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Constitutive Properties of Weld Metal and Heat-Affected Zone at a Butt Weld

Submitted by

Zuhair Naqvi, B. Sc (Eng.)

University of Engineering and Technology Lahore, Pakistan

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirement for the degree of Master of Applied Science

Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario

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Abstract

Material properties of steel change with welding. Welding reduces the ductility and alters the strength of the material around the weld. An experimental and numerical study to characterize the variation of the material properties across the regions from the heat-affected zone to the weld metal of ASTM A572 grade 50 steel plates was carried out. Three plate thicknesses of 15.9 mm, 19.1 mm and 25.4 mm were investigated in this study. Plates of equal thickness were butt welded together. Tension coupons from regions around the butt weld from the base metal to the weld metal were machined and tested.

There is an increase in the ultimate strength and a reduction in the ductility close to and at the weld. The true stress versus true plastic strain relationship of the material can be reasonably approximated by the proposed function that uses only the measured tension test data directly up until 90% peak load.

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List of Symbols

A	-	Current cross-section area
A_0	-	Undeformed cross-section area
A_m	-	Mean cross-section area
A_{max}	-	Maximum cross-section area
A_{min}	-	Minimum cross-section area
A_{mf}	-	Mean cross-section area at fracture
C	-	Parameter used in the proposed function (5.8)
d	-	Current diameter of the coupon
d_0	-	Undeformed diameter of the coupon
E	-	The modulus of elasticity
H	-	Linear hardness coefficient in (2.3)
H_r	-	Vickers hardness
L	-	The current gauge length
L_0	-	The original gauge length
n	-	Parameter used in the proposed function (5.8)
T_{max}	-	The maximum thickness of the coupon
T_{min}	-	The minimum thickness of the coupon
W_{max}	-	The maximum width of the coupon

$W_{\min}$	-	The minimum width of the coupon
δ	-	Saturation exponent in (2.3)
ε^e	-	The engineering strain
ε^p	-	The true plastic strain
$\bar{\varepsilon}^p$	-	The equivalent plastic strain in (2.3)
ε^t	-	The true strain
ε_0^p	-	The true plastic strain at the start of the strain hardening or the end of yield plateau
ε_f^p	-	The true plastic strain at the peak load
σ	-	The stress
σ_0	-	The elastic limit stress in (2.3)
σ_0^t	-	The true stress at the start of the strain hardening or the end of yield plateau
σ^e	-	The engineering stress
σ_f^t	-	The true stress at the peak load
σ_r	-	The ultimate to yield strength ratio
σ_{ult}	-	The ultimate strength
σ_y	-	The yield stress
σ_{∞}	-	The saturation flow stress in (2.3)

Chapter 1 Introduction

Welding is extensively used in steel structure construction. Due to the non-homogenous nature of welding, it is essential that the material behavior of the weld and regions around it be understood. Better characterization of material properties for each region will lead to a better understanding and assessment of a welded connection.

At a welded connection, the material properties, such as ultimate strength, ductility and true stress versus true strain relationship, vary from one region to another around the weld. One of the main reasons for these variations is the effect of intense heat as a result of welding and the non-uniform cooling rate across the weld.

Material properties are determined by testing and numerical modeling of tension specimens. Due to the variation in material properties from one region to another around the weld, small specimens (tension coupons) should be fabricated in such a way that it can represent each region accurately. The coupon should be able to capture the material behavior of not only the weld metal and base metal, but also the heat-affected zone (HAZ) between the weld metal and base metal.

The post peak load true stress versus true strain relationship for steel is normally obtained by trial and error or iterative technique through numerical simulation of a tension test. So far, there is no direct simplified approach in determining the true stress versus true strain relationship of steel beyond the peak load. Furthermore, very few studies have been carried out to study the true stress versus true strain relationship of regions around a weld. Most finite element analyses of welded connections also have not incorporated different material properties for different regions around the weld.

1.1 Objective of the Thesis

The objective of the thesis is to study the variation of material properties at regions across a butt weld. These properties include ultimate strength, ductility, engineering stress versus deformation and true stress versus true strain relationship. In order to assist in characterizing the variation of the true stress versus true strain relationship, a simply function that can be employed to establish the true stress versus true plastic strain relationship using test data directly, is developed and verified. The thesis does not look into the material science aspect of the welding effect, nor does it look at the residual stress developed due to welding.

1.2 Methodology Used in the Research

Small tension coupons, 5.9 mm to 6.0 mm in width and 1.9 mm to 2.3 mm in thickness, were fabricated from 15.9 mm, 19.1 mm and 25.4 mm thick plates and tested in tension. The plates were butt welded, and tension coupons were cut and prepared from the weld metal to the base metal. Manual measurements of cross-section change in area were taken during the test with a digital caliper and a digital micrometer. These measurements were used to develop the engineering stress versus deformation relationship of the coupons.

