NPRE 432: Lab 7

Welding and Allied Processes

University of Illinois at Urbana-Champaign

Department of Nuclear, Plasma, and Radiological Engineering

Lab Section 2

Author

Joseph Specht

jspecht3

Professor and Teaching Assistants

James Stubbins

Silvana Tabares-Burgos

Tahmid Omi

November 12, 2024

Contents

1 Abstract

Metals are a ubiquitous part of modern society. As such, different methods of joining metals-to-metals have been established. The most popular method for joining metals is welding. However, different metals have different welding characteristics. Along with material, weld geometry and power influences the final weld. Therefore, in this laboratory, tensile tests were performed to determine the effect of material and weld parameters on the final weld strength. The tested materials were 1018 steel and 6061-T6 aluminum. For each material, three weld configurations were tested: chamfer, butt, and low-power butt. From the tensile testing, the strongest weld configuration for both materials was the chamfer weld due to the increased contact area between the weld and base metal. Additionally, the butt weld was carried out at the specified operating power and an operating power lower than specified. From these power variation, the low-power weld was weaker due to insufficient melting between the base metal and the weld. Next, the chamfer welded specimen were compared to homogeneous specimen of the same material. From this comparison, the welded specimen for both materials were weaker than the homogeneous specimen. However, the welded 6061-T6 aluminum was substantially weaker than the homogeneous 6061-T6 aluminum. From this difference, the 6061-TS was determined to be far less weldable than the 1018 steel. Finally, the microstructure and hardness were investigated for welded samples, which both corroborated the fact that 6061-T6 aluminum is less weldable than 1018 steel.

2 Introduction

When working with materials, it is often prohibitively expensive to generate large-scale specimen in a single, continuous piece. When constructing large-scale projects are often made piecewise and joined together on-site. Each class of material has a method for joining separate pieces. To join wooden materials, carpenters use wood-screws and or wood glue. For bricks, masons lay mortar between each brick. For plastics, either epoxy or another adhesive is used to join separate materials. For metals, welders join metals together by welding them. Welding is the process of using a metal as an adhesive to join metals together.

As expected of the extremely diverse group of materials called metals, many characteristics need to be taken into account. Each metal has a different affinity to being welded, which is known as weldability. Highly weldable metals form stronger bonds between the weld and the base material – weldable metals are more favorable as they preform better under the forces seen during operation. To characterize weldability, this laboratory determined the effect of material, weld geometry, and weld power on weld strength via tensile testing. The welded materials were then compared to homogeneous materials to determine the effect of welding on relative material strength.

3 Theoretical Models

To understand welding, a theoretical foundation needs to be developed. This section covers the theory required to understand the process of welding.

3.1 Welding Overview

A metal is highly weldable if it can be easily joined to a another metal through welding. When welding, one or more different metals are joined together by melting the base metals and joining said base metals with a filler metal. Filler metals can be either different from the base material or the same as the base material.

To join the metals together, the welder supplies heat to the weld, cleans and prepares the joint faces, and prevents contamination during the weld. Supplying heat to the weld can be done in five major ways: (1) mechanical where the heat is generated as friction between the metals being rubbed together, (2) thermo-chemical where an exothermic chemical reaction is used heat the materials, (3) electrical resistance where the heat is generated from the metal dissipating flowing electrical energy by heating up, (4) electrical arc where high voltages and high currents supply heat between an electrode and the workpiece, and (5) radiation where the heat comes from focused beams of radiation. With the heat supplied, the welder then prepares the weld surface by sanding or applying flux until the desired sheen. During welding, the weld target is shielded from the air by flowing an inert gas over the weld site.

Several welding processes exist that are of interest to engineers: (1) arc welding, (2) gas welding, (3) resistance welding, and (4) laser welding. Arc welding is a type of electrical arc welding where an arc is created between the electrode and workpiece melting a region of the workpiece and forming the weld.

Arc welds can use AC or DC. Alternating current is more convenient as the power supplied from the utilities is alternating. Direct current is requires power modulation, but gives good penetration and a more controlled, narrower weld.

Gas welding uses a gas fuel, usually mixed with pure oxygen to increase the flame temperature. For gas welding, the most important gas characteristics are: flame temperature, flame propagation rate, and the energy released during combustion. The flame temperature determines which metals can be melted with the flame temperature needing to be higher than the metal melting temperature. The flame propagation rate is most important for the gas stability with slower propagation rates being more stable. Finally, the energy released per combustion determines the efficiency of the welding with more energy per reaction leading to a higher efficiency.

