Chapter

Engineering Challenges Associated with Welding Field Repairs

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Abstract

Welding as technology exists in two worlds. Manufacturers execute designs typically based on professional society-backed standards. Repair service centers that administer field repairs where welding applications are required can sometimes have staff members with little formal education. The challenges of a technical manager seeking welded field repairs to equipment are significant and numerous. This chapter will seek to outline the process of executing a successful welding field repair by breaking down the analysis into three parts—(1) the identification of the engineering challenges associated with a specific job, including significant stresses, difficult materials or locations, and adequate piece preparation to ensure of weld integrity; (2) the ability to properly specify the type of repair, including knowledge of the types of weld junctions and preparations, the various types of welding processes and their features, weld types and associated drawing symbols, and the repair design and repair support process; and (3) the challenges for field engineers and technical managers in identifying weld defects, executing measures, and providing adequate examination and evaluation of weld quality in the field. This chapter tries to bridge the gap between the formal, engineered welds used in manufacturing and the sometimes-needed expediency of fieldwork.

Keywords: welding, repairs, MIG, TIG, arc, weld defects

1. Introduction

Welded connections play a substantial role in the manufacturing processes of many types of parts, structures, equipment, and materials. Equipment manufacturers for vehicles and implements use a considerable amount of advanced welding techniques and applications throughout the design of their manufactured products. In the industrialized world, frequent breakdowns, failures, and the necessity of repairs are a part of ongoing operations. Mechanical and structural component failures are inevitable, particularly with mobile agricultural and construction equipment. Therefore, it is essential for engineers, field technicians, and those in similar roles to be educated on the characteristics of a successful weld repair, welding fundamentals, and the associated challenges of executing field repairs.

Identifying the engineering challenges of field repairs will be examined first. Properly executed welding techniques incorporate an extensive amount of engineering fundamentals to maintain the original assembly's design and ensure adequate structural integrity once complete. There are many types of welding repairs that can be categorized by location, component type, design criteria, and the degree of critical quality requirements. Understanding basic material properties and identifying the material to be repaired is important for the welding process selection and the structural analysis of the proposed repair design. Certain repairs may not be accessible enough to clean the mill-scale, corrosion, or debris away, thereby narrowing the choice of possible welding processes, so repair preparation may also influence the welding process selection.

Understanding the various types of welding processes is vital to a manager seeking repairs. Each welding process features unique characteristics, often making one process more suited for a specific repair than other potential processes, based on the technical characteristics of the welding process equipment. Identifying the base material properties and measuring the thickness of pieces are both easily quantifiable metrics that are used to determine the proper weld size. For economic reasons, this analysis is always performed in manufacturing applications, but it is also necessary for quantifying the strength of a repair weldment to ensure that enough weld material has been applied to a given joint. Weldment strength mathematical field calculations will be examined in the chapter and illustrated with appropriate figures.

Finally, challenges for field engineers and technical managers will be summarized with emphasis on the identification of weld defects, preventative methods, and suggestions that can be used to minimize the occurrence of weld defects when conducting field repairs. Technical procedures for weld quality examination in field repairs should be useful for managers when instructing repairmen on alleviating defects or challenges within a job. Finally, the chapter concludes with a discussion of the importance of repairs to business enterprises. There is value in having basic welding technical knowledge for an array of industry specialists. This chapter seeks to promote further education and interest in the engineering properties of welding repairs, their application to practical problems, and provide some value to operational managers utilizing heavy field equipment.

A variety of primary sources have been used for this chapter. Various sections of Blodgett's *Design of Welded Structures* (1972) are used heavily throughout the chapter [1]. This classic textbook incorporates a significant amount of published welding calculations, and its primary focus is on welding in industrial and manufacturing environments. However, many of the calculations and formulas are valid across all fields of welding technology and application. Information regarding material properties and analysis comes from the *American Society of Mechanical Engineers* (ASME), the *American Institute of Steel Construction* (AISC), and the *American Society for Testing Materials* (ASTM) publications. These organizations are responsible for writing many of the technical standards and recommended protocols for design, material testing, and property specification in the industry. Codes and practical definitions regarding welding standards are from the *American Welding Society's* (AWS) *Structural Welding Code* [2]. The AWS provides detailed information in its standards for a diverse array of welding applications. Various standards include code requirements, measurements, strength, specific practice recommendations, given constants for equations, education, safety practices, and other facets of welding. Where appropriate, the reader will be directed to primary sources for specific information.

2. Identification of engineering challenges in repairs

There is a multitude of jobs and types of repairs requiring welding applications. Challenges can often be categorized by the location, component type, design criteria, and the degree of critical quality needed in the repair. Repair location presents its own challenges from a logistical sense. Outdoor welding applications require mobilized welding equipment to access the repair. Mobilized welding equipment can require a fuel-based power source, due to a remote location or conditions. Due to the space constraint of certain repairs, it is common for mobile welding equipment to feature lengthy leads, which can also create unique circumstances. Outdoor welding repairs can present additional challenges derived from environmental factors, such as weather, terrain, and less than ideal base material circumstances. Not all welding processes are well-suited for this type of environment, limiting available repair options. These challenges call for strategic planning and an understanding of certain technical properties for repairs made in outdoor environments. There are fewer constraints for indoor welding repairs, where a variety of processes are available. Indoor welding environments found in machine shops, manufacturing facilities, prototype shops, and fabrication workshops are well equipped for operator comfort and process quality, without exposure to adverse environmental conditions.

2.1 Repair preparations

Pipeline and structural welding are common examples of strictly outdoor welding applications. Professional welders of this category are highly skilled, due to the criticalness of their weldments and their ability to produce quality welds in difficult or uncomfortable body positions. This may consist of laying under a pipe in the mud to bevel, grind, mate, and weld pipe together, or it may mean being suspended hundreds of feet in the air, welding steel beams for structural applications. Critical preparation techniques are always used during the preliminary repair preparation process to ensure the quality of the weldment because, in many circumstances, time in the repair zone or position is limited.

Metal cleanliness and preparation are the most critical features for any field repair. Insufficient attention to base metal preparation will lead to unwanted imperfections in the repair. While certain welding processes are capable of penetrating through some surface rust, failing to clean the intended weld area of contaminants will always yield certain weld defects, such as slag inclusions, porosity, and craters. Weld defects lead to unwanted future cracks in the weldment, causing the component to lose structural integrity and have progressively weaker joint strength. Metal preparation is usually conducted using an electric angle grinder with a variety of disc attachments. Standard grinding discs are used to remove material quickly, and they perform well for removing large amounts of surface rust, paint, and other contaminates. Sanding disks, also referred to as “flap disks,” are effective at removing mill-scale on the base material and polishing the metal surface.

Material fitment to maintain proper dimensions and alignment with other components during the welding process is nearly as vital as material preparation. Repairs due to a defect or flaw causing a component or related component to be displaced from their original state must be approached with caution. These conditions require the fitment of material to be returned to a near-original state prior to the repair process. However, the removal of old material often includes the removal of the original weldment or the removal of material near the damaged area. Taking measurements beforehand or using a secondary, mirrored part for dimensioning can be helpful for reestablishing the original location of a displaced component in need of repair. When proper material fit-up is completed, weld material can be added to the removed areas by making a series of weld passes to build up the filler material. Adding an amount of weld material more than what is necessary is generally recommended, so later grinding can remove the excess.

