controllers cannot compensate automatically for shunting effects.

Joint Accessibility. The joint should be designed in consideration of the size and shape of commercially available electrodes and electrode holders, as well as the type of spot welding equipment that will be used. Each side of the weld joint should be accessible to the electrodes mounted on the welding machine or to backup electrodes in the case of indirect welding. Chapter 4, “Resistance Welding Equipment,” contains information on electrodes and electrode holder designs. It should be noted that while offset points are shown on standard electrode designs, the electrodes must be installed with the correct orientation, which may be difficult to maintain in a production environment.

SPOT WELD QUALITY

Spot weld quality involves a combination of positive attributes related to the strength and fatigue life of the weld and negative attributes such as surface marking, workpiece distortion and adherent expulsion that results from a poorly controlled resistance welding pro-

cess. Maintenance practices and proper setup can reduce marking and distortion and assure that the weld strength is consistent.

Indentation

Indentation, or surface marking, is a depression on the exterior surface of the workpieces. It is an undesirable effect resulting from workpiece shrinkage, which is caused by a combination of the heat of welding and electrode penetration into the surface of the workpiece.

When the welding current is on, the workpiece is resistance-heated locally and has a tendency to expand in all directions. Because of the pressure exerted by the electrodes, expansion transverse to the plane of the sheets is restricted. As the weld cools, contraction takes place almost entirely in the transverse direction and produces concave surfaces or marks at the electrode locations, as shown in Figure 1.14. This type of weld shrinkage is different from excessive electrode indentation into the workpieces caused by improper welding procedures. The contraction shrinkage is almost certain to occur to some degree and seldom exceeds a few tenths of a millimeter.

A circular ridge around the spot weld concavity occurs when the expanding workpiece upsets in the plane of the sheets around the electrode face, as can be observed in Figure 1.14. This ridge is caused by the relatively high electrode force and occurs to some extent with all shaped electrodes. The ridge is even more obvious with coatings such as galvanizing, where the coating melts during the weld process and is squeezed out from under the electrodes.

After some finishing operations, such as painting, the marks may be very conspicuous. It is difficult to eliminate the marks completely, but they can be reduced materially by modifying the welding procedure. For example, the indentation into the sheet can be minimized by welding in the shortest time practical.

Various techniques are used to minimize these markings. A common method is to use a large flat-faced electrode against the “show side” of the joint (the side that is visible when the assembly is in use). The electrode

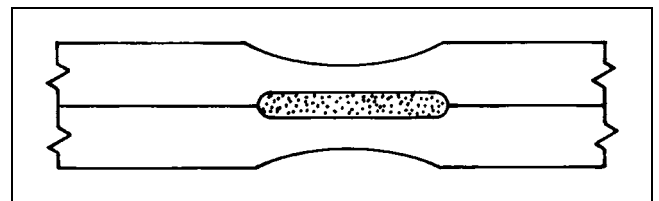


Figure 1.14—Indentation Produced by Shrinkage During Spot Welding

used for this technique should be made of a hard copper alloy to reduce wear. This method can be used in manual welding applications with galvanized steel; however, in automated welding, the weld is made at precisely the same location each time. Therefore, precision placement results in more rapid wear of the backup electrode and will require frequent maintenance to preserve surface shape. Another technique is to use indirect welding arrangements such as those shown in Figure 1.15 (also refer to Figure 1.10). Attempts to minimize weld markings are associated with higher maintenance costs and the process becomes less robust in achieving correct weld size. Achieving balance between acceptable weld size and acceptable appearance raises issues between the competing requirements of appearance and product performance. Some projection welding machines use stored energy and high-performance follow-up systems to make welds with very little marking because the short weld time minimizes the heat input. Additional information is presented in Chapter 2 of this volume, "Projection Welding."

Surface marking also may occur when an electrode or the electrode holder accidentally contacts the workpiece adjacent to where the spot weld is to be made. The resultant arcing may produce a small pit in the workpiece, which is undesirable in some applications. If localized melting occurs as a result of the contact, cracks may result in some materials.

Electrode misalignment, skidding, or deflection of the supporting machine component under load also may result in undesirable surface marking. Localized overheating and electrode deflection will not be a problem if the correct joint design, electrodes, and equipment are used.

Weld Strength

The strength of a single spot weld in shear is determined by the cross-sectional area of the nugget in the plane of the faying surfaces. Strength tests for spot welds are published in *Recommended Practices for*

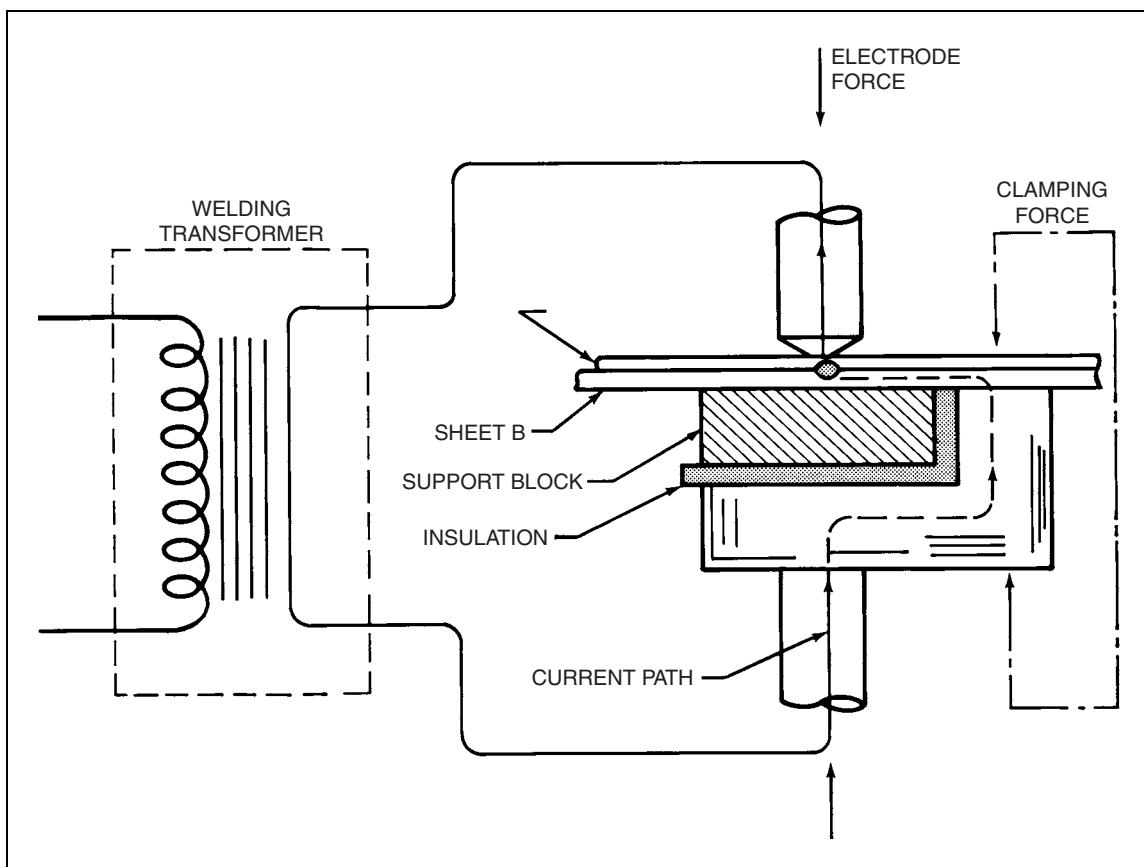


Figure 1.15—Application of Indirect Welding to Minimize Weld Markings on One Side

Resistance Welding, AWS C1.1.⁷ Additional information on spot weld test procedures can be found in Chapter 12, *Welding Inspection and Nondestructive Examination*, in Volume 1 of the *Welding Handbook*.⁸

Lap joints tested with the weld in shear will undergo an eccentricity of loading resulting in rotation of the joint at the weld as the test load increases. Resistance to joint rotation increases in proportion to increasing sheet thickness. The joint may fail either by shear through the nugget, or by tearing of the base metal adjacent to the weld nugget, as shown in Figure 1.16. Normally, in mild steels with tensile strength below approximately 550 megapascals (MPa) (80 kips per square inch [ksi]), low weld strengths are associated with weld nugget shear failure, and high strengths are associated with base metal tearing. As the base metal tensile strength approaches the weld nugget strength, more nugget shear can be expected for a specific weld

7. American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, Miami: American Welding Society.

8. American Welding Society (AWS) Welding Handbook Committee, Jenny, C. L. and A. O'Brien, eds., 2001, *Welding Handbook*, 9th Ed., Vol. 1, *Welding Science and Technology*, Miami: American Welding Society.

