Selection and Design of Welds

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I. Introduction

A. Theory of Welding

The theory behind welding is to join metals at a molecular level. This process is distinctly different from the use of fastenings and adhesives. At our current technology level, metals are often joined by the addition of heat. This can come from a flame, electricity, concentrated light, or friction. Also, many metals can be contaminated by elements in the air, so a shielding gas is often used. In cases when material needs to be deposited at the weld location, a filler metal is added.

B. Purpose of Welding

The purpose of welding is to attach materials in a strong, inexpensive, and permanent fashion. Many types of equipment in use today would be almost impossible to transport or construct without welding. Fasteners can only be used on certain types of joints and even then they can come loose or break easily. Welding allows for a uniform and strong joint made out of metal itself, which no other fastening method can even come close to imitating. Welding is invaluable also in situations where metal needs to be formed into a shape that cannot readily be extruded and casting is prohibitive because of material properties or cost.

II. Different Styles of Welds

A. Welding Processes

Gas Welding

In gas welding, a gas flame is used to provide the heat that is used to join the metals. Often, a rod of filler material is used to provide extra material to the weld joint. The most common type is oxyacetylene welding because the mixture of oxygen and acetylene has a higher flame temperature than other oxygen mixtures, at approximately 5800 degrees Fahrenheit. In this case, the shielding gas is the carbon dioxide formed in the combustion reaction. It is a relatively slow process that is mainly used for brazing and soldering [1].

Shielded Metal Arc Welding

Shielded Metal Arc Welding is also referred to as stick welding, from the welding rods used in the process. This approach uses a high current electric arc to provide heat. The electricity flows through the welding rod (the electrode), the metals being joined, and out through a ground. The welding rod is coated in a special coating that provides a shielding gas when the rod is melted by the current. However, this coating then hardens on top of the weld as "slag" and must be chipped off. This type of welding is very widely used because it is a fast process that does not require almost any equipment beyond a power supply. It is useful for both ferrous and nonferrous metals [1].

Gas Metal Arc Welding

Gas Metal Arc Welding is also referred to as Mig, metallic inert gas welding. Like stick welding, an electrical current is used to provide heat to the weld joint. However, this differs from stick in some very important ways. First of all, the electrode is consumed, but is continuously fed through the torch at a controlled speed so welding can be continuous. Also, shielding gas is used instead of an electrode coating so there is no slag that needs to be chipped off. These mean that Mig isn't as portable as stick because it requires more equipment but it can produce welds much more easily and much faster. This means that it is very widely used in production. It is very flexible and can be used with a large variety of metals such as aluminum, steels, nickel, copper, magnesium, titanium, and zirconium [1].

Gas Tungsten Arc Welding

Gas Tungsten Arc Welding is also referred to as Tig, tungsten insert gas welding. In this type of welding, the electrode is made out of tungsten and is not consumed, as it is in stick and Mig. This has similarities to oxyacetylene because a rod of filler material is often used to add to the weld pool. It is one of the best methods for making small welds or repairs because it is very precise and controllable. However, this is not a good method for laying down a lot of weld material, the strong point of Mig. It is very flexible and can weld a wide range of metals, especially dissimilar metals [1].

Resistance Welding

Resistance welding is a very interest approach that uses the inherent resistance of the materials and an electrical current to apply heat to the weld. It is mainly used for spot and seam welding. These welds are interesting because the weld is formed between materials instead of on the surface. Also, this process only requires a closed circuit so no special equipment is needed, except such to regulate the current and duration. This means that machines can be set up that spot weld very quickly and accurately. While this approach requires closer design than other types to ensure that the correct amount of current is applied for the correct time, it is very easy to automate and a good way to accomplish small welds [1].