After achieving proper fitment of the base pieces, constructing a jig or welding additional structures to the member may be necessary to maintain the position of the pieces while welding. Welding induces rapid temperature changes with the heat concentrated in a small area. This thermal transfer of energy causes the metal to expand slightly, and under extreme conditions, it can cause warpage and deformation. High temperatures cause a crystalline structural rearrangement and reduction in tensile and yield strength in most metal materials [3]. Metal warpage is more likely to occur when applying a large amount of weld material to thinner materials with thicknesses of less than 30 mm. Part of the preparation process for the repairman is evaluating and mapping out the intended weldments in an effort to evenly distribute heat applied to the material during the repair. If the material movement cannot be avoided by distributing weld material and heat evenly, a temporarily fixed member can be welded in place to prevent movement from occurring. The temporary support can later be removed and grinded away.

2.2 Material analysis

Welding repairs may be necessary on a variety of metal components that can be made from ferrous materials, such as carbon steel, stainless steel, and cast iron, as well as non-ferrous materials, such as aluminum and titanium alloys. Identification of the material is essential to executing a welding repair. Repairmen need to accurately be able to access which materials they are dealing with. All raw materials have specific properties associated with the type of material. Material properties are defined as measurable, quantifiable properties associated with the material. The material properties help categorize different materials and ease the process of material selection. Evaluating categories of mechanical properties of the material is an effective way to identify material for a field repair. Documentation is always best, but in the field, it seldom exists. When confronted with an unknown material, investigation should include at a minimum, a chemical test, and a hardness test. These two property indicators will help qualify the weldability of the material. Other properties can help narrow uncertainty in the base material. There are generally considered to be five categories of mechanical properties for common building materials [4], which are as follows:

- physical properties;
- mechanical properties;
- thermal properties;
- electrical properties; and
- chemical properties.

Physical properties are perhaps the most easily identifiable material characteristics when conducting field repairs. These properties include the shape, size, color, texture, finish, porosity, and luster of the subject material [4]. Technological properties are also referred to as basic mechanical properties for the metal, and these include hardness, malleability, machinability, weldability, and formability. It is recommended that the material's physical properties be evaluated first. This will allow an easier understanding and identification of mechanical properties, once known. In a repair situation, material identification is important for understanding the behavior of the component's base metal and how it is likely to react to different welding processes.

Mechanical properties are critical to understanding structural repair applications, particularly when there are critical zones of stress and strength maintenance requirements. Material properties commonly found in engineering material references are as follows [3]:

- ultimate tensile strength;
- elongation;
- modulus of elasticity;
- compressive strength;
- shear strength; and
- fatigue strength.

Tensile strength for different types of material is experimentally determined by a standard testing method, conducted using a tensile test machine. The selected material is marked at two locations, 50.8 mm apart. Once the selected material is placed on the machine, an axial load is applied by pulling the material in opposite directions at a constant rate. As the test progresses, the load divided by the original cross-sectional area of the material within the marked area represents the resistance that the material has to the tensile load being applied [1].

The stress (σ) unit is in force per area, while the strain (ϵ) unit is formally dimensionless, it is expressed as displacement in length per original length. The maximum load applied before failure of the material, divided by the static cross-sectional area of the material being tested is equal to the ultimate tensile strength (σ) of the material. From stress and strain values, the modulus of elasticity of a material can be calculated as [1]:

$$Modulus\ of\ Elasticity\ (E) = \frac{Stress\ (\sigma)}{Strain\ (\epsilon)} \tag{1}$$

Modulus of elasticity (E) is a way to quantify the springiness of a material or the stress value of a given material as it is deformed by a force in one direction. It is also commonly referred to as Young's Modulus, after English physicist, Thomas Young. The AISC states that the standard for all low-carbon steel is a modulus of elasticity of 200,000 mPa [5]. Section area is an important metric, used when calculating the stress and strength of materials with loads applied in compression, tension, and shear configurations. If the member is not symmetric throughout the length of the applied load, then the section at which the material or structure will induce the most stress is used in the calculation. Once the desired cross section is found, the neutral axis must be located. The neutral axis of a section represents the plane of zero strain and zero stress, and it can be a good place to locate a spot weld during the fitment process [1].

Material hardness is a well-correlated property with many other physical properties, and it is determined using a Brinell hardness test. The test is conducted by applying a known load to the surface of the material using a hardened steel ball. The diameter of the impression that the ball leaves on the tested material is the measured result of the test. The diameter of the impression can be converted to the Brinell number as follows [6]:

$$BHN = \frac{2P}{\left(\pi D\left(D - \left(D^2 - d^2\right)^{0.50}\right)\right)} \tag{2}$$

where BHN = Brinell Hardness Number;
P = Load on indenting tool (kg);
D = Diameter of hardened steel ball (mm); and.
d = measured diameter at the rim of the impression (mm).

Fortunately, the Brinell Hardness Number does not typically need to be calculated. For most materials, the number can be found using various Brinell charts. One might be exposed to materials with a high Brinell hardness utilized in high wear environments, as in abrasive situations, due to contact with other moving components. The Brinell hardness can be increased using a thermodynamic hardening process. There are various methods of hardening materials, but in the simplest form, hardening is achieved by increasing the temperature of the material to a modest degree and then rapidly cooling it by quenching the material. The quick change from a high temperature to a cold temperature hardens the material by locking-in elevated temperature crystal structures.

Tool steel used for drill bits, mill cutters, and hand tools is typically hardened, along with other critical mechanical components, such as shafts, bearings, and gears. Hardened materials can be a challenge for welding repairs, due to their impenetrable nature of the material. The heat applied to the material during the welding process, along with the rapid cooling typically present in welding, can make the hardened steel base material brittle and cause cracking along the joint. Heating the material slowly and evenly with an oxygen-acetylene torch, while monitoring the temperature of the joint before welding, will soften the material and allow the weld process to penetrate deeper. After the weld is complete, cooling the material around the joint slowly will maintain the material's hardness, but make the material less brittle. This softening process is also referred to as annealing [7].

The ASTM is an organization established to produce standards for material properties of all sorts. For nearly 120 years, ASTM has written technical standards for materials, products, and other systems [8]. Physical properties are defined by characteristics, such as corrosive resistance, hardness, density, and thermal conductivity, to name a few. When choosing metal material or evaluating an existing component for repair, corrosive resistance is an important factor to consider. Understanding the environment that the material is exposed to aids the welder in selecting preparation requirements and the welding process. In general, the welder should determine the following material properties before starting a repair:

- the material hardness;
- the moisture exposure;
- will paint need to be removed; and

- whether is it outside or inside the application.

It is commonly known that mild steel is corrosive, but when painted, the structural life of the steel is lengthened significantly. The corrosion rate is simply measured by the millimeters of corrosive penetration into the material per year. A common alternative to painting is the plating of the metal. Materials can be plated with a variety of different plating materials. Zinc-plated bolts are a common example of a component that receives plating for increased durability. It might be best to use stainless steel for structures exposed to salt water or high moisture atmospheric environments. Stainless steel is highly resistant to oxidation and a popular choice to use for marine structures, along with many industrial food processing applications having health code precautions. Materials with any of these anti-corrosion features must be treated specially, and repair welders must take these elements into account when planning repairs. Additionally, a repair technician should almost always consult a specialist, if they spot a highly stressed area, find corrosion or hydrogen embrittlement, or have a high-temperature operational environment [9]. Finally, if chemical information about the base material is available, levels of carbon and other alloying materials provide critical information to the repair technician. Certain stainless steels cannot be effectively welded, and in general, a 0.35% carbon level is typically considered the upper limit for welding. Material chemistry mainly identifies what cannot be welded or where extreme caution should be applied when making repairs. There are now test kits available that can determine a metal's chemical content within a matter of hours [10]. There is simply no excuse for not knowing what material you are dealing with anymore.