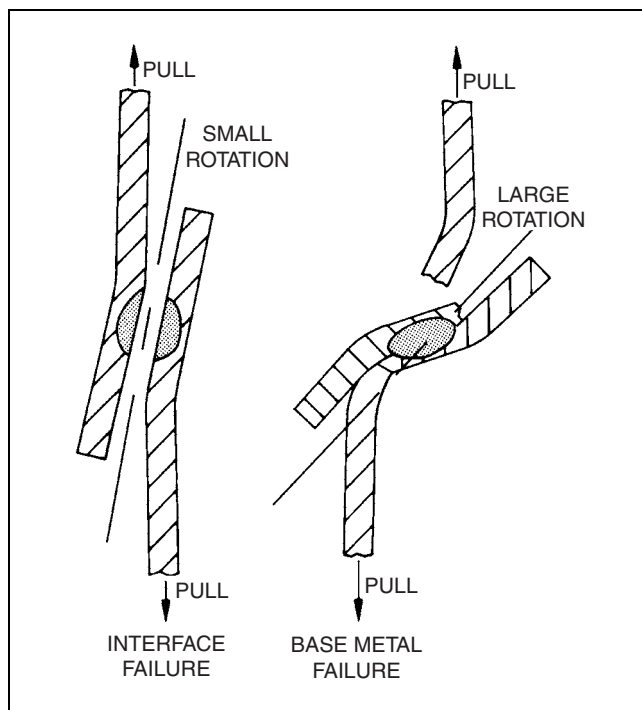


Figure 1.16—Types of Failure in Tensile Shear Test as a Function of Rotation

size. A specific minimum-size nugget diameter is required to obtain failure by base metal tearing. The specific nugget diameter necessary to produce base metal tearing is directly related to the type of base material, surface condition, and, if applicable, coating type.

Increasing the nugget diameter above this minimum value may result in some increase in the weld strength. Figure 1.17 shows the slight increase in strength values for low-carbon steel as the nugget size increases.

Spot welds have relatively low strength when stressed in tension by loading transverse (normal) to the plane of the sheets. This is due to the sharp notch between the sheets at the periphery of the weld nugget; consequently, when the weld will be subjected to loading of this type, the weld must be designed to compensate for this lower mechanical performance.

The strength of multiple spot-welded joints is dependent on material thickness, weld spacing, and weld pattern. The spacing between adjacent spot welds may alter the weld strength of the joint due to current shunting through previous welds. As the spacing between adjacent spot welds decreases, the joint shear strength may decrease.

Figure 1.18 shows the effect of shunt distance (weld spacing) on the tensile shear strength of spot welds. Data were taken from welds made on 6.35 mm (1/4 in.) thick by 76 mm (3 in.) wide strips of mild steel. All welds were made with one shunt circuit. The average shear strength of twenty-four welds was 8000 kg (17 570 lb).

To obtain a desired joint strength, the number of required welds must satisfy minimum spacing requirements in order to reduce the effects of current shunting. A staggered weld pattern of multiple rows provides better strength than a rectangular pattern because the staggered pattern distributes the load more efficiently among the spot welds.

Table 1.1 summarizes the relationship between resistance spot welding variables and joint strength and suggests resistance spot welding schedules for welding two equal-thickness uncoated low-carbon steel sheets, showing the resulting minimum shear strengths and the diameters of the nugget and button (a button is the part of a weld, including all or part of the nugget, that tears out during destructive testing).

Electrode Maintenance

Proper maintenance of electrodes is necessary for the production of consistently good welds. An abnormal increase in the size of the electrode faces contacting the workpieces is detrimental to weld strength and quality. For example, if an electrode face 6.3 mm (1/4 in.) in diameter is allowed to increase to 7.9 mm (5/16 in.) by mushrooming, the contact area will decrease 90% with a corresponding decrease in current density and

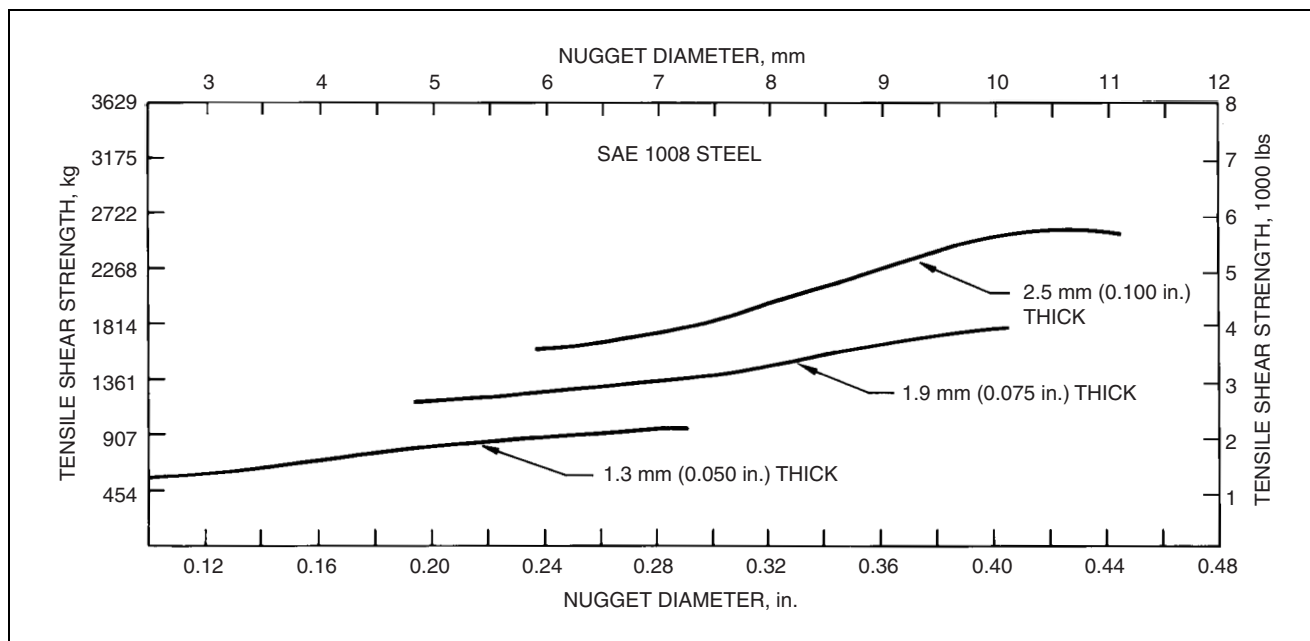


Figure 1.17—Effect of Nugget Size and Sheet Thickness on Tensile Shear Strength, Failure Occurring by Base Metal Tear-Out

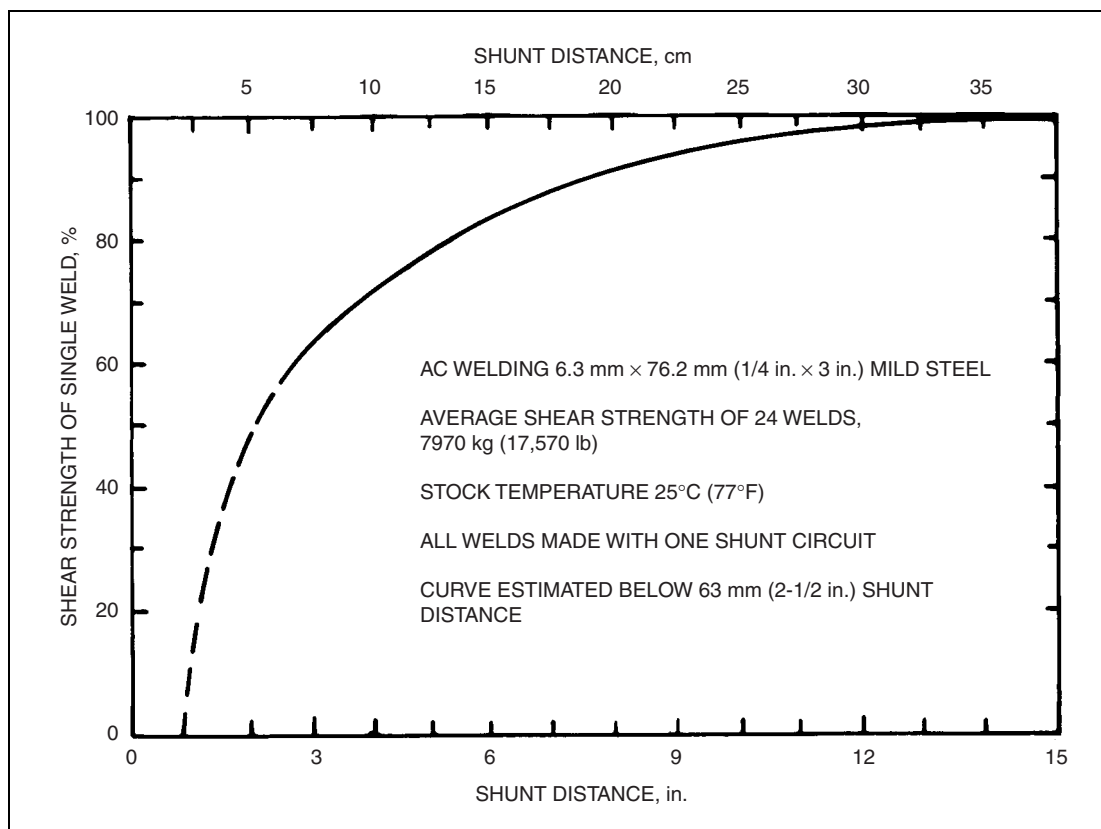


Figure 1.18—The Effect of Shunt Distance (Spot Spacing) on the Loss of Tensile Shear Strength