B. Welding Design Process

In the design process, the goal is to produce a product that satisfies all requirements at the lowest cost. Welding is a vital approach in design because it is arguably the best joining process. The main processes for joining materials are fastening, welding, and casting. Fastening is a good approach for a joint that needs to be removable, but this approach is inferior for permanent joints. Casting is a good approach because the piece can be created all at once with no excess cost or equipment. However, welding is still less expensive than casting and it is a more flexible. Welding is 3 to 4 times stronger than other processes so much less total material is required. It is also stiffer, has greater ductility, and is less likely to crack than castings. Lastly, welding resists impact loads better than castings [1].

When welding is the selected design process the first step is to choose the type of joint used. To chose, the orientation, function, and loading must be determined. The section titled "Types of Joints" is a good reference to help determine what type of joint should be used. Once the type of joint is selected, the size, number, and locations of the welds must be determined. The information above and the section titled "Selecting Joint Design" are good references to help determine this.

Economics is another important design consideration. Once the basic design is made, changes should be made to optimize the design for lowest cost. The design should be just above the requirements for strength and rigidity, including the factor of safety. The factor of safety should be large enough for contingencies, but not excessively large. To obtain rigidity, stiffeners are much more cost effective than increasing size of materials. Lastly, as in all other areas of machine design, using standardized components always is a good choice [1].

C. Selecting Joint Design

Square joints are the most economical type, but this is only a good choice for thin materials. Thicker materials will not have full penetration and therefore require beveling. Beveling should be done carefully with openings and angles that reduce the amount of filler material needed. It is highly preferable to weld a joint on both sides; however, if only one side of a joint is accessible, a single sided joint should be used [1].

The thickness of a weld is also very important. Weld material should always be at least as strong as the base materials, so the effective thickness of a weld should be about equal to thickness of the material. For a butt weld this is simple to insure with complete penetration but a fillet weld requires some mathematics. The effective thickness is equal to the shortest distance from the base of a weld to the surface assuming that the cross-section is an isosceles right triangle. This effective length is equal to the leg length divided by the $\sqrt{2}$. For a single sided fillet weld, the required leg length is 1.5 of the material thickness. For a double sided fillet weld, the required leg length is .75 of the material thickness [1].

D. Specific Weld Considerations

The location of a weld is of great importance and must be carefully selected to enhance strength and reduce possible stress concentrations or excessive material. Welds should be designed perpendicular to stresses as opposed to parallel. Avoid placing welds under bending or shearing forces. When supporting a moment load, welds should be kept far apart to decrease the force. To avoid possible stress concentrations, joints should be kept symmetrical and welds should have smooth faces. The last and most important consideration is to make sure that there is adequate access to the weld, otherwise the joint cannot be welded and therefore must be redesigned [1].

III. Material Properties Effects and Joint Selection

A. Different Defects and Their Effects

With any form of manufacturing, defects will occur. Welding defects are geometrical imperfections in the welded joints. These may be propagated in forms such as: pores, solid inclusions, incomplete fusion, unsatisfactory penetration, undercuts, misaligned edges, and others. Each defect can occur in different ways, as each is individual and difficult to reproduce. They affect the standard with which the quality is determined for each weld, but they cannot be quantified easily to the standards because of their individuality [3].

- **Cracks**

  Cracks are separations along the planes in the materials with a sharp crack tip. They occur in parallel or transverse directions to the weld, but can occur in any direction from a central starting point (usually a star-shaped crater). The end crater, where the crack has begun or ended due to loss of material, tends to be the worst risk, due to large pockets of micro cracks and associated stresses and strains from the deformity. Cracks are formed by several factors, most due to change in temperatures. Hot cracks are created in extreme hot temperatures where solid and liquid phases occur together. Cold cracks, due to age, weathering, hardening, and other reasons, occur at lower temperatures when the ductility of the material has failed. Cracks reduce fatigue strength, especially in transverse loading. They can be avoided by taking proper manufacturing measures [3].

- **Pores and Shrinking Cavities**

  Pores are cavities, usually with gas residues, which have been trapped due to rapid solidification. Size determines the specific classification; single pores, linear pores, and wormhole pores. Shrinking cavities occur during solidification. Pores occur because of too much sulfur impurity in the base and filler material, too high of moisture content in the electrode coating, or nitrogen entering through shielding gas. They also occur when welding through primer paint, even more when in a fillet weld. These pores cause a sharp decrease in fatigue strength of transverse welds; longitudinal welds are affected slightly [3].