3. Welding fundamentals and equipment

There are three primary welding processes—gas metal arc welding (GMAW/MIG), gas tungsten arc welding (GTAW/TIG), and shielded metal arc welding (SMAW/Stick/Arc). This section will describe the characteristics and advantages of each process. Various welding positions, the different weld joint types, weldment preparations to the base materials, the calculation of weld fillet size, and weld strength will additionally be reviewed.

3.1 Arc welding

Shielded metal arc welding (SMAW/Stick/Arc) is chosen for a variety of applications due to its uniquely robust properties, allowing it to be used in many environments. Stick welding is heavily used in structural and industrial heavy metal applications when less than ideal conditions are present. Common SMAW/Stick/Arc welding joints include the assembly of structural frameworks for buildings and the joining of pipe segments together in pipeline applications. The connections of high-pressure pipeline segments are generally made by SMAW/Stick/Arc welding. The pipe ends are typically beveled, mated, and welded with an E6010 electrode. This is called a root pass. There can be several root passes depending on the application. Root passes are then overlaid and capped by several additional weld passes, building additional filler material with each pass. This kind of weld is durable and self-healing around small weld defects. It is the oldest form of electrode welding and is still preferred when deep penetration is required.

There is an assortment of consumable electrodes available to the repairman. These are also referred to as “rods.” Electrodes are 30 cm long sticks of filler metal, wrapped with a flux coating. As shown in **Figure 1**, they are referenced with a four-digit numerical code with each number referencing a specification for the electrode. The first two numbers reference the tensile strength of the weld material that the rod will produce. The third number refers to the position(s) in the electrode that can be used for welding. One means that it can be used in all positions, and two means it can only be used in the flat and horizontal positions. The fourth number refers to the type of flux coating, the hydrogen content of the electrode, and if it can be used with alternating current, direct current, or both. An advantage of the stick welding process is its ability to make high penetrating welds on imperfectly prepared material with oxidation and mill scale, the oxidized scaly substance on the surface of most hot-rolled material.

This makes SMAW/Stick/Arc welding an excellent choice for field repairs. The stick welding process is commonly used by repair shops for agricultural, off-road, and construction equipment repairs. With the correct rod, rusty and dirty metal can be welded effectively with minimal preparation. This process produces a very strong weldment with high material penetration and can produce an esthetically pleasing weld bead using certain electrodes. Unfortunately, as shown in **Figure 2**, it generates far more splatter and slag peel than other welding processes. However, those other processes require clean metal with minimal mill scale to make solid weldments. Stick welding can operate with either direct current or alternating current. Stick welding machines use a ground clamp and an electrode holder, commonly referred to as a “stinger” to make the necessary electric circuit.

SMAW/Stick/Arc welding is the generally preferred choice of the process by many repairmen for field repairs. As previously mentioned, field repairs often require the use of mobile welding equipment. Notable welding equipment manufacturers, such as Lincoln Electric and Miller Electric, manufacture gasoline and diesel-powered welders for this purpose. Test engineers, pipefitters, construction crews, and other field repairmen will generally have their service vehicles equipped with machines of this category. Mobile welding rigs typically have electrode holders and ground leads in lengths of 15–30 m for repairs and jobs, where only limited vehicle access is available. If the stick welding process is utilized for repair work to an appearance-critical piece of equipment, extreme care must be taken to effectively tarp and shield the balance of the unit from the inevitable splatter of the process.

3.2 MIG welding

Gas metal arc welding (GMAW/MIG) is the predominate joining method in manufacturing and industrial settings. This process is preferred, because of its weld

Figure 1.
Electrode specification stamped on the flux coating of a typical welding rod.

Figure 2.
Stick welded components showing the splatter form the process.

quality and speed, making it less expensive to implement in production situations. GMAW/MIG welding produces very little slag and creates a very clean welded connection when welding clean material. MIG welding is often referred to as “wire feed welding.” As shown in **Figure 3**, its nickname is due to the spool of wire fed through the MIG gun by the machine. When the trigger on the gun is actuated by the operator, electrified wire is fed through the end and shrouded by a gas cloud. A typical combination of shielding gas for welding mild steel is 75% argon and 25% CO_2. As the welding wire is pushed toward the base material, it strikes an electric arc and melts the target material and filler materials together. Filler metals are rated by their tensile strength. A tensile strength rating of 482 mPa is common for most spools of filler wire. MIG welding is not as effective as SMAW/Stick/Arc for use on oxidized material, without significant clean-up and material preparation. However, it is more time-efficient than other processes for clean assemblies, making it an excellent process in production environments. As shown in **Figure 4**, it makes a beautiful, clean weld on clean material. Materials such as steel, aluminum, magnesium, carbon steel, nickel, and other alloy metals can be welded with the GMAW/MIG process, making this a

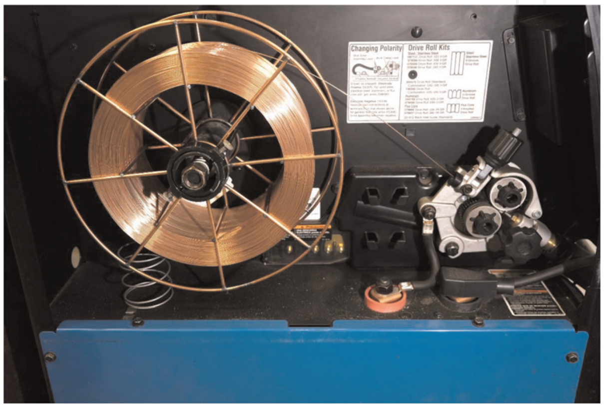

Figure 3.
Spool of 0.58 mm filler wire mounted on MIG welding machine.

versatile industrial tool, when multiple materials are in use. The ability to weld a variety of materials makes it a top choice in high production manufacturing [11].

3.3 TIG welding

Gas tungsten arc welding (GTAW/TIG) is a process commonly used for specialty welding repairs and applications, where additional craftsmanship is necessary. The GTAW/TIG welding process is commonly used on components that are made of stainless steel and other non-ferrous metals. TIG welding is expensive and time-consuming, due to its precision, but as shown in **Figure 5**, the quality of the GTAW/TIG weld is unsurpassed. Consequently, it is not often used for facilitating field repairs, but may be used for smaller repairs, especially for stainless-steel repairs. Stainless steel is an alloy with unique properties that do not allow it to be welded easily with other welding processes or without specific equipment configurations. Stainless steel material is subject to cracking at high welding temperatures from other welding processes, causing additional weld defects, which result in weld quality issues. However, stainless can be welded nicely with the use of a TIG welder, due to its low heat application from the tungsten rod in tandem with an argon shielding gas. The user has the ability to control the welding heat with great precision. TIG welding uses a foot pedal to control the machine amperage. It can operate on direct current or alternating current, but the tungsten electrode rod is not actually consumed very rapidly. The process requires filler metal to be fed manually by the welder into the arc that is struck by the tungsten rod attached to what is referred to as a “TIG torch.” TIG welding is commonly used in applications where bead esthetics are preferred because it produces no weld slag. These applications include stainless-steel exhaust headers, pipe/tubing, and roll cages. TIG welding produces a high tensile strength weld and is a very good choice for a variety of applications requiring clean-finished beads or the repair of exotic materials. It is a well-suited process for applications requiring clean, good-looking welds, and it is a highly regarded choice for critical stainless-steel joints and connections.