A simple function was used to obtain the true stress versus true plastic strain relationship of the material based on the test data. Comparisons of the results from the test and the finite element analysis using the true stress versus true plastic strain from the function were made in order to verify the suitability of the function. After verification, the function is then being used in characterizing the true stress versus true plastic strain

relationship of regions around the weld. The finite element modeling and analysis was performed using the commercial finite element software ABAQUS (2002).

1.3 Organization of the Thesis

Chapter 2 consists of a literature review on the basics of welding, studies on weld and regions around the weld, and material modeling. This chapter also highlights a few research studies conducted so far on the variation in material properties for various weld regions.

In Chapter 3, the experimental program on testing tension coupons is presented. This chapter deals with the various steps involved in the preparation of tension coupons, the testing procedure and data collection.

Chapter 4 explains methods used in calculating ultimate strength, ductility and stress versus deformation relationship and discussions of test results.

Chapter 5 deals with the numerical modeling and analysis of tension coupons. The proposed simple function that is used in determining the true stress versus true plastic strain relationship after the peak load is discussed and verified. Details of the finite element mesh used in the numerical simulations and the variation of true stress versus true plastic strain relationship are also discussed in this chapter.

Chapter 6 comprises the summary of the thesis along with conclusions and recommendations for future work.

Appendices are attached at the end of the thesis.

Chapter 2 Literature Review

Connections are one of the main components of steel structures. Most connections used in steel construction are either welded or bolted. Welding is a non-homogenous process, and it involves intense heat and fusion of metals. Therefore, the determination of actual material properties around the weld has always been a challenge for scientists and researchers.

2.1 Basics of Welding

Welding is an art of joining of metals or plastics by methods that do not employ fastening devices. Welding technology is quite diverse as welding is used in complex electronic circuits to large steel structures and ships

The most common method used in welding of metals can be generalized into four categories.

- i) Gas welding.
- ii) Electric resistance welding.
- iii) Electric arc welding.
- iv) Other special methods.

2.1.1 Welding in Steel Structures

Welding plays a significant role in structural steel construction. It is used mainly in joining members and components of a structural system.

Welding normally requires heating. Most welding processes in structural steel construction use electrical energy as the heat source. The common method employed in steel structures is electric arc welding. Arc welding involves the use of electric current to create an electrical arc to generate the heat and temperature required to fuse the materials. In this process, an arc is created between the piece to be welded and the electrode. The electrode also supplies the material that is needed to fuse the parts.

The subject on welding in steel structures is covered extensively in many steel structures design books. It will only be briefly described here. There are a number of electrical arc welding methods being used, namely:

- Shielded metal arc welding (SMAW)

In this process, heating is accomplished by means of an electric arc between a coated electrode and material being joined. The electrode is a solid wire covered with a coating of flux. During the welding process, the coated electrode is consumed as the metal is transferred from the electrode to the base material. The electrode wire becomes filler material and the coating is converted partly into a shielded gas and partly into slag.

- Submerged arc welding (SAW)

In a submerged arc welding, the arc is not visible because it is covered by a blanket of fusible granular flux. Usually, the granular flux is laid automatically ahead of the advancing electrode. The metal electrode is a bare wire that it is deposited as filler material. The end of the electrode is kept continuously shielded by the molten flux over which is a layer of unfused flux. The flux provides the cover that allows the weld to be made free of smoke and sparks.

- Gas metal arc welding (GMAW)

In this method, the electrode is a continuous bare wire that is fed from a coil through the electrode holder. The shielding is provided entirely by an externally supplied gas or gas mixture. Since the process does not use slag forming flux, the quality of the weld is more sensitive to impurities on the base metal surface.

- Flux cored arc welding (FCAW)

The process is similar to gas metal arc welding, except that the filler metal electrode is tubular and contains the flux material within its core. The material in the core provides the same functions as does the coating in SMAW or the granular flux in SAW.

Besides the method of welding, there are also different types of welding used to join the parts. Some common types of welding are listed below.

- Groove weld

Groove welds are used to connect structural members that are aligned in the same plane. Normally the welds have the same strength as the pieces being joined for a proper transfer of load between the members. The type of weld could either be complete joint penetration groove weld or partial joint penetration groove weld depending on the extension of the weld through the thickness of the pieces being joined. Different types of groove weld are shown in Figure 2.1.

- Fillet weld

Fillet welds are generally used to join two overlapping pieces of metal. They are most widely used because of the ease of welding and economy. This type of welding

requires less accurate alignment of members and end preparation as compared to groove weld. Typical configurations of fillet welds are shown in Figure 2.2.