Resistance welding uses the friction forces between two metals to fuse the two together. Spot welds are the most common type of resistance weld with the specimen being under pressure as well.

Laser beam welding uses light amplified by the stimulated emission of radiation focused on the desired location. The light supplies enough energy to melt the surface in a very focused area. The focusing of the laser means the heat affected zone will be much smaller than other weld types.

3.2 Welding Metallurgy

During welding, the rapid temperature changes the microstructure radically. There are three main zones formed during welding are: the fusion zone, the heat-affected zone, the base metal. The fusion zone is the region where the maximum temperature exceeds the solidus temperature resulting in localized annealing and a softer material than the base metal. Next, the heat-affected zone is next to the fusion zone and extends until the microstructure of the bulk material is no longer affected by the weld. The heat-affected zone is generally the weakest region as it has been heated enough to cause recrystallization and grain growth. Finally, the base metal is the region where no microstructure changes were caused by the welding.

3.3 Residual Stress and Distortion

As the weld site is heated to extreme temperatures, the localized heating and cooling causes uneven expansion and distortion. One distortion is a longitudinal distortion where the material changes longitudinal dimension after welding. Similarly, a transverse distortion is where the material changes transverse dimension after the welding. Finally, angular distortion are when the outer edges lift off the material plane.

As the weld pool solidifies, heat leaves the weld and enters the base metal. The base metal then elongates and contracts over time, which leave residual stress in the material. For equilibrium, the tensile and compressive stresses are equal and opposite. If the internal stresses are high enough, plastic deformation will occur in the base material. Deformation is undesirable as increased residual stress reduces the fatigue life of the welded component. There are several methods to reduce deformation: preheating the base material, annealing or tempering after welding, shot-peening the weld and cause a compressive residual surface stress, and physically restraining the weld during cooling, which increases the residual stress.

4 Experimental Methods

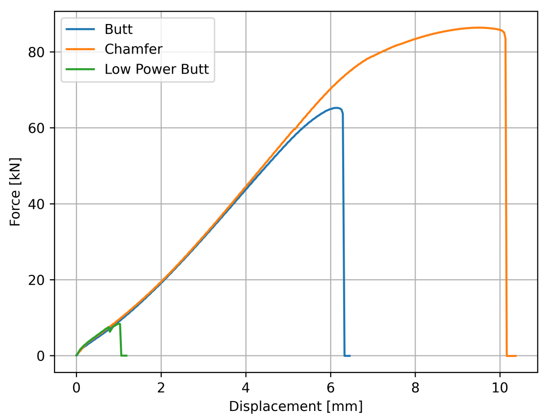
For this laboratory, tensile tests were preformed on two materials with three different welds each. The materials were 1018 steel and 6061-T6 aluminum with the weld types being chamfered, butt, and low-powered butt welds. These methods are form the lab manual [1].

The experimental procedure is as follows:

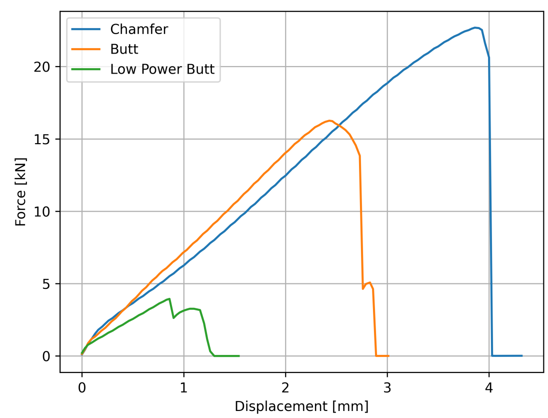
1. Measure the base material and weld dimensions and record these values.
2. Make a line with a Sharpie marker 45 mm from each end of the specimen and mount the specimen in the test frame with the Sharpie lines aligned with the grip jaw end.
3. Perform the tensile tests on the two different materials for each weld type.
4. After the tensile test, examine the fracture surface, measure any flaws, and note where the sample failed.
5. After the tensile tests, observe the micro-hardness tests associated with each weld and observe each material zone.
6. Finally, watch the videotape presentation of the welding process.

5 Results

After performing the procedure covered in the *Experimental Results* section, the data were processed and are given in this section. First, the load-displacements curves for each material and each weld type, which are given below.