Figure 4.
Horizontal fillet weld on clean material done by GMAW/MIG welding.

Figure 5.
GTAW/TIG fillet weld on aluminum material.

3.4 Welding positions

The American Welding Society identifies four basic welding positions. These positions characterize the position of the electrode in relation to the object being welded. The four welding positions are described as the horizontal position, flat position, vertical position, and overhead position. These welding position definitions have been established by the AWS, due to the subtly, but critically differing, techniques associated with each position. Professional welders must pass welding application tests in each position to prove their competence for all of the established welding positions [3]. Weld metal behaves differently in all positions, creating challenges to consider when conducting a field repair. Identifying where the welding material will travel due to gravity, is a major consideration when making repairs in each welding position. **Table 1** summarizes several of the welding symbols associated with different welding positions and types of weld. Well-specified repair instructions identify the welding position, weld type, and joint preparation to be used.

3.4.1 Flat position

The flat position is the simplest position and the easiest to execute by novice welders. Most welders find welding in this position to be natural and comfortable, typically traveling from left to right. It is generally recommended that the component being welded be turned to the flat position for easier constructability, if possible. **Figure 6** shows the location of the material and fillet in a flat position weld. Molten weld material travels downward naturally in the flat position, penetrating the material adequately. The flat welding position is executed similarly for both fillet and groove joint configurations [12].

3.4.2 Horizontal position

The horizontal welding position is similar to the flat position with the joint rotated at 90°. A fillet weldment in the horizontal position can be slightly more challenging to execute than weldments made in the flat position. Horizontal groove welds typically require more attention and control of the weld pool to establish an equal penetration

Welding positions and symbols		
Position	**Weld type**	**Symbol**
Flat	Fillet	1F
Flat	Groove	1G
Horizontal	Fillet	2F
Horizontal	Groove	2G
Vertical	Fillet	3F
Vertical	Groove	3G
Overhead	Fillet	4F
Overhead	Groove	4G

Table 1.
Welding positions and weld types identified by welding symbols for technical drawings.

Figure 6.
Base material orientation and working position for flat position fillet weld (1F).

Figure 7.
Base material orientation and working location for horizontal position fillet weld (2F).

into both base metals. Again, left to right travel is generally preferred. **Figure 7** shows the location of the material and the fillet in a horizontal position weld.

3.4.3 Vertical position

The vertical position requires traveling uphill or downhill when welding. The vertical welding position is illustrated in **Figure 8**. It can be difficult to perform, due to the downward gravitational pull on the weld material before it cools. This can cause the weld material to build up when traveling uphill, and it can extinguish the arc when traveling downhill. To decrease the occurrence of material build-up, welders typically lower the amperage on the machine slightly. This allows the weld material to cool faster, decreasing its ability to move gravitationally. Traveling uphill is the preferred direction of travel for vertical position welding. This gives the welder more weld pool visibility, without the weld material blocking the welder's view of the arc. The weld pool will cool away from the arc, so the proper speed of travel is critical to executing a proper vertical weld.

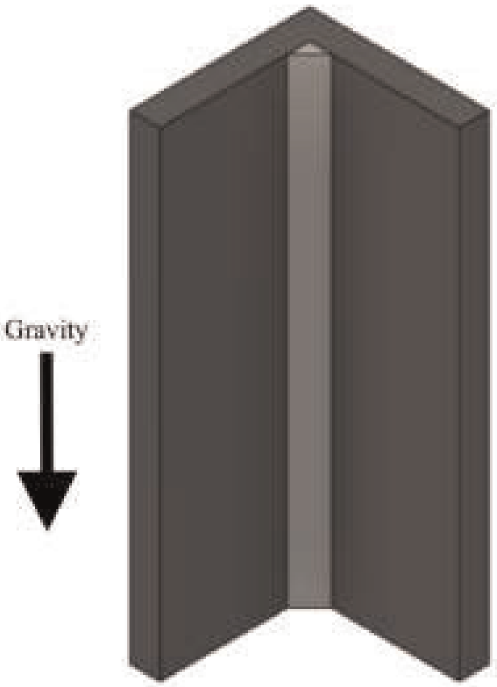

Figure 8.
Base material orientation and working location for vertical position fillet weld (3F).

3.4.4 Overhead position

The overhead welding position is the most difficult, even for the most skilled tradesman. **Figure 9** illustrates some of the challenges posed by the gravitational vector in executing an overhead weld. In the overhead position, the weld pool wants to naturally flow in the opposite direction of the joint. This will cause weld material to sag away from the joint as it cools, creating a crown [12]. A crown is an excess concavity of the face of the weld material that sags away from the joint [13]. Poor

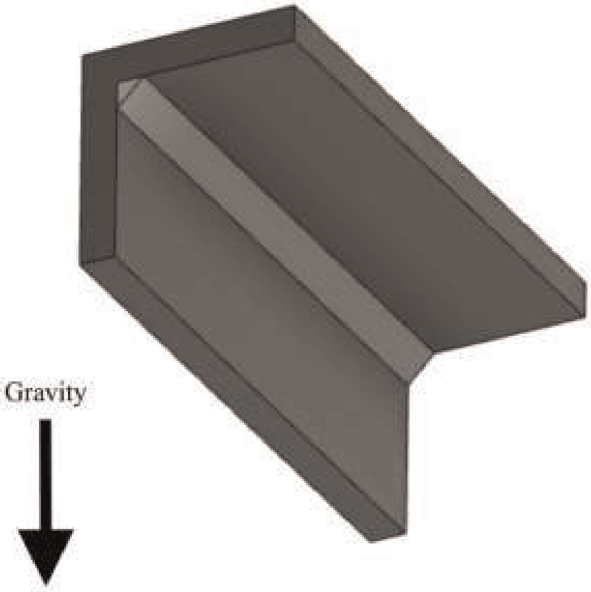

Figure 9.
Base material orientation and working position for overhead position fillet weld (4F).

overhead welds can have void spaces, so keeping the arc tight and the diameter of the weld pool small helps avoid this defect. Welding in the overhead position is generally avoided if possible, but if required, additional care must be taken to identify problems and correct deficiencies. A project manager must understand that this weld is extremely challenging and to be approached with caution in a repair.

3.5 Weld joint types

In a welding repair scenario, there will have been a joint already constructed. Identifying the joint type is critical to know what type of weld should be applied to repair the member. There are five primary joint configurations established by the AWS shown in **Figure 10**. The five weld joint configurations are described by the physical intersection between two joining materials. The shape of the base pieces is irrelevant to the joint classification. All metal joints can be classified under one of these five categories, whether the joint is constructed on a plate, pipe, or pre-made structural shapes. Weld joint classification is different from the weld type. The former depends on the relative position of the base pieces to one another, while the latter depends primarily on the joint preparation. In general, there are three weld types: fillet, groove, and slot types. The various weld types are illustrated in **Figure 11**.