Table 1.1
Suggested Schedules for Spot-Welding Two Equal-Thickness Uncoated Low-Carbon Steel Sheets

Sheet Thickness		Electrode						Weld Time (60-Hz)	Welding Current (Approx.)	Minimum Contact Overlap		Minimum Weld Spacing				Minimum Shear Strength		Button Diameter	
		Face Dia.		Bevel Angle**	Force		2 Stack					3 Stack							
							mm					in.	mm	in.					
mm	in.	mm	in.	Shape*	Degrees	kN	lbf	Cycles	A	mm	in.	mm	in.	mm	in.	kN	lb	in.	mm
0.5	0.02	4.7	0.188	E, A, B	45	1.8	400	7	8500	11.0	0.44	9.5	0.38	15.5	0.62	1.4	320	0.10	2.5
0.6	0.03	4.7	0.188	E, A, B	45	2.0	450	8	9500	11.8	0.47	15.5	0.62	22.0	0.88	2.0	450	0.12	3.0
0.8	0.03	6.3	0.25	E, A, B	45	2.2	500	9	10 500	11.8	0.47	15.5	0.62	22.0	0.88	2.6	575	0.14	3.6
0.9	0.04	6.3	0.25	E, A, B	45	2.7	600	9	11 500	13.3	0.53	18.8	0.75	26.5	1.06	3.3	750	0.16	4.1
1.0	0.04	6.3	0.25	E, A, B	45	3.1	700	10	12 500	13.3	0.53	18.8	0.75	26.5	1.06	4.1	925	0.18	4.6
1.1	0.05	6.3	0.25	E, A, B	45	3.3	750	11	13 000	14.8	0.59	23.5	0.94	29.5	1.18	5.1	1150	0.19	4.8
1.3	0.05	7.8	0.312	E, A, B	30	3.6	800	12	13 500	14.8	0.59	23.5	0.94	29.5	1.18	6.0	1350	0.20	5.1
1.4	0.06	7.8	0.312	E, A, B	30	4.0	900	13	14 000	15.8	0.63	26.5	1.06	32.8	1.31	7.5	1680	0.21	5.3
1.5	0.06	7.8	0.312	E, A, B	30	4.4	1000	14	15 000	15.8	0.63	26.5	1.06	32.8	1.31	8.2	1850	0.23	5.8
1.8	0.07	7.8	0.312	E, A, B	30	5.3	1200	16	16 000	16.5	0.66	29.5	1.18	37.5	1.50	10.2	2300	0.25	6.3
2.0	0.08	7.8	0.312	E, A, B	30	6.2	1400	18	17 000	18.0	0.72	34.5	1.38	40.0	1.60	12.0	2700	0.26	6.6
2.3	0.09	9.4	0.375	E, A, B	30	7.1	1600	20	18 000	19.5	0.78	39.0	1.56	47.0	1.88	15.3	3450	0.27	6.9
2.6	0.11	9.4	0.375	E, A, B	30	8.0	1800	23	19 500	21.0	0.84	42.0	1.68	50.0	2.00	18.5	4150	0.28	7.1
3.0	0.12	9.4	0.375	E, A, B	30	9.3	2100	26	21 000	22.0	0.88	45.3	1.81	62.5	2.50	22.2	5000	0.30	7.6

*Shape Definitions:

E = Truncated cone

A = "A-Nose" pointed

B = 3-in. radius

**Applies to truncated-cone electrodes only and is measured from the plane of the electrode face.

Notes:

1. For metals of intermediate thickness, force and weld time may be interpolated.
2. Minimum weld spacing is measured from centerline to centerline.
3. The data in this table were supplied by the AWS D8 Subcommittee on Sheet Steel and represent an average of typical variables used by the automotive industry. Refer to AWS D8.6, *Standard for Automotive Resistance Spot Welding Electrodes*, for electrode specifications.

pressure. Depending somewhat on the weld schedule, the result may be weak or defective welds. A visual indicator is the production of poorly shaped spots, which may be caused by the following conditions:

1. Noncircular electrode faces,
2. Too large a flat face on the electrode,
3. Concavity or convexity of the electrode face, and
4. Misalignment of the electrodes with respect to the workpiece.

Correct electrode alignment is relatively easy to maintain with stationary welding machines and proper supporting fixtures; however, misalignment is common with portable gun-type machines. The seriousness of this condition depends on the ease with which the

equipment can be manipulated and correctly positioned for welding. It is likely that the electrodes will have longer life between maintenance dressings when welding positioned workpieces with stationary machines than when welding non-positioned workpieces with portable welding guns.

WELD BONDING

Weld bonding is a resistance spot welding process variation in which the spot-weld strength is augmented by an adhesive at the faying surfaces. Weld bonding is a combination of resistance spot welding and adhesive bonding. An adhesive in the form of a paste is placed between the workpieces. resistance welds are

then made through the adhesive layer. The adhesive is allowed to cure either at ambient temperature or by heating in an oven, as required by the adhesive manufacturer. The principal purpose of the spot welds is to hold the joint together during curing, since the welds do not contribute greatly to the strength of the joint. When large bond areas are used, fewer spot welds may be used than otherwise would be required. Adhesive around the weld also greatly increases the fatigue life of the joint. Chapter 10 of this volume, “Adhesive Bonding,” provides more detailed information.

Structures common to the aerospace and transportation industries are joined by weld bonding. For example, weld bonding is used to attach beaded panels to aircraft skins, and aircraft or truck skins to channels, angles, and other types of reinforcement.

The adhesive, whether paste or film, can be applied to one or both joint surfaces. The electrode force during welding squeezes out the adhesive at the spot weld locations, creating a current path through the sheets. The adhesive must have good wetting and flow characteristics in order to create a secure bond at the faying surfaces. Premature curing of the adhesive, prior to or during spot welding, may hamper proper adhesive movement and result in high resistance between the faying surfaces. High resistance may impede weld current or result in excessive heating and subsequent metal expulsion. The application of a precompression electrode force prior to the welding cycle may help displace the adhesive at each weld site.

Advantages and Limitations

Among the advantages of weld bonding are improved fatigue life and durability of the joint compared to joints made with spot welding alone. The process also may improve stress distribution and joint rigidity and result in higher resistance to buckling in thin sheets. The adhesive in the joint dampens vibration and noise and provides some corrosion resistance. In some aircraft components, greater cost effectiveness is obtainable with weld bonding than with mechanical fastening or adhesive bonding alone.

In most applications, the limitations of weld bonding include the additional costs of the adhesive, added time required for the curing operation, and the time and labor costs of cleaning the components. Additional cost factors include treating the workpiece surfaces, applying the adhesive, and maintaining the desired bond line thickness in the joint. Bond line thickness is sometimes maintained by the addition of glass beads or conductive fillers of a specified diameter. Used as fillers, these beads may interfere with weld nugget development. Another limitation is that operating temperatures in service for the component are limited to the effective service temperature of the adhesive.

The presence of adhesive in the joint makes welding more difficult, and may contribute to significant variations in weld quality. Regardless of welding conditions, not all of the adhesive will be displaced from between the sheets; therefore the contact resistance will be higher than with clean sheets.

RESISTANCE SEAM WELDING

A resistance seam weld is made on overlapping workpieces and is a continuous weld formed by overlapping weld nuggets, by a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by resistance to the flow of welding current.

ADVANTAGES AND LIMITATIONS

Resistance seam welding has the same advantages and limitations as resistance spot welding. An additional advantage is the ability to produce a continuous leak-tight weld. Seam welds must be made in a straight or uniformly curved path. Corners can be welded by interrupting the weld and crossing the end of the first with the start of the next weld. Leak-tight joints must be made with a continuous weld seam. A continuous weld seam cannot be produced if abrupt changes occur in welding direction or in joint contour along the path. This limits the design of the assembly.

The strength properties of seam-welded lap joints are generally lower than those of fusion-welded butt joints due to the eccentricity of loading on lap joints and the built-in notch along the nugget at the sheet interface.

TYPES OF SEAM WELDS

Details of three types of seam welds in sheet metal: the lap seam weld, mash seam weld, and metal finish seam weld are shown in cross section in Figure 1.19. The joint in Figure 1.19(A) is classified as a lap seam weld, a joint in which the workpieces are overlapped sufficiently to prevent the sheet edges from becoming part of the weld. Lap seams are commonly used in automotive applications such as fuel tanks, catalytic converters, mufflers, and roof joints. Other applications include the manufacturing of furnace heat exchangers, water tanks, and cans of all types. The lap-seam welding of multiple stackups and material of dissimilar thickness is possible.