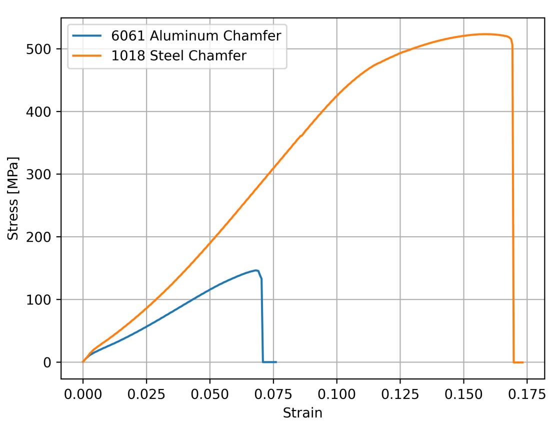
(a) 1018 Steel



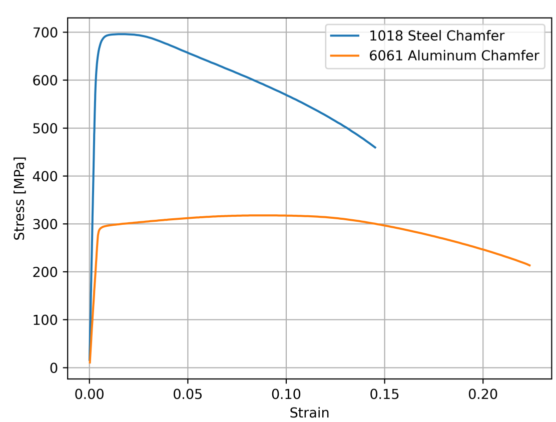
(b) 6061-T6 Aluminum

Figure 1: Load-Displacement Curves for each Material and Weld Type.

From Fig. 1, the chamfer welds were the strongest for both materials. These chamfer welds were then used to plot the stress-strain curves for these strongest welds. Alongside the strongest welds, the regular, non-welded materials were also plotted from regular tensile tests. Both plots are given below.



(a) Butt Welded Specimen



(b) Non-Welded Specimen

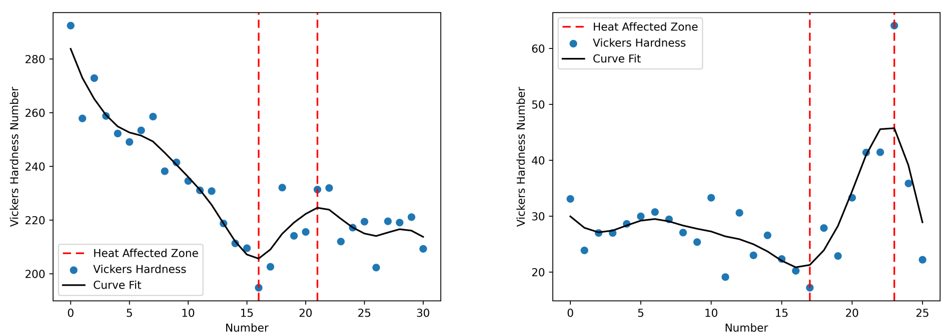
Figure 2: Stress-Strain Curves for each Material.

The mechanical performance of the specimen differ radically based on the weld treatment, which is evident from Fig. 2. These mechanical performance metrics are also tabulated below for ease of comparison.

Table 1: Specimen Measurements Based on Temperature.

Material		**Yield Str. [MPa]**	**UTS [MPA]**
1018 Steel	Chamfer Weld	512.823	523.180
	Homogeneous	602.143	695.849
6061-T6 Al	Chamfer Weld	142.432	146.300
	Homogeneous	280.260	317.578

Finally, the Vicker's Hardness for each metal were calculated and plotted along with the heat affected zone, which is given below.



(a) 1018 Cold-Rolled Steel

(b) 6061-T6 Aluminum

Figure 3: Vicker's Hardness Values for Each Metal.

6 Analysis and Discussion of Results

The results for this laboratory agreed very closely with what theory suggested. However, there were two noticeable errors. First, there were minor discrepancies between the extant files and the file naming convention. Second, to verify the theory that the bulk material has a constant hardness, the hardness of locations farther from the weld site should be measured.

7 Answers to Questions

With the results, this section details the pertinent information and gives a discussion of the results.