3.5.1 Fillet welds

The fillet weld is a type of weld used in most applications and is notable for being the most common type of welded joint connections. Fillet welds are used to make lap joints, corner joints, and T-joints [14]. The basic shape of a fillet weld is a right

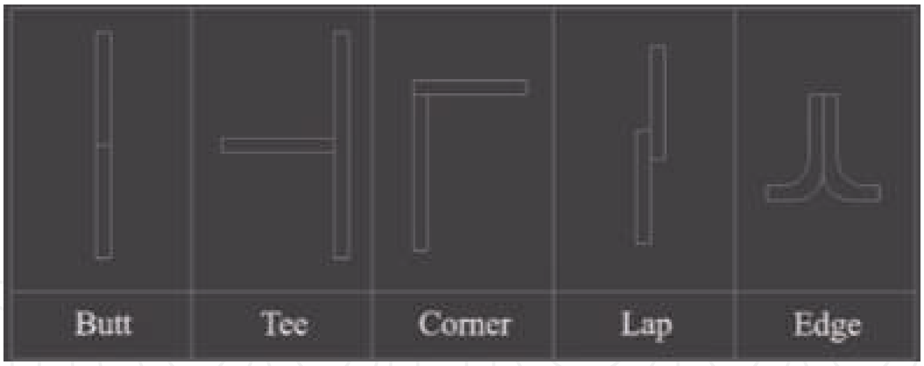

Figure 10.
The five established weld joint configurations.

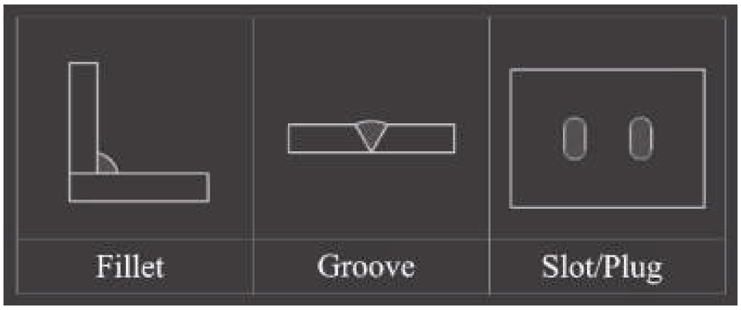

Figure 11.
The three established weld types.

triangle with two equal leg sizes. However, it is difficult to make a fillet weld that formulates a perfect right triangle. There is a reasonably generous tolerance for the shape of a fillet weld. The weld throat is assumed to be the length of the hypotenuse, across the weld shape. Fillet welds must maintain a certain size relative to the thickness of the base metal. In other words, the throat of the weld cannot be too convex or too concave. A fillet weld with a throat that is too convex means there is not enough penetration into the joining material. A fillet weld with a throat that is too concave results from not enough weld metal applied. Either condition creates a weak weldment, and both should be flagged for repair, at present.

3.5.2 Groove welds

Groove welds are classified by the various shapes and sizes of the preparation on the base materials. The types of groove weld classifications are shown in **Figure 12** and listed below:

- square groove;
- V-groove;
- bevel groove;
- U-groove;
- J-groove;
- flare V-groove; and
- flare bevel groove.

Groove welds can be used in corner joints, T-joints, and butt joints. Groove welds are often used for tight fitment applications. Each of the groove weld types listed in the text above has its own symbol and associated dimensioning method per the AWS symbol standard. There are significant material preparation techniques associated with groove weldments, and they typically concern the construction of the specific groove. These details are specified within the weld symbol structure. Beveling the ends of the material in a specific manner is necessary to form the groove. The beveling

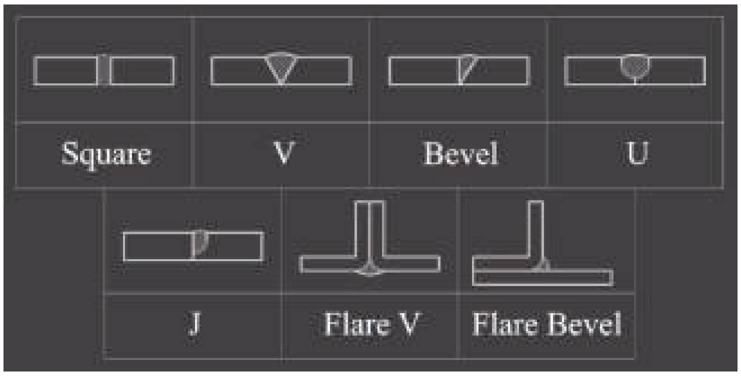

Figure 12.
Groove weld preparations in base material to be joined.

extent is specified by different bevel angles. Bevels allow for weld metal to fill the beveled-out area more easily and increase the strength of the weld.

Figure 13 above represents the material preparation of two steel plates for a 60° V-groove weldment. The angular dimension for the groove is specified within the weld symbol structure. After the weld has been applied between the pieces of base metal, the excess can be ground-away to present a smooth surface of the steel plates, as if the plate is one piece. If executed properly, groove welds can provide superior penetration and strength.

3.5.3 Plug and slot welds

Plug welds and slot welds are similar and are often used to join two overlapping plates. One of the two plates will have drilled holes or milled-out elongated slots. This internal opening to the second piece is where the weldment will be produced. When dimensioning a plug or slot weld, the hole diameter will be shown to the left of the plug symbol, and the plug spacing (distance between each hole) is shown to the right of the symbol. For slot welds, the width of the slot is shown to the left of the symbol, while the length and pitch are shown to the right of the symbol. A drawing detail is often referenced in the tail of the weld symbol structure. If the slot or plug is not to be filled completely with weld metal, the fill depth will be specified [14].

3.6 Determining weld size

Determining the proper size of a weld is essential in conducting a welding repair. Over-welding by repairmen does not generally enhance the chances of success for a repair. A common misconception is that applying an excess of weld material provides additional strength to the joint. This is false, and over-welding can actually weaken the joint by the additional application of heat transferred to the material around the joint. Over-welding is quantifiable and can be calculated in manufacturing applications to minimize production costs. For repairs, it adds time to the job without any benefit to the customer, and it may be counterproductive. The depth of weld penetration is a more important factor in creating a good weld, and it can be properly gauged by correctly sizing the thickness of the weld.

The thickness of the weld is controlled by the depth of the material being welded. It is critical to understand that the material thickness input must be the thinnest material associated with the joint that is being welded. This is especially important in weldment strength calculations. *Design of Welded Structures* define the recommended size of a fillet weld using Eqs. (3) and (4) [1]:

$$L_s = \frac{3}{4} * (M_t) \tag{3}$$

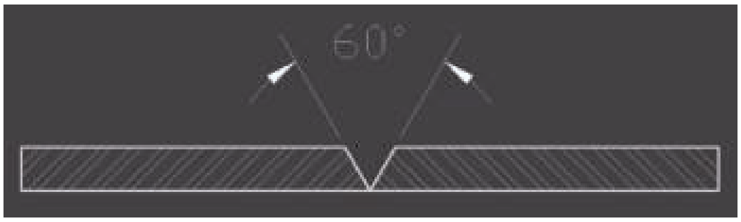

Figure 13.
Material preparation for V-groove weldment.

$$W_t = \cos(45°)(L_s) \tag{4}$$

where M_t is the base material thickness;
L_s is the weld leg size; and.
W_t is the weld throat size.

Figure 14 illustrates these variables on an illustration of a cross section of a tee joint. Following this recommendation for the fillet size will create the proper amount of weld penetration into the base material for a solid joint.