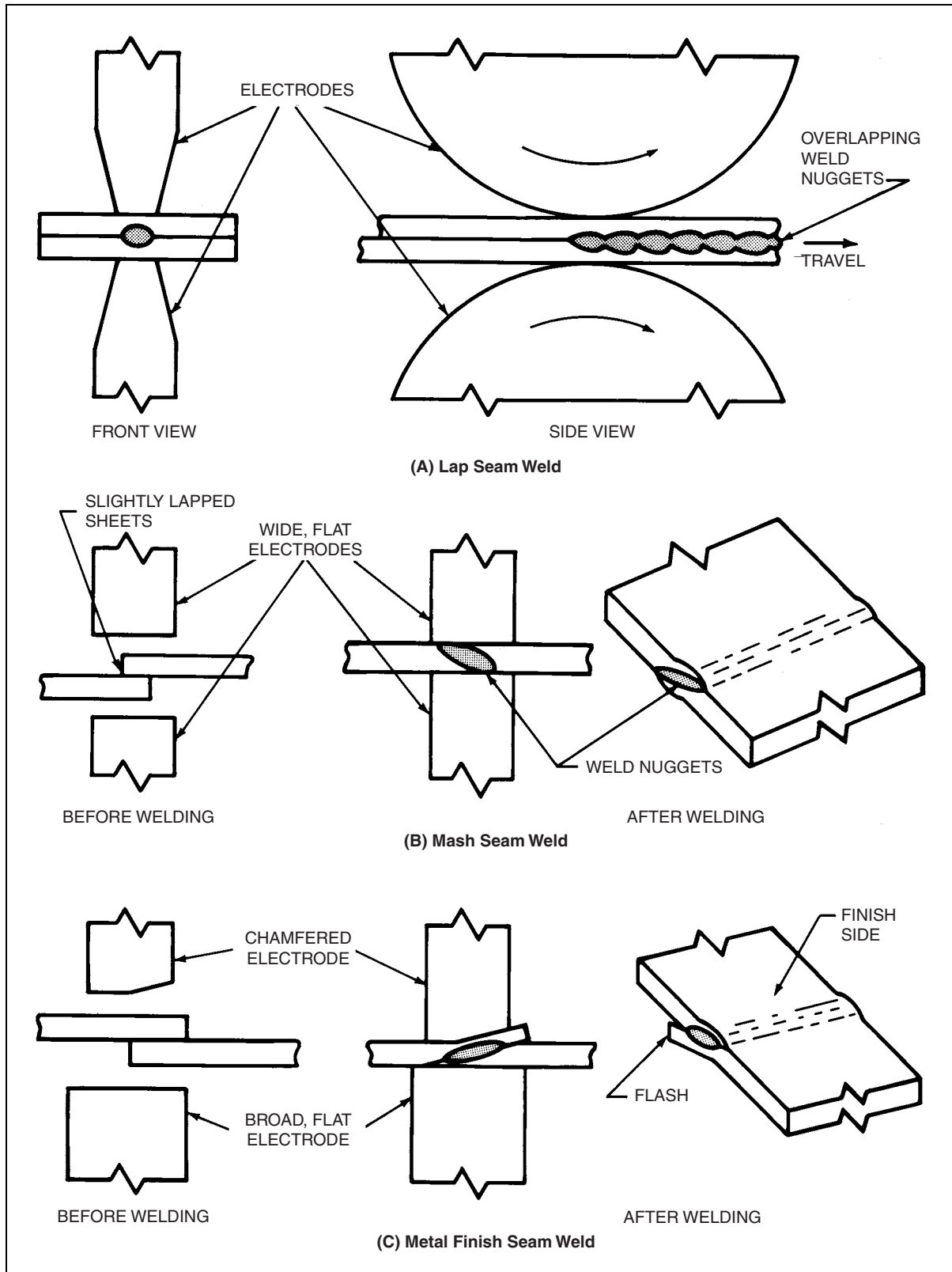


Figure 1.19—Resistance Seam Welding Variations



Lap joints can be seam-welded using two wheel electrodes, as shown in Figure 1.20, or with one wheel and a mandrel. The minimum joint overlap is the same as for spot welding: two times the minimum edge distance (the distance from the center of the weld nugget to the edge of the sheet).

When surface appearance is not a concern, radius-face wheels generally will provide a wider current range because as the weld becomes hotter the wheels sink in more, thus increasing the area and reducing the current density. The wheels generally will require continuous dressing or rolling to maintain shape.

APPLICATIONS

Seam welds typically are used to produce continuous gas-tight or liquid-tight joints in sheet assemblies, such as automotive gasoline tanks. The process also is used

to weld longitudinal seams in structural tubular sections that do not require leak-tight seams. In most applications, two wheel electrodes or one translating wheel and a stationary mandrel are used to provide the current and pressure for resistance seam welding. The position of the electrode wheels on a resistance seam welding machine is shown in Figure 1.20. Leak-tight seam welds also can be produced using spot welding electrodes. This requires the purposeful overlapping of the spot welds to obtain the leak-tight weld. Overlapping spot welding requires an increase in power after the first spot weld to offset the shunting effect in order to obtain adequate nugget formation as welding progresses. Figure 1.21 shows a resistance seam welding machine making a leak-tight joint on a coated-steel fuel tank. This machine does not use a knurl wheel as an electrode but uses a wheel to deliver a wire electrode, which is wrapped around the wheel so that it always presents a new contact surface to the workpiece.

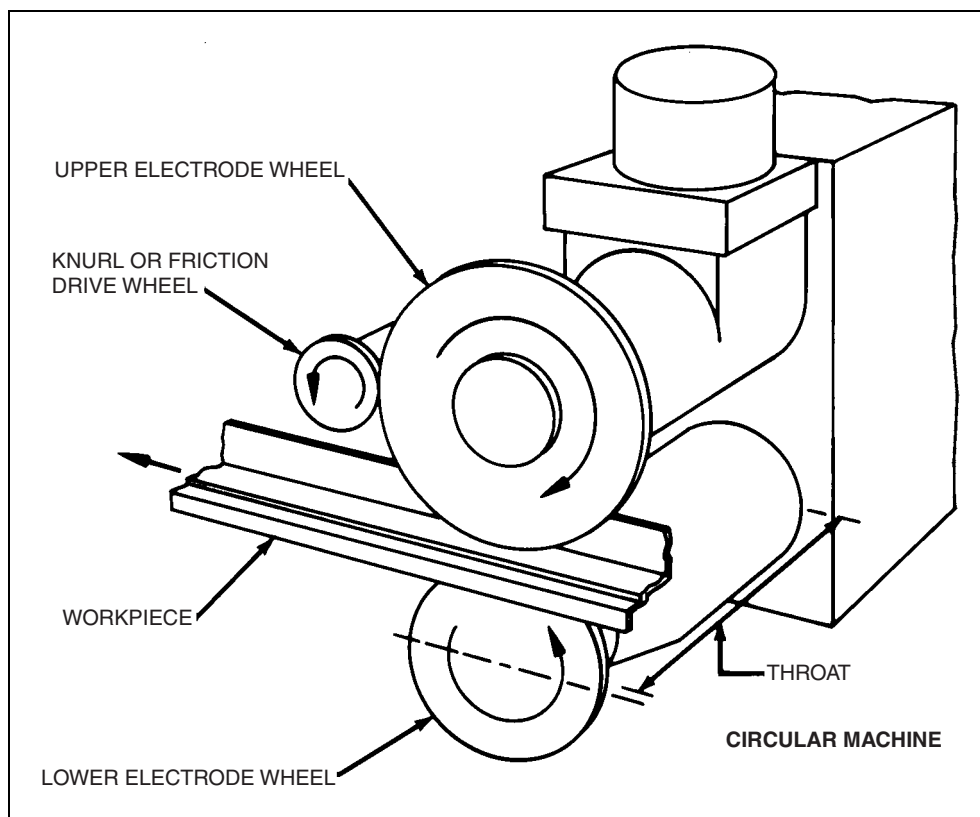
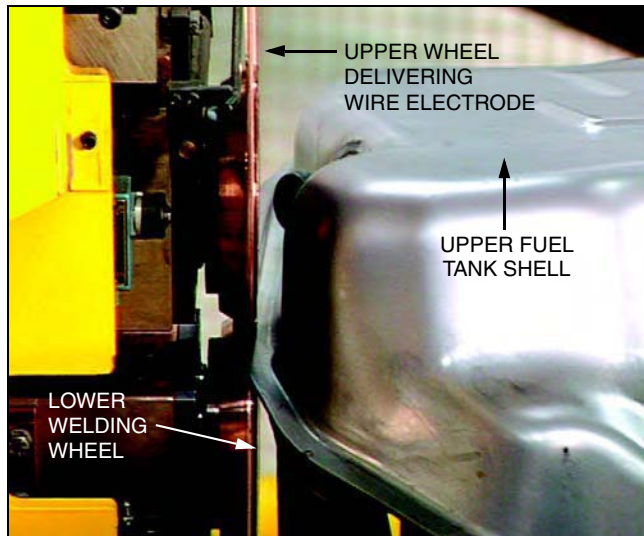


Figure 1.20—Position of Electrode Wheels on Resistance Seam Welding Machine



Photograph courtesy of Soudronic Automotive AG

Figure 1.21—Resistance Seam Welding of a Coated-Steel Fuel Tank

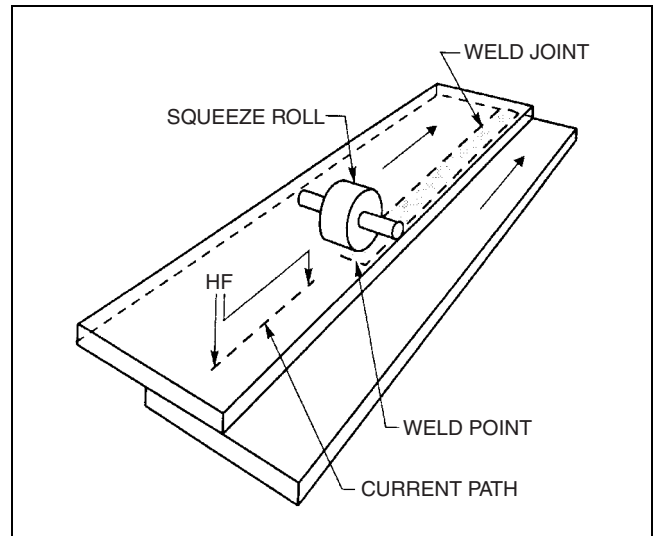


Figure 1.22—Configuration for a Lap Joint Made by High-Frequency Seam Welding

SEAM WELDING PROCESS VARIATIONS

High-frequency seam welding, induction seam welding, and mash seam welding are variations of the resistance seam welding process. Other modes of seam welding operations described in this section are metal finish seam welds, electrode wire seam welds, and roll spot welding.