- Plug and slot welds

The main use of this type of welding is to transmit shear in a lap joint when the size of the connection limits the length available for fillet or other edge welds. Slot and plug welds are useful in preventing overlapping parts from buckling. They can also be used in combination with fillet and groove welds as shown in Figure 2.3.

2.2 Process and metallurgy involved in welding

Whenever two pieces of metals are joined by welding, there are chemical and metallurgical changes involved in the process. In addition, parts of the metal also undergo different rates of heating and cooling. As a result, welding changes the grain size, the crystalline structure and characteristics of the metal. The region around the weld also becomes non-homogeneous and thus, both mechanical and chemical properties are no longer uniform. The area affected by welding can be broadly classified into three major regions. They are:

- i. Weld metal (WM).
- ii. Heat-affected zone (HAZ).
- iii. Base metal (BM).

Weld metal (WM) is the region that actually contains the weld itself. It is the portion of a weld that has melted during welding. Heat-affected zone (HAZ) is the region adjacent to the weld metal, which is subjected to severe heat transfer from the weld metal. It is basically a portion of the metal piece which has not melted, but whose

mechanical properties and microstructure, mainly grain size and crystalline structure, have been altered by the heat of welding and subsequent cooling. For these reasons, this region has different material properties as compared to the original metal. Base metal (BM) is the remaining part of the metal piece that is not affected by welding. This region is the farthest from the weld, and it retains its original mechanical and chemical properties.

2.3 Effects of Welding on Steel Structures

As discussed in the previous section, welding affects the metallurgy of the metal. During a welding process, the temperature of the molten metal reaches 2500 to 3000 °C, and the weld may be considered as a region of cast steel. Since regions near the weld may be comparatively cool, this creates a steep thermal gradient from the weld to the parent metal. As a result, there is a large variation in the rate of heating and cooling at regions around the weld. This results in sharp changes in the grain size, crystal structure and material properties over a short distance.

Other factors that also affect the strength and ductility of the weld region include the formation of blowholes, cracks in steel, and the composition of the filler and electrode used. Oxygen has tendency to form CO (carbon monoxide) with carbon in the steel upon cooling. This leads to the formation of blowholes (small cavities) which affect the integrity of the weld. The composition of the filler metal and electrode used in welding also affects the weld properties. Higher carbon content in the electrode makes the weld harder and more brittle. Cracks can occur as a result of different heating and cooling rates between the weld metal and the base metal. Different cooling rates also change the

stress state of the material and cause significant residual stresses to exist in regions around the weld.

2.4 Mechanical Properties of Weld and Heat-Affected Zone

The true stress versus true strain relationship of the material is required in assessing the performance of a steel structure in a finite element analysis that involves large strains. In a welded connection, failure may take place at the end of the connection where stress concentration occurs as shown in Figure 2.4. The region of stress concentration normally is at the weld and heat-affected zone (HAZ). Thus, it is especially important that true stress and true strain relationships of the weld metal and the heat-affected zone are correctly characterized in the finite element analysis.

Since welding is a non-homogeneous process, the exact properties of the weld are not known with confidence. Furthermore, there is a large variation in the material properties going from the weld metal to the base metal. Thus, analyzing and predicting the response of welded connections has been a challenge for researchers and scientists. However, most studies that have been carried out only look at the variation of yield strength, ultimate strength, hardness and ductility around the weld. There are very few studies that have investigated the variation of the true stress versus true strain relationship of the material. A few studies on the effect of welding on the yield strength, ultimate strength, hardness and ductility are discussed below.

2.4.1 Factors Affecting Mechanical Properties of Weld and Heat-Affected Zone

The heat produced during the welding process causes changes in the mechanical properties of the regions around the weld. These regions show a non-uniform strength variation due to differences in the microstructure from the weld metal to the base metal. Normally, a hardness test is carried out to study the effect of welding. Research has shown that there is a correlation between the hardness value and the tensile strength of steel. A higher hardness value can be associated with a higher strength. Some major factors that may affect the material properties of the weld regions are plate thickness, cooling rate and heat input.

Eroglu et al. (1999) carried out studies to find the hardness and toughness of weld metal and HAZ (heat-affected zone) of SAE 1020 hot rolled steel. Two specimens with different grain size were used in their studies. One specimen had the original grain size and the other was heat treated to obtain a coarser grain size. Both specimens were 150 x 200 mm and 12.5 mm thick. The specimens were heated until 1100°C for 45 minutes and then cooled in a furnace in order to obtain a coarser grain size. Welding was carried out with different heat inputs in order to find the optimal heat input that gives the maximum toughness of the weld metal and HAZ.