When calculating the throat size, a 0.71 scale factor sometimes appears in the equation for calculating throat size. This is the rough equivalent of $\cos(45°)$. Depending on the structural application, type of stress on the effective weldment, and how much stress the weld will endure, different welds will require different lengths of run. Determining the proper length for a weld minimizes the potential for over-welding. For instance, if two plates needed to be joined, but no load or minimal load was applied in shear, then the most effective way to join the two plates would be to apply a series of small stitch welds across the connection. Stitch welds are intermittent, rather than continuous welds. Fillet welds used to transmit forces should not be less than four times its leg size in length or 3.8 cm, whichever is greater [1]. Neither should the effective weld size of the fillet weld exceed ¼ of the length of the weldment [1]. **Figure 15** presents these fillet length constraints graphically.

Stitch welding is a technique used to connect base material pieces that will see little stress and fatigue in their duty cycles. Additional weld fillet length beyond the structural need is wasteful and costly. Stitch welding is generally a great technique for field repairs that require lengthy connections, eliminating the need to weld a solid bead that would introduce a significant amount of heat into the base material, potentially causing distortion and warpage. Engineering drawings feature unique callouts for stitch welding that include dimensions referencing the length of the stitch weld, the distance between each stitch weld, the weld type, and the size of the weld [15]. The drawings will also feature callouts for the intermittence of the weldment, such as intermittent welds on one or both sides of the joint and the staggered intermittent interval for the weldments [15]. In field repairs, it is usually up to the repairman to evaluate the stitch weld dimensions and the weld runs intermittently, depending on

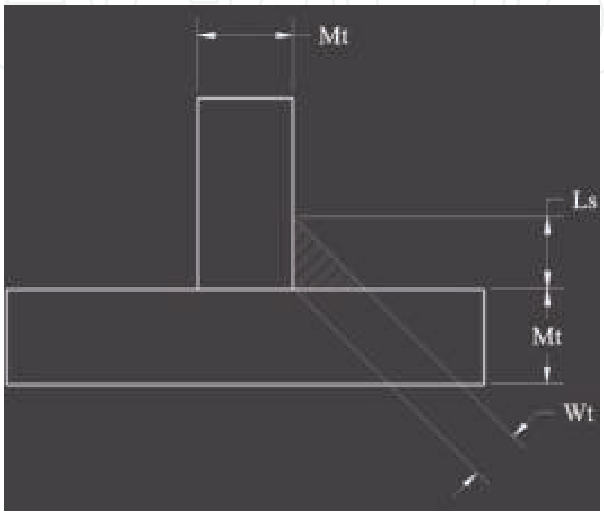

Figure 14.
An illustration of fillet weld size variables used in weld strength calculations.

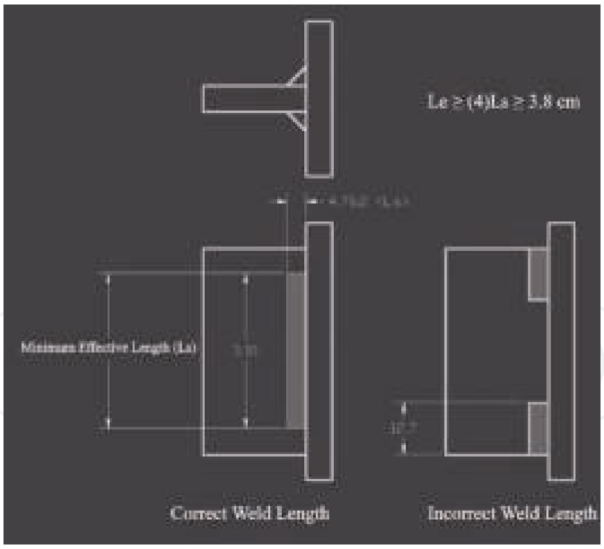

Figure 15.
Minimum effective weld length of run.

the stress of the joint. Significant guidance for the design of the weld can be had through the proper estimation of the needed weld strength.

3.7 Weld strength

Weld metal has tremendous strength, generally higher than the raw strength of the base metals that are being joined. This strength can be calculated with the type of load the material will face. Welded components may endure multiple different types of stress in unison. Fortunately, the superposition of loads principle allows the calculations of each type of stress remain separate. Transverse and shear loads represent the two most common load orientations.

The fillet welds represented by the right triangles shown in **Figure 16** are very resistant to the transverse type of loading. However, if the load follows the direction of the arrow and only one fillet weld existed on the right-hand side of the plate, the connection would be weakened and would likely bend over itself and break off at the joint, toward the right-hand direction. In general, the best practice would be to weld both sides. However, if the application required only one fillet weld, due to a low load application, then the weld should be placed on the side of the plate that places the weld in tension, not compression. In this case, it would be the arrow side of the plate. If the load was in the opposite direction, then the preferred weld location would move to the other side.

Transverse loading is only when the load applied is perpendicular to the weldment. If the load is present in a direction parallel to the weld, as shown in **Figure 17**, then the

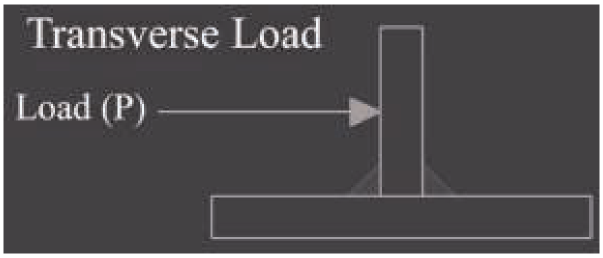

Figure 16.
Illustration of transverse loading on weldment.

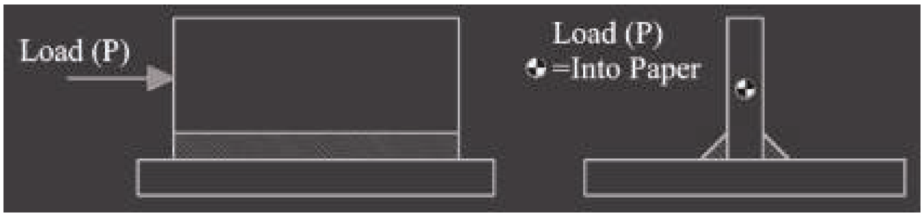

Figure 17.
Illustration of shear loading on weldment.

strength of the weld must be calculated in shear. Shear loading is more detrimental to the structural integrity of a weldment than a transverse load. The decreased structural strength of the weld means that the weld strength cannot be calculated using the full tensile strength of the filler metal. Instead, the AWS recommends that the tensile strength of the filler material be reduced by multiplying by a value of 0.30, reducing the tensile strength by 70% [2]. Otherwise, the strength calculation process is the same.

The calculation of weld strength for transverse load is straightforward, but it is important to emphasize that this is the calculated static strength of the weldment, without measurement against an applied load. Transverse loading requires three basic inputs for determination: filler tensile strength (T_F), the thickness of base material (M_t), and length of weld applied (L_W). Eqs. (3) and (4), along with Eqs. (5) and (6), are used to successfully calculate the strength of a weld under transverse load [1]:

$$A = W_t * L_W \tag{5}$$

$$F = T_F * A \tag{6}$$

where A is the sectional area of the weld;
W_t is the weld throat size;
L_W is the length of the applied weld;
T_F is the tensile strength of the weld filler material; and.
F is the resistive force the weld is capable of supporting.