High-Frequency Seam Welding

High-frequency seam welding (RSEW-HF) is a resistance seam welding process variation in which high-frequency welding current is supplied through electrodes into the workpieces. The configuration for a lap joint using high-frequency seam welding is shown in Figure 1.22. High-frequency seam welding is discussed in Chapter 5 of this volume.

Induction Seam Welding

Induction seam welding (RSEW-I) is a resistance seam welding process variation in which high-frequency welding current is induced in the workpieces. This process is used mainly in the production of tubes. Another application is to provide annealing of weld joints.

Induction seam welding is discussed in detail in Chapter 5, “High Frequency Welding.”

Mash Seam Welding

Mash seam welding (RSEW-MS) is a resistance seam welding process variation that makes a lap joint primarily by high-temperature plastic working and diffusion as opposed to melting and solidification. The joint thickness after welding is less than the original assembled thickness.

A mash seam weld is a joint in which the contact overlap of the two metals is only one to two times the thickness of the thinner sheet. Two exceptions are welds in tailored blank welds, in which the recommended overlap is the sum of the two sheet gauges but with a 3.5 mm (0.14 in.) maximum, and the welding of tinplate cans with a sheet overlap of two to four times the sheet thickness. The weld area is forged or mashed down during welding to a total thickness of 5% to 25% greater than the original starting thickness of a single sheet. Even in this instance, welds in tailored blanks and in can bodies are exceptions, with a thickening of up to 50% of a single sheet or the thinner sheet if the two sheets are different. It is necessary to have some overage of thickness so the current density in the electrode wheels can be confined to the weld area. This

is needed because the resistance welding electrodes used in mash seam welding are flat-faced wheels and usually are wider than the required weld. The final thickness and surface appearance of the finished weld can be improved and controlled by planishing. Planishing wheels are hardened steel or carbide wheels that cold-work the joint after welding. Because of hardening induced by cold-working of the planishing process, postweld heat treatment may be necessary.

Mash seam welding, shown in Figure 1.19(B), requires considerably less overlap than the conventional lap joint. Wide, flat-faced wheel electrodes that completely cover the overlap are used. Mash seam welding requires high electrode force, continuous or pulsed welding current, and accurate control of force, current, welding speed, overlap, and joint thickness in order to obtain consistent welding characteristics. Overlap is maintained at close tolerances, usually by rigidly clamping or tack-welding the workpieces.

In certain applications, the exposed surface or show side of the welded component is placed against a mandrel, which acts as an electrode and supports the workpieces. A wheel electrode is applied to the side of the joint that does not show. The show surface of the joint must be mashed as nearly flat as possible so that it will present a good appearance. Proper positioning of the wheel with respect to the joint is required to obtain a smooth weld face. When the appearance of the finished product is important, some polishing of the weld area may be required before painting or coating.

Mash seam welding produces continuous seams that have good appearance and are free of crevices. Crevise-free joints are necessary in applications that have strict

contamination or cleanliness requirements, such as joints in food containers or refrigerator liners.

Applications. Typical applications of mash seam welding include the manufacturing of drums, buckets, vacuum-jacketed bottles, aerosol cans, and water tanks. Sheets of dissimilar thickness with or without coatings also can be successfully mash seam welded. The development of this capability has created a new set of applications in tailored blank manufacturing, primarily for automotive use. Another important application is in steel mills for the joining of sheets to produce continuous coils of sheet metal. Figure 1.23 shows tin-coated steel cans manufactured with the mash seam welding process using intermediate copper wire electrodes. A typical mash seam welding machine can weld up to 1000 can bodies per minute.

Disadvantages of the mash seam welding variation include the following:

1. Offset occurs at the joint due to the inability of the process to completely flatten the seam,
2. Distortion caused by the inherent lateral flow of metal as it is welded requires restraining by fixturing or by tack welding, and
3. Very rigid fixturing is required to resist weld distortion.

To obtain acceptable welds, the materials to be joined by mash seam welding must have wide plastic temperature ranges. Low-carbon steels or stainless steels can be joined by mash seam welding in certain applications.



Photograph courtesy of Soudronic Automotive AG

Figure 1.23—Tin-Coated Steel Can Bodies Welded with the Mash Seam Welding Process

Metal Finish Seam Welding

Metal finish seam welds, lap welds, and mash seam welds differ with respect to the amount of forging, or “mash down” that takes place during welding. Practically no forging occurs in lap welding while the thickness of a mash seam weld approaches that of one sheet thickness. Metal finish seam welding is a compromise between lap and mash seam welding; forging occurs on only one side of the joint, as shown in Figure 1.19(C).

The amount of deformation, or mash, is affected by the geometry of one electrode wheel face and the position of the joint relative to the face. The wheel face is beveled on one side of the midpoint, as illustrated in Figure 1.24. This configuration varies the amount of deformation across the joint. Good surface finish can be produced on the side of the joint against the flat wheel when proper welding procedures are used.

The location of the edge of the sheet contacting the flat-faced electrode relative to the bevel on the other electrode must be held within close tolerance, as shown in Figure 1.24. For example, with 0.8 mm (0.031 in.) low-carbon steel sheet, the edge must be within 0.4 mm (0.016 in.) of center. The overlap distance is not critical.

Higher amperage and electrode force are required for metal finish seam welding than for mash seam welding

because of the greater overlap distance. Materials that are easily joined with mash seam welding (materials with wide plastic temperature ranges) also are easily welded using the metal finish seam welding technique.

Electrode Wire Seam Welding

Electrode wire seam welding is a technique that uses an intermediate copper wire electrode between each wheel electrode and the workpiece, as shown in Figure 1.25. The technique is used almost exclusively for mash seam or overlap welding of tin mill products to fabricate cans and as overlap welding for the welding of fuel tanks made from metallic-coated or organic-coated steel sheets.

Figure 1.26 shows a seven-axis, programmable wire electrode seam welding machine designed to weld fuel tanks using intermediate copper wire electrodes. Travel speed in this type of application is 5 to 8 meters per minute (m/min) (16.4 to 26.2 feet per minute [ft/min]), depending on the sheet quality, thickness, and coating. Figure 1.27 shows a close-up of the wheel electrode assembly. In this system, the copper wire electrode travels around the wheel electrodes at the selected welding speed. The copper wire electrode provides a continuously renewed surface, but it is not consumed in the welding operation. This avoids the buildup of coating material that would occur on a copper wheel electrode. The copper wire electrode may have a circular, flat, or other cross section profile.

Figure 1.28 shows profiles of copper wire electrodes used to overlap welds on sheet metal with coatings of varying thicknesses. A cross section of the weld and recommended wire profiles and diameters also are shown.

Electrode wire seam welding requires specially designed welding systems. The seam welds may be made with two wheel electrodes, or one wheel electrode and a mandrel electrode.

The temperature range of a mash seam weld made with electrode wire should provide good solid-phase bonding and should not exceed the melting point of the base metal. If the surface of the seam weld reaches temperatures greater than the melting point of the base metal, spikes or splashes of molten metal will be expelled from the seam weld. Splashes of this material can lead to corrosion of the weldment, and therefore are undesirable.