- **Solid Inclusions**

  Solid inclusions are foreign material embedded in the weld; steels usually contain slag or impurities left over from the conversion process. In lighter alloys, it may be a foreign material that may appear singly, in lines, or clusters. Slag inclusion can be produced when slag from a previous weld was not removed. Slag must be thoroughly removed by grinding or milling. Inclusions can also occur at a groove face if the electrode is passed over in a certain way. They reduce fatigue strength; however in multilayer welds they have positive effects, but negative effects when combined with heat treatment [3].

- **Lack Of Fusion Defects and Inadequate Penetration**

Fusion defects occur when there are interfaces that have not fused between filler and base metal or between different layers of the filler material. The most frequent cause is due to foreign matter on the surface to be welded, slag or mill scale for steel and oxide film for light alloys. In steels, this can also be caused by an incorrect electrical current. In light alloys, this can be caused by a large molten pool. They reduce fatigue strength similarly to cracks.

Inadequate penetration is the term for a weld pool that does not reach the weld root, where the base of the weld begins, resulting in a root gap. Poor fit or use of a poor welding method can cause lack of penetration. Fatigue strength may decrease steeply depending on the size and area of defects; there is also a noticeable influence from residual stresses. Inadequate penetration defects also behave similarly to cracks [3].

- **Undercuts, Misalignment and Other Shape Imperfections**

These defects are all types of shape imperfections that occur in the weld itself. They can cause loss of strength, added stress, or even added effects. Undercuts are groove depressions at the weld toe, root, or between beads caused by incorrect welding. They reduce the cross sectional area and increase the notch effect. This reduction is about double the magnitude of the ratio of the notch depth to plate thickness. Axial and angular misalignments come as a result of inaccuracy in assembly and from welding distortion. The effect on fatigue strength can be seen from the deviation in shape of the stress distribution. This effect causes superimposed bending stresses and additional notch stresses which reduce strength considerably [3].

B. Types of Joints

There are many different types of joints. Each of the different types of joints has its own pros and cons and is limited by thickness and other factors. Below, each of the different types of joints is described in detail [1].

Butt Joints (end to end)

- **Square Butt Joint**

  The square butt joint is good for material that is 3/8" or thinner and in static tension. This type of joint is very simple prepare and is very economical. However, this method is not good for bending stresses, fatigue or impacts.

- **Single Vee Butt Joint**

  The single vee butt joint is good for material that is greater than or equal to 3/8" and is in static tension. This method is also bad for bending, fatigue and impact loads. The difference between this and the square butt joint is that it requires more extensive preparation and is consequently more expensive.

- **Double Vee Butt Joint**

The double vee butt joint is the best joint to use for all loading conditions and can be used for thick plates. The preparation is much more difficult than the single vee, but it uses less filler material. A consideration is that the weld must be accessible from both sides.

- **Single U Butt Joint**

This joint is used for ordinary loading conditions and can be used for material that is 1/2 to 3/4" thick. This method is used when high quality is required.

- **Double U Butt Joint**

This method is used for ordinary loading conditions and is used for material 3/4" or thicker. As with the Double Vee Butt Joint method the welder must be able to weld on both sides of the material.

Tee Joints (90° into middle of plate)

- **Square Tee Joint**

In a square tee joint, a fillet weld is used for a wide variety of material thicknesses. However, in this type of joint the longitudinal shear stress is not uniformly distributed. This method is also poor for impact or transverse loads and requires large amounts of filler metal if high strength is desired.

- **Single Bevel Tee Joint**

This method is restricted to 1/2" thickness or less, but has a more uniform stress distribution than the square tee joint. This means that it can handle higher loads. This method only requires welding from a single side however, and requires more preparation than a square joint.