Table 2 shows the application of this model in calculating the weld strength for material and weldment length using specific values. The tensile strength for the most common MIG filler wire is 483 mPa, and that has been used here. The calculations show that the maximum strength of the weldments under transversal load is 200 and 198 kN in shear load. This number would be an upper bound for loading because the calculation lacks any accounting for imperfections. Any weld imperfections, defects, undercut, material imperfections, material fit-up problems, or dynamic or thermal loading during welding will reduce the strength of a welded joint. This calculation merely provides the theoretic strength of the specific design under specific conditions. In manufacturing, weldment specifications are properly simulated using finite element analysis, tested, and inspected to ensure that the applied loads do not exceed the factor of safety in the design. However, this level of analysis and design is typically not available to repair specialists. They simply tend to increase the factor of safety within their designs, accordingly.

All of the necessary parameters for the basic weldment strength calculations can be easily obtained when conducting field repairs. A tape measure and a phone calculator are the only tools truly needed to execute this calculation in the field. The tensile strength of the filler wire can be found on the wire spool attached to the welding

Name	Value	Unit	Description
Strength of weldments			
Inputs			
TF	482	mPa	Tensile strength of filler
TM	3.18	mm	Thickness of material
LW	1092.2	mm	Length of weld applied
Transverse loading			
LS	2.38	mm	Leg size
TS	1.25	mm	Throat size of weld
A	1366.26	cm^2	Effective area of weld
F	658,536	N	Strength of weld
STF	482	mPa	Tensile strength of filler
STM	3.18	cm	Thickness of material
SLW	1092.2	cm	Length of weld applied
Shear loading			
SF	197,561	N	Strength of weld

Table 2.
Spreadsheet calculation for weld strength under transverse and shear loading.

machine. For arc welding applications, the tensile strength is called-out on the electrode. Proper weldment design in repairs is just as critical, perhaps more so than in original manufacture.

Stitch welding is a technique used to connect base material pieces that will see little stress and fatigue in their duty cycles. Additional weld fillet length beyond the structural need is wasteful and costly. Stitch welding is generally a great technique for field repairs that require lengthy connections, eliminating the need to weld a solid bead that would introduce a significant amount of heat into the base material, potentially causing distortion and warpage. Engineering drawings feature unique callouts for stitch welding that include dimensions referencing the length of the stitch weld, the distance between each stitch weld, the weld type, and the size of the weld [15]. The drawings will also feature callouts for the intermittence of the weldment, such as intermittent welds on one or both sides of the joint and the staggered intermittent interval for the weldments [15]. In field repairs, it is usually up to the repairman to evaluate the stitch weld dimensions and the weld run intermittence, depending on the stress of the joint. Significant guidance for the design of the weld can be had through the proper estimation of the needed weld strength.

4. Challenges for engineers and technical managers

One of the more difficult tasks for an equipment manager is signing off on the acceptance of repair work when the work falls within the domain of a specialist. Welding repairs certainly meet these criteria for most individuals. This section will examine weld defects and how to recognize them. It will cover the repair of defective welds and then go into detail about more extensive examination methods necessary to verify the quality of a critical weld.

4.1 Weld defects

Defects in repair welds can have calamitous results. Therefore, it is necessary to identify defects and imperfections within a repair weld, before returning equipment to duty. Understanding the allowable variations in weld material's physical and mechanical structure will provide a reasonable basis for inspecting welds for imperfections. Pockets of impurities and variations in the weld that are within the acceptable tolerance range are called "discontinuities." Discontinuities that exceed the acceptable tolerance are called weld "defects" [16]. Defects must be ground away and repaired. Defects are generally caused by a poor welding technique, poor joint fit-up, or both. In the world of repair, poor joint fit-up is the most common cause of defective weldments. Repair jobs often consist of components that have separated and are no longer in their original position, making it difficult for the repairman to achieve the original geometry. This can be accomplished for many repairs, but sometimes it requires significant attention to detail and a bit of creativity to manipulate the original material into an acceptable repair position.

Defective welding techniques can cause impurities that affect the shape and size of the weldment, cause imperfections in the internal structure of the weld, and create other defects that adversely affect the weld's strength. The basic categories of weld defects are overlapping, undercutting, distortion and warpage, cracks, craters, porosity, and inclusions. Overlap is excess weld metal that reaches beyond the joint onto the base metal. The primary cause of overlap is an incorrect angle of the electrode with respect to the base material. If the electrode is not angled away from the weld pool on the leading edge, the arc will manipulate the weld pool, causing notches to form between the overlap and the base metal.

Undercutting defects occur when electrode travel speed is too fast, causing grooves or gaps on the toe of the weldment between the base metal and weld metal. The rapid travel speed does not allow enough time for the weld metal to fill in after penetration has occurred into the base metal. A thin or narrow weld bead also indicates excessive travel speeds. Good technique and weld speed will eliminate this problem.

The misconception that over-welding creates stronger joints was mentioned previously. Over-welding can also cause distortion and warpage of the base metal by the excessive application of heat. This occurs due to an improper joint design from the base metal thickness and dimensions. Applying a large amount of weldment in several passes can induce a large amount of heat, and it will also cause thin materials to flex and warp. This weld defect is extremely difficult to correct after the fact, due to the alteration of the base metal's natural shape. Heavy clamping in critical locations, before welding materials are likely to deform, is usually best. Once a piece has deformed into a complex shape, corrective choices become limited and generally involve minimizing further damage.

Cracks in the weld metal are often caused by other weld defects or excess stress induced at the joint. There are several classifications of cracks. Some cracks are internal and cannot be identified from the surface or at the throat of the weld. The stress-induced area at the toe of weldment is a common origination site for weld cracks [16]. Craters can form in the weld bead, causing a gap or hole in the weld metal due to the lack of filler metal deposited. Craters are easily corrected by revisiting the defect area after the weldment is complete. A new electrode should be used, beginning the tie-in 2.5 cm or so in front of the crater, allowing weld metal to melt and deposit into the crater, and extinguishing the arc after the proper amount of weld metal has filled the depression.

Porosity occurs when gas bubbles become trapped within the weld metal. This creates an uneven distribution of foamy weld metal. Porosity weakens the weld and can generally be identified at the surface of the weldment. Visible porosity is an indication that there is also porosity located below the throat of the weld. Inadequate weld preparation and contamination are the most common cause of weld porosity. The trapped gases are usually do not shield gases from the welding process, but gases from the oxidation and vaporization of the contaminates on the surface of the base metal [16].

Slag inclusions can result from trapped welding slag within the weld metal. This occurs only when using the SMAW/Stick/Arc welding process since GTAW/TIG and GMAW/MIG processes produce little slag peel. Slag inclusions can happen when an electrode has been consumed, and the welder ties into the old weldment with a new electrode, before removing the slag peel on the surface. Defects caused by improper welding techniques can be easily eliminated by following established welding procedures and maintaining the proper travel speed, arc length, and electrode angle recommended for the specific welding process.

4.2 Repairing weld defects

Welding defects must be repaired by the complete removal of the defect using either torch removal or grinding methods. Portable grinders with stone wheels are an excellent tool for the removal of weld defects. There is a selection of sizes in grinding wheels, and some wheels are designed to use the surface of the wheel, while others are designed to be used only on the edge. Grinding wheels designed for grinding with the outer edge of the wheel are a popular choice for removing joints, where a groove or bevel is present. Once the defect has been ground away completely, another welding attempt can be tried. For long stretches of removal, an oxygen-acetenyl torch may be used to gouge out the defect. This can be a more efficient method of removal in certain situations. Torch gouging may also be the only practical choice, if the joint is space-constrained, with little room to reach the defect area with a grinding wheel.