First, the students performed the tensile test for each material and for each weld type. From these results (Fig. 1), the weld geometry and weld power both have profound impacts on the strength and ductility.

Regarding the weld geometry, the strongest weld for both materials was the chamfer weld, which makes sense as the chamfer weld has the most surface area available for welding to occur. The chamfer is cut out of the material at a 45 °angle, which generates $\sqrt{2}$ times the surface area for welding compared to a butt weld. Regarding the weld power, the regular powered butt weld had a substantially higher strength than the low power butt weld. The higher power butt weld being stronger is expected as a higher heat flux will cause more melting, which results in stronger adhesion.

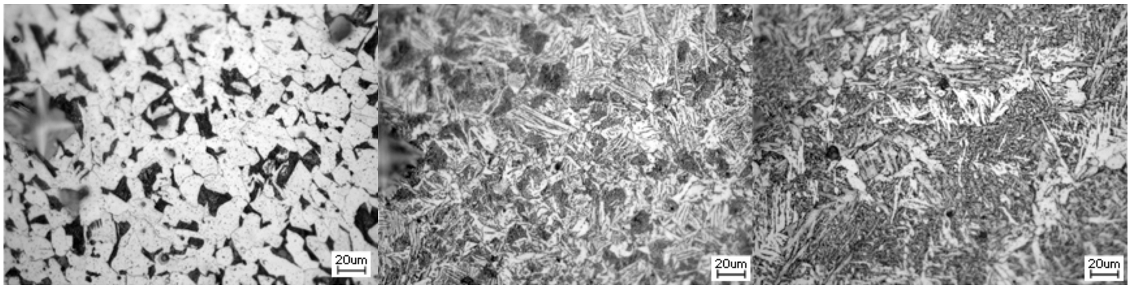
Like material strength, material ductility was highly affected by the manipulated variables. For both materials, the most ductile weld was the chamfer weld, which makes sense. As the point of failure for welds is most commonly the weld site, if the weld sites are larger with the base metal and weld being more interstitial, the ductility of the specimen will be higher. Similarly, the lower power butt weld performed the worst due to a small weld site and lower interstitiality of the weld and base metal.

Next, the strongest welds, the chamfer welds, were plotted for each material against a homogeneous specimen to demonstrate the deleterious effect of welding on material strength. Figure 2 shows the welded specimen for both materials having a lower strength and ductility. To quantify these results, the 0.2% offset yield strength (YS) and the ultimate tensile strength (UTS) were calculated and tabulated in Table 1.

For 1018 steel, the chamfer weld specimen had a YS of 512.823 MPa, which is roughly 100 MPa lower than the homogeneous specimen of 602.143 MPa. The UTS differed even more than the YS with the chamfer weld specimen having a UTS of 523.180 MPa being nearly 180 MPa lower than the homogeneous specimen of 695.849 MPa. From these results, even the strongest weld will decrease two of the most desirable material characteristics: strength and ductility.

For 6061-T6 aluminum, the chamfer weld specimen had a YS of 142.432 MPa, which was nearly half the YS of the homogeneous specimen of 280.260 MPa. Similarly, the UTS for the chamfer weld specimen was less than half the value of the homogeneous specimen at 146.300 MPa compared to 317.578 MPa. As the ratio of weld specimen strength to homogeneous specimen strength was lower, the 6061-T6 aluminum has a lower weldability than the 1018 steel.

After analyzing the tensile tests, a specimen of each metal were investigated under the microscope to determine the microstructure and heating zone at various locations. These microstructures are given for the 1018 steel as:

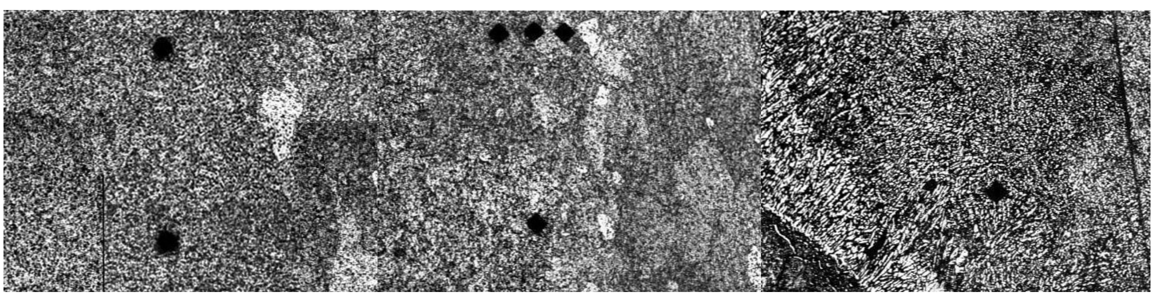


(a) Location 0, Fusion Zone (b) Location 20, Heat-Affected Zone (c) Location 30, Base Metal

Figure 4: Microstructure for 1018 Steel in Various Welding Zones.