Electrode wire seam welding has little tolerance for temperature variation, but very high welding speeds are obtained by the very constant resistance maintained between the weld wheel, the intermediate copper wire electrode, and the sheet surface. As examples, in the welding of can bodies, the welding speed is up to 100 m/min (328 ft/min). The welding speed in fuel tank welding is in the range of 5 m/min to 8 m/min (16 ft/min to 26 ft/min). Variations in welding temperature resulting from

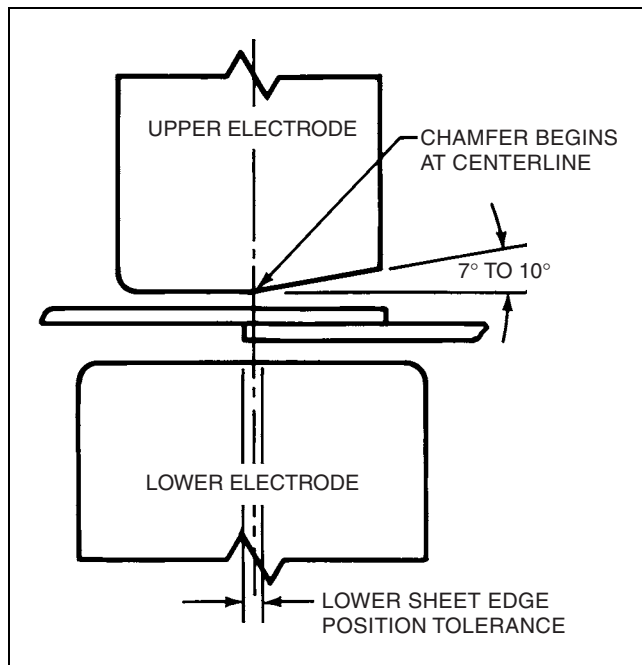


Figure 1.24—Electrode Face Contour and Joint Position for Metal Finish Seam Welding

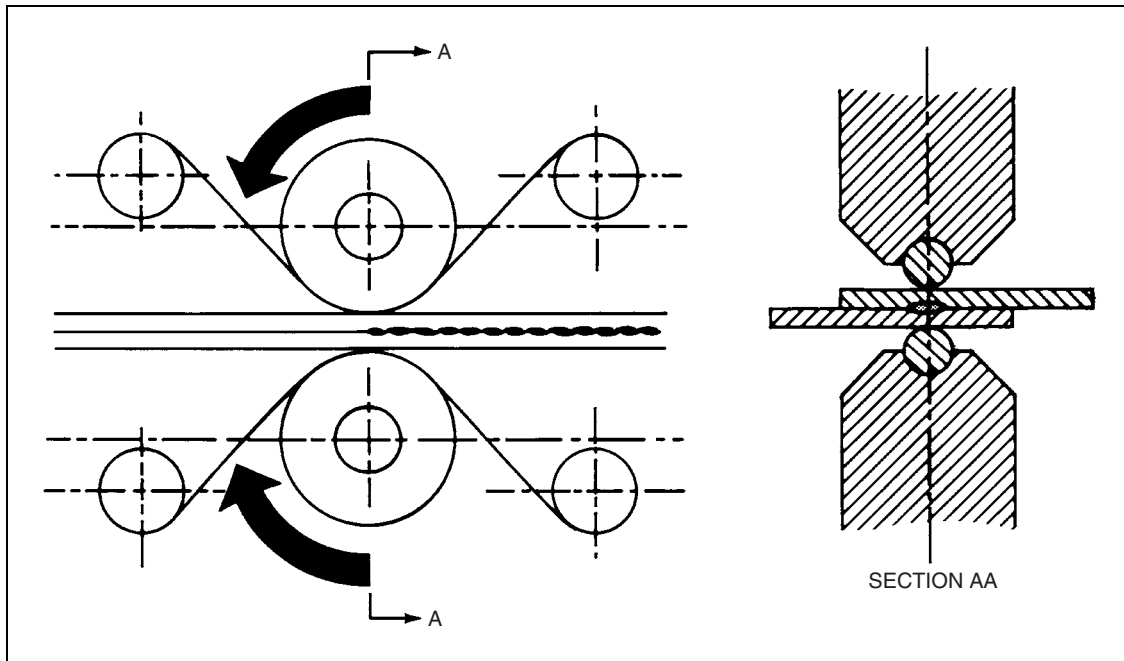
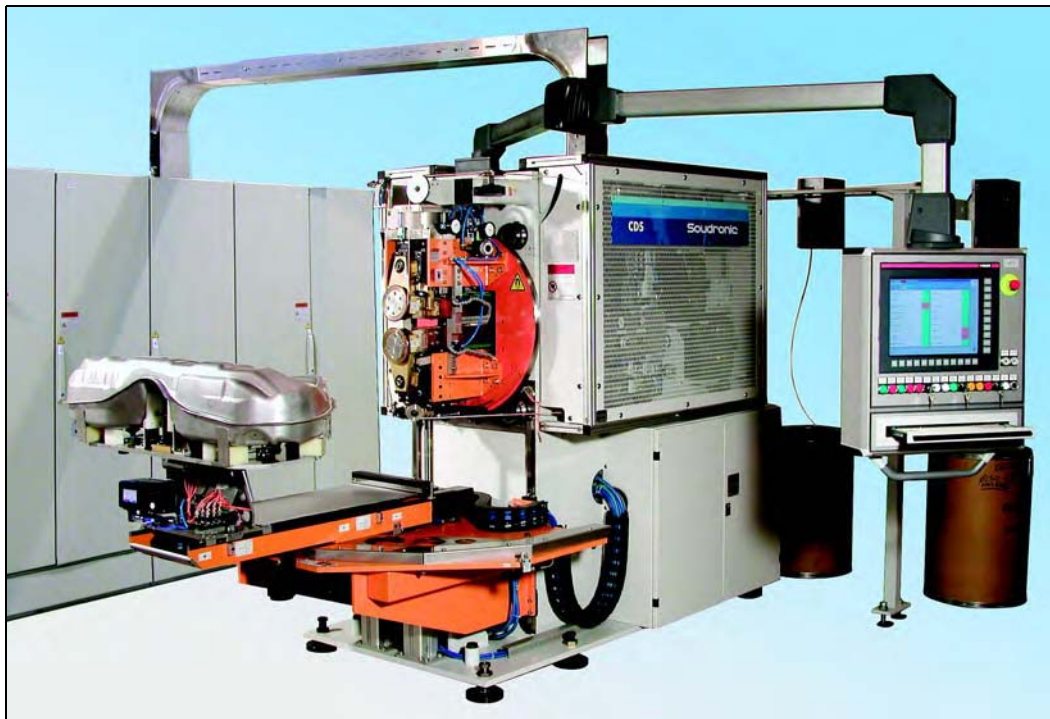
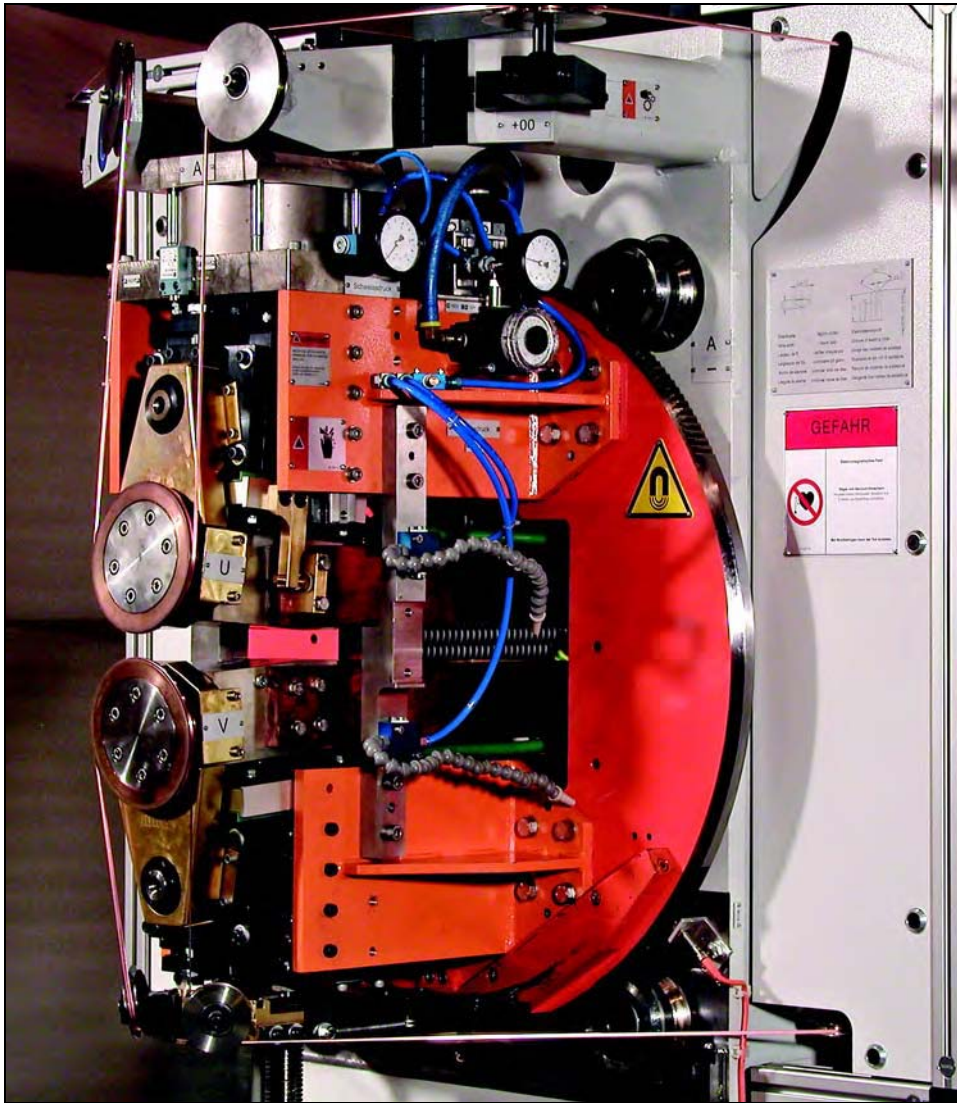


Figure 1.25—Electrode Wire Seam Weld



Photograph courtesy of Soudronic Automotive AG

Figure 1.26—Seven-Axis, Programmable Wire-Electrode Seam Welding Machine Customized for Welding Fuel Tanks



Photograph courtesy of Soudronic Automotive AG

Figure 1.27— Close-up of the Wheel Electrode and Wire-Electrode Assembly in a Seam Welding Machine

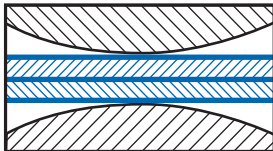
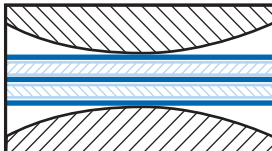
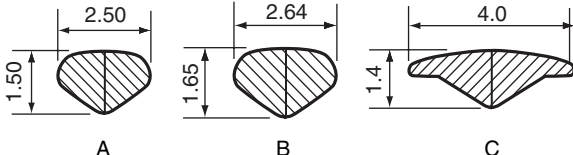
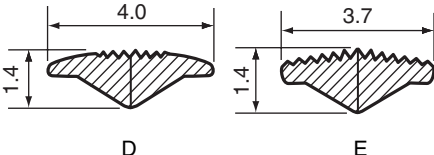
fluctuations in electrical power or electrode pressure and changes in overlap distances usually are acceptable.