4.3 Weld quality and examination

It is important for field engineers and welders to evaluate the quality of their weldments. Each kind of defect displays unique characteristics, simplifying the identification and analysis process. Some defects are visually obvious, but a surprising number of repairmen do not thoroughly inspect their work after completion. Visually inspecting the weldment is vitally important to ensure the integrity of the repair, and it does not require significant effort. Cleaning the weldment and the area around the joint by removing slag with a wire brush is an easy process that results in improved visibility. The visual examination of a weld can usually be conducted with a flashlight, looking closely for the undesirable characteristics associated with the defects previously discussed.

The best practice for larger repairs and welding jobs is to have the inspection process functioning throughout the repair, conducted by a trained inspector at each step of the way. This preventative inspection protocol eliminates the continuance of defects during a repair [1]. However, an independent inspector for field repairs is not usually feasible. Therefore, it is vital for the welder to be capable of identifying defects as they occur. Quality control can be improved by having two or more qualified persons provide inspections. A fillet weld gauge is a handy tool for determining the size and quality of welded field repairs. This device is a measuring tool for checking the leg size and throat size of the weld [17].

In specialty applications where structural integrity is of utmost importance, inspections must be regular, and welds must meet the acceptable defect tolerance level. Specialty applications, such as underwater bridge welding, ship welding, and oil-rig applications must adhere to strict guidelines, codes, and are classified as a Class A weld. Welders in these fields must be licensed by passing a series of weld tests for joints configured in the 3F and 4F positions, administered and evaluated by AWS certified inspectors before beginning a new job, regardless of the prior experience of the welder. This requirement is due to the potential ramifications of a failed weldment [18].

4.4 Filling gaps and repairing cracked components

Cracked components are common in the mechanical industry and are a regular failure mode for many pieces of equipment. These repairs are some of the toughest to execute, and this section will illustrate the overall process, so the equipment manager has an idea of the complexity of the operation. To repair a crack in carbon steel, a bevel directly on the crack must be ground to allow the weld metal to penetrate the base material, creating a tight joint at the crack. An electrode diameter size close to the width of the groove made by the grinder must be used. A standard size filler of 0.89 mm wire is generally sufficient if using a MIG welding process. Depending on the size and characteristics of the crack, an E6010 electrode and capped with a low-hydrogen E7018 electrode would be recommended to eliminate any undercut or hydrogen deposits created by the E6010 electrode, if using a GAW/Stick/Arc process. Finally, the weldment should be ground flush with the base metal to maintain its original appearance.

A field technician might encounter a situation where a gap needs to be bridged between two base pieces. A gap is when two materials should be welded together, but the pieces should not contact each other, as in **Figure 18**. The gap must be filled with weld metal, as in **Figure 19**. This technique should be considered the second stage in repairing a crack. A break that needs to be fixed by bridging a gap often originates from a hairline fracture or crack. When the material separates, it cannot always be drawn back together for repair. Filling gaps can be done in a variety of ways with different welding processes. Large gaps can be filled by using a backing strip. A

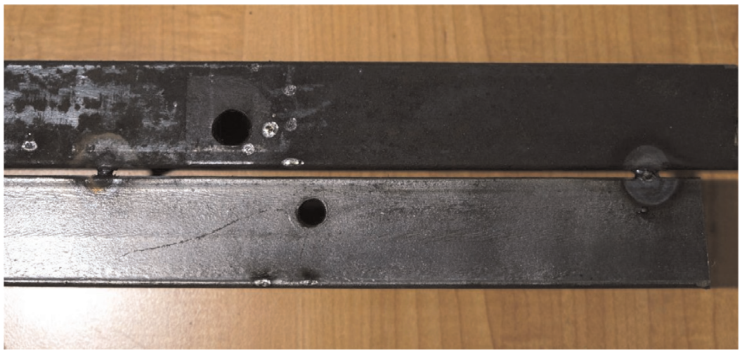

Figure 18.
Tack welds applied to establish a 0.3 cm gap between the separated pieces.

Figure 19.
Multiple large tack welds used to fill the gap between the separated pieces, where a continuous weld would likely blow through the gap.

Figure 20.
Welds ground-down to remove defects that occurred during the tack welding process joining the two separated pieces.

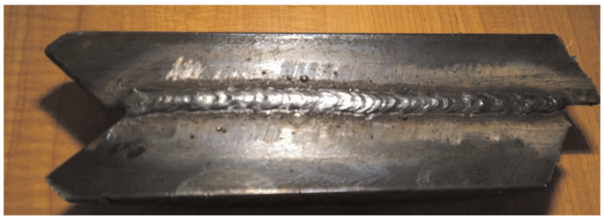

Figure 21.
A fine cap fillet pass used to finish joining two separated pieces, which may be ground flush for a solid appearance.

backing strip is a section of material tack welded or stitch welded onto the base metal. This provides a surface for multiple welding passes without burning through. If a backing strip is used, it can later be grinded off and removed, or it can be left in place, depending on the criticality of the original dimensions. One simple technique to execute a gap fill is by making a series of tack welds along the joint, evenly spaced out. This allows the joint to be welded solid, while the tack welds provide enough weld metal to not blow through the joint. The fillet is typically ground flush after sufficient penetration and connection between the pieces has been established, as in **Figure 20**. Finally, a finish fillet can be applied to cap the weld, as in **Figure 21**.

5. Closure and value of welding technical knowledge

Field repairs are frequently needed and often encountered by many technical professionals. Certified welders in manufacturing, pipeline, industrial, and fabrication shops gain a large amount of theoretical and application-based welding knowledge during their skilled-trade education. On the other hand, engineers and technologists are typically provided with very basic knowledge of welding processes and applications and have minimal field experience. These career areas may experience the need for welding repairs, especially when prototyping and testing. Gaining additional knowledge to further understand the theoretical process and mathematics behind welding techniques will increase the ability to execute, facilitate, and manage repairs of this nature. Management professionals will likely encounter the need to retain welding services, and they need to be able to competently specify the work to be done and be able to inspect it.

Challenges are present in all welding repairs. Critical considerations of these challenges are often not made, due to a lack of knowledge surrounding some of the more advanced topics. It can be difficult to evaluate all the factors in-field repair environments when time is constrained. Material properties, hardness of the material, and stress characteristics should really be thoroughly investigated when the repair is critical. Welding processes, equipment, and weldment preparation can provide the basis for conducting a proper field repair or general welding task, and it is incumbent upon a good equipment manager to understand the basics of welding. A breakdown of fundamental welding positions and types of welds has been shown. It has been demonstrated that the repairman's physical position in relation to the weld is important to constructing a proper joint and executing a sufficient weldment. It was shown that the calculation for the correct weld size in relation to the base material is a simple field calculation. In more advanced major repairs, where stress-induced members are present, further field calculations for structural analysis of the weldment can be performed without excessive computation. These calculations provide quantitative metrics to determine the integrity of the repair weldment design if it were to be applied properly. The repairman can then judge whether the proposed weldment is adequate and sufficient for the repair.

The identification of welding defects, imperfections, and allowable tolerances for each is imperative in evaluating welds and managing quality repairs. The difference between an acceptable weld and an unacceptable weld can be minimal depending on the defect, and it is critical to be able to differentiate between the two. Finally, knowledge regarding the repairs and the correction of welding defects is perhaps the most valuable skill an equipment manager can have, as the correction of these deficiencies is frequently among the most commonly needed field repairs.

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Conflicts of interest

The authors declare no conflict of interest.

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