For 1018 steel, the microstructures in Fig. 4 show the fusion, heat-affected, and base metal zones. The fusion zone is characterized by large, roughly-equiaxed grains characteristic of high temperature annealing. These grains are also distinctly made of a single material, either iron or carbon, which indicates a high temperature from the increased diffusion rate. Next, the heat-affected zone is characterized by grains that are less distinguishable and are composed of both iron and carbon. However, these grains are also roughly equiaxed, which are characteristic of recrystallization and grain growth. Finally, the base metal has dendrites and elongated grains. These grains are characteristic of materials with no extant affect from high heat.

Next, the microstructures for 6061-T6 aluminum are given as:



(a) Location 13, Fusion Zone (b) Location 20, Heat-Affected Zone (c) Location 23, Base Metal

Figure 5: Microstructure for 6061-T6 Aluminum in Various Welding Zones.

For 6061-T6 aluminum, the grains are far less distinguishable than the 1018 steel. However, each zone can still be characterized. The fusion zone and heat-affected zone have similar microstructures. However, the fusion zone has smaller grains than the heat-affected zone. The base material differs radically from the fusion and heat-affected zones with large dendrites throughout the material. Once again, dendrites indicate no effect from heat treatment. As the fusion and heat-affected zones are so similar, the welding can be said to have less of an effect on 6061-T6 aluminum compared to the 1018 steel. As the microstructure is less responsive to welding, the 6061-T6 is less weldable than the 1018 steel.

Finally, a hardness test was performed at various locations for each metal to determine how welding affected the hardness of each specimen. From the microstructure pictures discussed previously, indentations were made and the Vicker's hardness was found with:

$$VHN = \frac{1.85M}{d^2}, \tag{1}$$

where M is the specimen mass in grams and d is the average of the x and y diameters of the indentation in millimeters. The VHN at various locations inside the specimen were plotted in Fig. 3 with the heat affected zones being labeled as well.

For the 1018 cold-rolled steel, the hardness was the highest in the fusion zone and continually decreased until the heat-affected zone. In the heat affected zone, the hardness increased until the base metal. In the base metal, the hardness was roughly constant. From these results, we see the hardness increases with proximity to the weld site in the fusion zone. Conversely, in the heat affected zone, the hardness increases with proximity to the base metal. Finally, the hardness in the base metal should be constant throughout.

For the 6061-T6 aluminum, the hardness started relatively high and also decreased until the heat-affected zone. In the heat-affected zone, the hardness radically increases until the base metal. There is little data for the base metal, however, it would be expected the hardness remained roughly the same. The results from both hardness tests corroborate the 1018 cold-rolled steel being more weldable as the ratio of max hardness in the fusion zone to the max hardness in the heat-affected zone being far higher in 1018 cold-rolled steel.

8 Conclusions

In this laboratory, the effect of material and weld parameters were determined through tensile testing. 1018 steel and 6061-T6 aluminum were tested with three weld types: chamfer, butt, and low-power butt. The chamfer weld was the strongest for each material as this weld had the highest weld-to-base-material contact area at the requisite power to form the weld. Regarding weld power, the butt weld tensile test was carried out at the specified operating power and an operating power lower than specified. From these power variation, the low-power weld was weaker due to insufficient melting between the base metal and the weld. Next, the chamfer welded specimen were compared to homogeneous specimen of the same material. From this comparison, the welded specimen for both materials were weaker than the homogeneous specimen. However, the welded 6061-T6 aluminum was substantially weaker than the homogeneous 6061-T6 aluminum. From this difference, the 6061-TS was determined to be far less weldable than the 1018 steel. Finally, the microstructure and hardness were investigated for welded samples, which both corroborated the fact that 6061-T6 aluminum is less weldable than 1018 steel.

References

[1] *Lab 7: Welding and Allied Processes*. University of Illinois at Urbana-Champaign. 15 pp.