Figure 1.29 shows a micrograph of transverse and longitudinal sections of the overlap of a seam weld in a fuel tank. The material is steel sheet with an electrolytic zinc-nickel coating and an additional coating of aluminum-rich paint. The seam is welded with copper wire electrodes Type E, shown in Figure 1.28.

Butt Seam Welds. Two types of butt joints, autogenous and exogenous, can be made with electrode wire

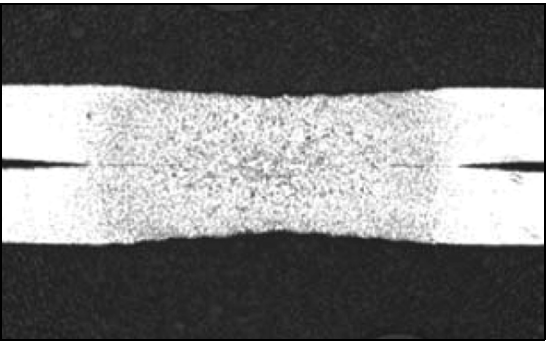
seam welding. A joint in which two abutting edges are welded without a filler metal is classified as an autogenous butt seam joint. The thickness of the weld should be approximately the same or slightly less than the thickness of the sheet. Autogenous butt seam welding typically is reserved for applications in which other butt-welding processes cannot be used, for example, for tube welding and for welding sheet metal in railroad cars.

A joint in sheet metal in which two abutting edges are welded using a strip of filler metal (usually called a

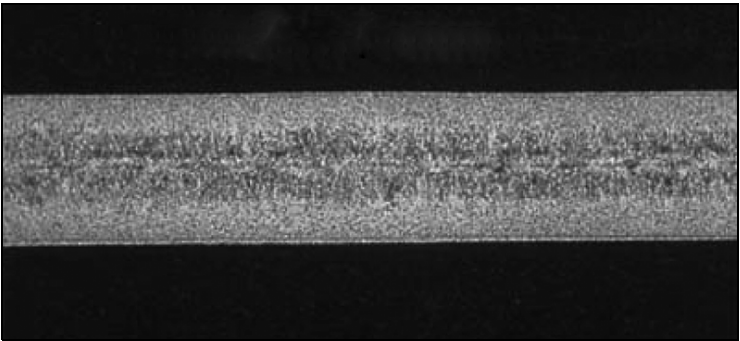
SIDE VIEW OF PROCESS (SEE FIGURE 1.25)					
CROSS SECTION OF WIRE PROFILE					
WIRE DIA. [mm]	2.0	2.2	2.5	2.5	2.5
SHEET THICKNESS [mm]	$t \leq 0.8$ mm	$t \leq 1.0$ mm	0.6–1.2 mm	0.6–1.2 mm	0.6–1.2 mm
COATING TYPE	METALLIC COATING			METALLIC COATING WITH ORGANIC TOP COATING	

Source: Adapted from Soudronic Automotive AG.

Figure 1.28—Profiles of Wire for Use with Various Types of Sheet Metal with Protective Coatings (Measurements are in Millimeters)



(A) Transverse Section



(B) Longitudinal Section

Figure 1.29—Seam Weld in Prepainted Zn/Ni-Coated Steel Using an Electrode Wire System

foil seam weld) that becomes part of the weld is classified as an exogenous butt seam weld. An exogenous weld is made by positioning the edges of the sheets to form a butt joint. The filler, usually a thin, narrow strip of metal that also serves as an electrode, is fed between the workpieces and the wheel electrode and welded to one or both sides of the joint. The metal strip bridges the root opening, distributes the welding current to both sheet edges, provides added electrical resistance, and contains the molten weld nugget as it forms. This

produces a flush or slightly reinforced weld joint, as shown in Figure 1.30.

Strip electrode configurations can be circular, triangular, or flat. The metal strip must be guided accurately and centered on the joint to ensure even distribution of current to both sheet edges. The strip may be welded to the sheets by roll spot welding at low power before the joint is seam-welded. Very little forging of the joint during welding is required; therefore, less distortion of the joint results compared to lap-seam welding. The travel speed for this joint

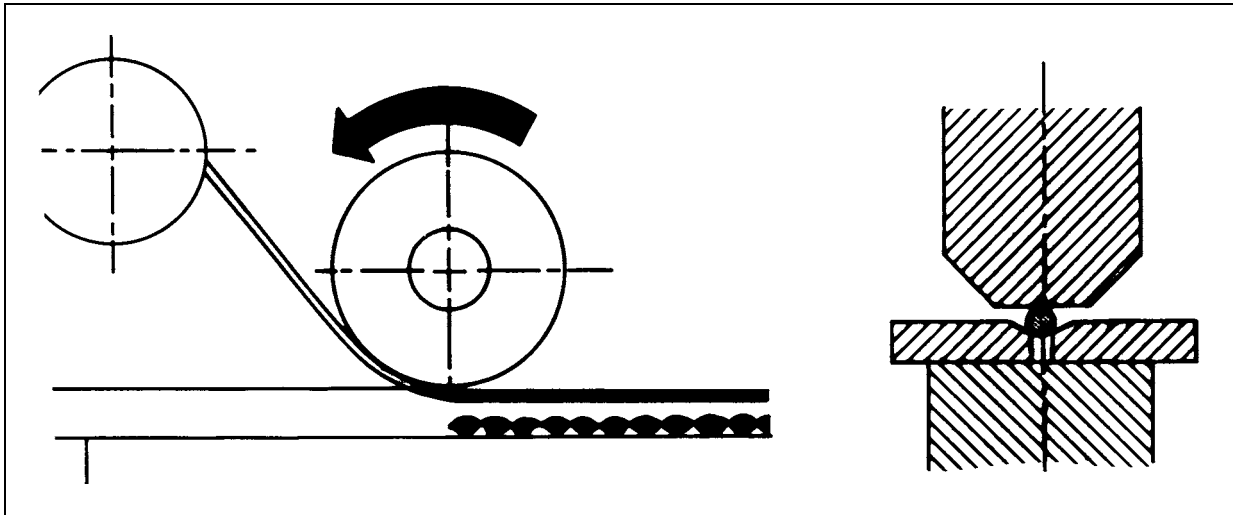


Figure 1.30—Exogenous Seam-Welded Butt Joint

seam welding of low-carbon steel is comparable to that for lap-seam welding. To achieve good corrosion resistance, welding procedures must ensure that welding of the strips over the entire width of the joint is maintained.

Roll Spot Welding

Roll spot welding is a resistance seam welding mode that makes intermittent spot welds using one or more rotating circular electrodes. The rotation of the electrode wheels may or may not be stopped during the weld cycle. In this method, a row of spaced spot welds can be made with a seam welding machine without retracting the electrode or removing the electrode force between welds. The radius of the wheel electrode, the contour of the face, and the weld time influence the shape of the nugget. The nugget usually is oval-shaped.

Weld spacing is obtained by the adjustment of cooling time with the wheel electrodes continuously rotating at a set speed. Holding time is effectively zero. Roll spot welding also may be done with interrupted electrode rotation when a hold-time period is needed to consolidate the weld nugget as it cools.

When continuously moving electrodes are employed, as commonly is the case, weld time usually is shorter and welding amperage higher than those used for conventional spot welding. The higher amperage employed sometimes may require the use of a higher electrode force. Otherwise, the recommended practices for spot welding apply.

Continuous Current. To weld low-carbon steel, welding current can be applied continuously along the length of the seam at high travel speeds if the waveform of the available current will produce the proper nugget size and spacing. In this case, the level of weld quality required may be secondary to high-production requirements. Continuous current can be used for sheet up to 1 mm (0.040 in.) thick. Above this thickness, the condition of the surface has a significant detrimental effect on welding and electrode life is short. Continuous-current welds in a particular thickness can be made over a wide range of speeds. For example, two sheets of 1-mm (0.040-in.) steel stock can be welded at speeds ranging from 44 mm/s to 131 mm/s (105 in./min to 310 in./min). Amperage requirements increase with travel speed.