- **Double Bevel Tee Joint**

The double bevel tee joint method is good for high loads and has a good longitudinal and transverse shear stress distribution. The only restriction is that the welder must be able to weld on both sides of the material. Like other double beveled joints, this requires a lot of preparation.

- **Single J Tee Joint**

This method is good for 1.5" or thicker plate and provides a high quality joint. However, for more severe loads the material must be welded on both sides.

- **Double J Tee Joint**

This method can handle more severe loads than the single J joint but must be welded on both sides. This also produces a high quality joint.

Lap Joints (one on top of other)

- **Single Fillet Lap Joint**

  This is a simple fillet weld that connects one material on the top of another material.

- **Double Fillet Lap Joint**

  This method is widely used in welding because it is simple and can withstand reasonable severe loads. Note that this is a double joint which means that access is required on both sides.

Corner Joints (90° edge)

- **Flush Corner Joint**

  This method works well for sheets of 12 gauge or thinner. However, weld penetration is difficult and only moderate loads can be supported.

- **Half Open Corner Joint**

  The Half Open Corner Joint method is a better selection for sheets that are thicker than 12 gauge and also provides better penetration of the weld.

- **Full Open Corner Joint**

  The last Full Open Corner Joint is the strongest and can support heavy loads. It has a good stress distribution that makes it choice for fatigue and impact loads. This type of joint can join materials of all thicknesses, but requires large amounts of weld material for thicker plates. It should be noted that it requires welding on both sides of the material.

- **Edge Joint**

  This last type of joint weld works well for 1/4" or less materials. It can only support light loads and should very rarely be used.

IV. Mathmatical Comparison

1020 Steel cold drawn

$F := 1000$

$S_y := 390 \cdot 10^6$

$t := 0.009525$

$S_{ut} := 470 \cdot 10^6$

$h := 0.01905$

$l := 5$

The first set of calculations that will be performed will calculate the shear stress of a Butt Weld in tension using the given Force, Thickness, Height, and other factors.

Butt Weld Tension:

$\tau_{all} := 0.40 \cdot S_y$ $\qquad$ $\tau := \dfrac{F}{2 \cdot h \cdot l}$

$\tau = 5.249 \times 10^{3}$

$\tau_{all} = 1.56 \times 10^{8}$

since t.all > t. the attachment is satisfactory near the weld beads

The Tensile Strength

$\sigma := \dfrac{F}{h \cdot l}$ $\qquad$ $\sigma = 1.05 \times 10^{4}$

Since the allowable tensile stress is greater than the tensile stress the shank tensile stress is satisfactory.

$\sigma_{all} := 0.6 \cdot S_y$ $\qquad$ $\sigma_{all} = 2.34 \times 10^{8}$

The calculations show that the shear stress does not exceed the allowable shear stress therefore this force will not cause the weld to fail. The same can be said for the Tensile Strength. The next calculation will be a involve a force applied at an angle.

Butt Weld in Tension at 45 degrees $\qquad$ $\theta := \dfrac{\pi}{4}$ Radians

$\tau_{all} := 0.40 \cdot S_y$ $\qquad$ $\tau := \dfrac{F \cdot \sin(\theta) \cdot (\cos(\theta) + \sin(\theta))}{h \cdot l}$

since t.all > t. the attachment is satisfactory near the weld beads

$\tau_{all} = 1.56 \times 10^{8}$ $\qquad$ $\tau = 1.05 \times 10^{4}$

The Tensile Strength

$\sigma := \dfrac{F}{h \cdot l} \cdot \left(\cos(\theta)^2 + \sin(\theta) \cdot \cos(\theta)\right)$

Since the allowable tensile stress is greater than the tensile stress the shank tensile stress is satisfactory.

$\sigma_{all} := 0.6 \cdot S_y$ $\qquad$ $\sigma_{all} = 2.34 \times 10^{8}$ $\qquad$ $\sigma = 1.05 \times 10^{4}$

The end result appears to come out the same as the one without an angle placed on it. Therefore, the weld is still safe in the given zone even if an angle was imposed on it.