A problem that may arise when operating with continuous alternating current is arcing between the wheel electrode and a localized region of the weld assembly on the exit side of the electrode. The arcing may produce superficial melting of the sheet surface and the electrode. In steels, the rapid cooling of molten metal that results from workpiece-to-electrode arcing can result in the formation of brittle martensite. The localized martensitic microstructure may provide initiation sites for the formation of cracks.

Welding Speed. The speed of welding depends on the metal being welded, stock thickness, and the weld strength and quality requirements. In general, the welding speeds are much lower when welding stainless

steels and nonferrous metals because of restrictions on heating rate necessary to avoid weld metal expulsion.

In some applications, it is necessary to stop the movement of the electrodes and workpieces as each weld nugget is made. This usually is the case for sections over 4.78 mm (0.188 in.) thick, and for metals that require postheating or forging cycles to produce the desired weld properties. Interrupted motion significantly reduces welding speed because of the relatively long time required for each weld.

When using continuous motion, welding machine adjustments for current, time, and speed must take place to maintain weld quality and joint strength: the welding current must be increased and the heating time decreased as welding speed is increased. There is a speed beyond which the required welding current may cause undesirable surface burning and electrode pickup. This will accelerate electrode wear.

Tandem Seam Welding

Two seam welds can be made in series by using two weld heads mounted side by side or in tandem. The two seams can be welded with the same welding current, and power demand will be only slightly greater than for a single weld.

A tandem wheel arrangement can reduce welding time by 50%, since both halves of a joint can be welded simultaneously. Thus, for a joint 182 cm (72 in.) long, two welding heads can be placed 91 cm (36 in.) apart, with the welding current path directed through the workpiece from one wheel electrode to the other. A third continuous electrode is used on the other side of the joint. The full length of the joint can be welded with only 91 cm (36 in.) of travel.

Electrodes. Seam welding electrodes normally are wheels ranging in diameter from 50 mm to 600 mm (2 in. to 24 in.). Typical wheel sizes are 175 mm to 300 mm (7 in. to 12 in.) in diameter and widths are 10 mm to 19 mm (3/8 in. to 3/4 in.).

The width of the cross section at the weld interface should range from 1-1/2 to 3 times the thickness of the thinner member. The ratio of weld width to sheet thickness normally decreases as the thickness increases. The weld width is always slightly less than the electrode face width when commercial welding schedules are used.

Seam welding electrodes are discussed further in Chapter 4, “Resistance Welding Equipment.”

SEAM WELDING VARIABLES

Several variables must be considered when planning a seam welding application, including heat balance,

welding cycle, current requirements, welding speed, electrodes, external cooling, and joint design.

Heat Balance

The seam welding of dissimilar types of metals or metals of unequal thickness presents the same heat balance problems as those of spot welding. The techniques for improving joint heat balance are similar. On workpieces requiring a low current density or fast cooling, the contact area between the workpiece and the electrode can be enlarged by increasing the diameter or width of the wheel electrode. As an alternative, one of the electrode wheels or mandrels may be made of an alloy with higher thermal conductivity to facilitate heat conduction from the workpiece via the electrode.

Welding Cycle

Resistance seam welds typically require higher welding currents than resistance spot welds due to the shunting of the welding current through previously made welds.

The resistance welding current normally is supplied in timed pulses (heating times) separated by periods of cooling times (hold times). A weld nugget is produced during each pulse of current. For a given welding speed and heating-cooling cycle, the welding current determines the depth of weld penetration. The weld nugget overlap is controlled by the welding current schedule and weld speed. As the welding speed increases, the ratio of heating time to cooling time must be increased in order to maintain weld overlapping of the nugget. The heating time controls the size of the weld nugget. Figure 1.31 shows the effect that cooling time has on weld nugget penetration (macrosection perpendicular to weld centerline) and weld overlap (macrosection parallel to weld centerline).

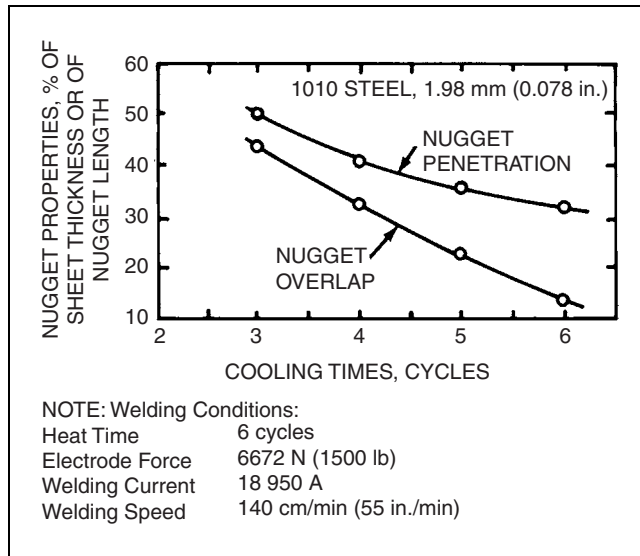
The use of welding current higher than required to obtain proper joint properties may result in excessive indentation or burning of the weldment. Short heating times or fast welding speeds require higher current levels for proper weld nugget formation, but may produce greater electrode wear.

Either pulsed (intermittent) current or continuous alternating current is used for resistance seam welding. As an example of the lap seam welding process, Table 1.2 provides suggested resistance seam welding conditions for welding uncoated low-carbon steel sheet.

Pulsed Current

Pulsed current usually is selected for most seam welding operations for the following reasons:

1. Good control of the heat can be maintained.



Source: Adapted from Resistance Welding Manufacturing Alliance (RWMA) Bulletin 23.

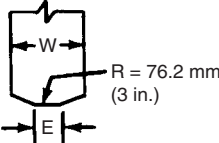
Figure 1.31—Effects of Cooling Time on Nugget Penetration and Nugget Overlap in Seam Welding

- Each weld nugget in the seam is allowed to cool under pressure,
- Distortion of the workpieces is minimized,
- Expulsion or burning is easily controlled, and
- Sound welds with good surface appearance are possible.

For a leak-tight seam, the nugget overlap should be 15% to 20% of the nugget diameter. For maximum strength, the overlap should be 40% to 50%. The size of the nugget depends on the heating time for a given welding speed and current. The amount of overlap depends on the cooling time.

The number of welds (nuggets) per unit of length that can be produced economically falls within a range specific to the type and thickness of the sheet metal. In general, as the sheet thickness decreases, the number of welds per unit of length must increase to obtain a strong, leak-tight seam weld. The ratio of welds per millimeter (in.) to welds per minute will establish the welding speed in millimeters (or inches) per minute. The number of welds per minute is the number of cycles of

Table 1.2
Suggested Schedules for Seam Welding Uncoated Low-Carbon Steel Sheet

Electrode Width (W) and Shape (E)*														Minimum Contact Overlap		
																
Thickness		W, Min.		E, Max.		Force		On Time	Off Time	Weld Speed		Welds	Welds	Current		
mm	in.	mm	in.	mm	in.	kN	lbf	(Cycles)**	(Cycles)**	mm/min	in./min	per cm	per in.	(Amp.)	mm	in.
0.3	0.01	9.5	0.38	4.5	0.18	1.8	400	2	1	2032	80	6	15	8000	9.5	0.38
0.5	0.021	9.5	0.38	4.8	0.19	2.4	550	2	2	1905	75	5	12	11 000	11.0	0.44
0.8	0.031	12.5	0.5	6.3	0.25	4.0	900	3	2	1829	72	4	10	13 000	12.5	0.5
1.0	0.04	12.5	0.5	6.3	0.25	4.4	980	3	3	1702	67	4	9	15 000	12.5	0.5
1.3	0.05	12.5	0.5	7.8	0.31	4.7	1050	4	3	1651	65	3	8	16 500	14.0	0.56
1.6	0.062	12.5	0.5	7.8	0.31	5.3	1200	4	4	1600	63	3	7	17 500	15.5	0.62
2.0	0.078	1.6	0.062	9.5	0.38	6.7	1500	6	5	1397	55	2	6	19 000	17.3	0.69
2.4	0.094	1.6	0.062	11.0	0.44	7.6	1700	7	6	1270	50	2	5.5	20 000	18.8	0.75
2.7	0.109	18.8	0.75	12.5	0.5	8.7	1950	9	6	1219	48	2	5	21 000	20.3	0.81
3.1	0.125	18.8	0.75	12.5	0.5	9.8	2200	11	7	1143	45	2	4.5	22 000	22.0	0.88

*Shape (E) is the width of a 75-mm (1/4-in.) radius on the electrode wheel face.

**On time and off time for 60-Hz power.

Notes:

- Type of steel: SAE 1010.
- Material should be free from scale, oxides, paint, grease and oil.
- Welding conditions determined by thickness (T) of outside piece.
- Data for total thickness of pile-up not exceeding 4 T. Maximum ratio between thicknesses: 3 to 1.
- Electrode material: Class 2; minimum conductivity: 75% of copper; minimum hardness: 75 Rockwell B.
- For large assemblies, minimum contacting overlap indicated should be increased 30%.