The following calculation displays what would happen if an angle of 30 degrees was placed on the same system.

Butt Weld in Tension at 30 degrees $\theta := \frac{\pi}{6}$ Radians

$\tau_{all} := 0.40\, S_y$ $\tau := \frac{F \cdot \sin(\theta) \cdot (\cos(\theta) + \sin(\theta))}{h \cdot l}$

$\tau_{all} = 1.56 \times 10^{8}$ $\tau = 7.171 \times 10^{3}$

since t.all > t. the attachment is satisfactory near the weld beads

The Tensile Strength

$\sigma := \frac{F}{h \cdot l} \cdot \left(\cos(\theta)^2 + \sin(\theta) \cdot \cos(\theta)\right)$

Since the allowable tensile stress is greater than the tensile stress the shank tensile stress is satisfactory.

$\sigma_{all} := 0.6 \cdot S_y$ $\sigma_{all} = 2.34 \times 10^{8}$ $\sigma = 1.242 \times 10^{4}$

As can be seen there is still no problem with this angle. It appears to be safe and able to withstand the given load, even though the stress increased compared to the calculation with the 45 degree angle.

When the calculation is done when considering an angle of 60 degrees the stress yet again decreases and the system is still well within the safe range when considering this force.

Butt Weld in Tension at 60 degrees $\theta := \frac{\pi}{3}$

$\tau_{all} := 0.40\, S_y$ $\tau := \frac{F \cdot \sin(\theta) \cdot (\cos(\theta) + \sin(\theta))}{h \cdot l}$

$\tau_{all} = 1.56 \times 10^{8}$ $\tau = 1.242 \times 10^{4}$

since t.all > t. the attachment is satisfactory near the weld beads

The Tensile Strength

$\sigma := \frac{F}{h \cdot l} \cdot \left(\cos(\theta)^2 + \sin(\theta) \cdot \cos(\theta)\right)$

Since the allowable tensile stress is greater than the tensile stress the shank tensile stress is satisfactory.

$\sigma_{all} := 0.6 \cdot S_y$ $\sigma_{all} = 2.34 \times 10^{8}$ $\sigma = 7.171 \times 10^{3}$

The final calculation with this force is when a Fillet weld is considered. The results are quite similar to all the Butt Weld calculations. The shear stress as well as the tensile strength is well below their respective allowable counterparts.

Fillet Weld in Shear

$\tau_{all} := 0.40 \cdot S_y$ $\qquad \tau := \frac{F}{2 \cdot h \cdot l}$

$\tau_{all} = 1.56 \times 10^{8}$ $\qquad \tau = 5.249 \times 10^{3}$

since t.all > t. the attachment is satisfactory near the weld beads

The Tensile Strength

$\sigma := \frac{F}{h \cdot l}$ $\qquad \sigma = 1.05 \times 10^{4}$

$\sigma_{all} := 0.3 \cdot S_{ut}$ $\qquad \sigma_{all} = 1.41 \times 10^{8}$

Since the allowable tensile stress is greater than the tensile stress the shank tensile stress is satisfactory.

To Fail:

$\tau_{all} := \tau$

so.....

$.40 \cdot S_y := \frac{F}{2 \cdot h \cdot l}$

This means a Force of:

$F_{fail} := .4 \cdot S_y \cdot (2 \cdot h \cdot l)$

$F_{fail} = 2.972 \times 10^{7}$

These calculations are for a Butt Weld in Tension. This means that in order for the weld to no longer be safe a force of (2.918*10^7) is required.

VI. *Conclusion*

Welding is a very useful technique that can be used for many different processes. Because of its broad use, a great deal of research should occur if it is going to be used properly, effectively, and safely. In order to properly design a weld, many important considerations must be covered. Some of these considerations are the size of a load that will be applied, what type of material would be best for the situation, the type of joint that would be best for this application, and the shape of the weld. A final consideration to remember is that all welds are unique and must be examined carefully on location to ensure that weld defects do not make a design unsafe.

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