The width of the HAZ was found to be the same for both specimens with the same heat input. There was a variation in the hardness with different heat inputs of 0.5, 1.0 and 2.0 kJ/mm. The specimen with 0.5 kJ/mm heat input had the highest hardness in both weld metal and HAZ for both specimens. The hardness was the lowest for in both WM and HAZ with the heat input of 2.0 kJ/mm. The reason being the formation of high carbon martensite and bainite at a low heat input, which would not have been formed at a

higher heat input. Out of the three heat inputs, the maximum HAZ toughness was obtained at heat inputs of 1 and 2 kJ/mm for the both specimens. The maximum toughness in weld metal was observed at heat input of 1 kJ/mm. This is related to the formation of acicular ferrite and pearlite.

Karthick and Radhakrishnan (1987) carried out experimental and analytical study on the size of the heat affected zone and the residual stress distribution of a plate due to welding. Their analyses took into account the variation of material thermal and mechanical properties with temperature. Mild steel plates of 300 mm long, 50 mm wide and 12 mm thick were initially heated to 400°C for 3 hours and annealed to relieve the stress. The plates were then prepared and groove welded at the centre along the length of the plate. The stress profile across the transverse cross-section was measured using X-rays diffraction techniques.

The extent to which the tensile residual stress was present was found to increase with the heat input, but its magnitude decreased. With increasing heat input, the width of the HAZ increased. For the heat input used in the experiment, the zone where the transition from HAZ to the base metal took place was measured to be approximately 0.5 cm from the weld line. It was also observed that grain refinement took place in HAZ, and the grain size was smaller than that in the base metal. At the transition zone, both the smaller grains and bigger grains were observed.

As shown in Figure 2.5 on the findings of Karthick and Radhakrishnan (1987), Vickers hardness test on the specimen showed a steep drop in the hardness value up to around 0.5 cm from the weld line. This distance corresponded approximately to the

extent of HAZ. Beyond the distance of 0.5 cm, the hardness value fell gradually up to around 2.5 cm, after which it was almost constant.

Shehata (1994) carried out studies on the influence of plate thickness on the mechanical properties of steel. Three plate thicknesses of 30 mm, 25 mm and 10 mm with V-groove welded joint were tested. It was observed that hardness decreased from the top surface towards the weld root. The top layer being exposed to air, cools at a faster rate than the bottom layer. As a result, finer grains formed in the top layer and coarser grains formed in the bottom layer. In general, the reduction in the grain size increases the hardness. Hardness also decreased with the plate thickness and as the distance from the weld centerline increases. The thickest plate was found to have the highest ultimate strength and hardness, but the lowest toughness and ductility.

Pimenta and Bastian (2002) investigated the influence of plate thickness on the mechanical properties of welded joints subjected to post weld heat treatment. Grade 70 A516 plates with two thicknesses of 46.4 mm and 65.0 mm were subjected to post weld heat treatments at approximately 620°C for 2.3, 6.3, 14.2 and 21.2 hours. Tensile and Charpy impact tests performed on these plates showed that the thinner plate consistently have a higher ultimate strength, yield strength, ductility, hardness and Charpy absorbed energy than the thicker plate. However the results are not conclusive because both plates have different chemical composition

Akselsen et al. (1989) carried out an investigation on the HAZ tensile properties of high strength steels. In general, the HAZ was found to have a higher tensile strength than the base metal. The tensile strength also increases with the cooling rate.

2.4.2 Test Specimen Size on the Mechanical Properties

The mechanical properties of steel vary with the distance from the weld. Since the region affected by the welding is small, non standard tension tests have been carried out to study the properties variation.

Beghini et al. (2000) carried out test on small scale specimen to characterize the mechanical properties of a seam weld in a large diameter pipe. A pipe was formed by bending an X70 grade (70 ksi yield strength) rolled plate into cylindrical shape and seam welded with a double-V butt weld. Since the width of the heat-affected zone was small, a small scale non-standard tension specimen was used to study the properties around the weld. Small scale specimens were prepared from the base metal, weld metal and the heat-affected zone. Standard specimens were machined only from the base metal. The cross-section of the small scale specimen was 1.5 mm wide x 0.9 mm thick. The longitudinal displacement of the specimen was measured with a LVDT (linear voltage differential transducer). For the base metal, there was a good agreement in the measured yield strength and the ultimate strength between both standard and small scale specimens. The difference in the elongation at rupture for the base metal was smaller among its own group of small scale specimens and standard specimens than between the two groups. The microstructure in the weld metal and HAZ is less uniform compared to the base metal. Since the HAZ is the least uniform, the HAZ specimens showed the greatest difference in yield strength, ultimate strength and the elongation at rupture. Unlike HAZ specimens, the yield strength and the ultimate strength differences were smaller for weld metal specimens.

LaVan and Sharpe (1999) developed a system to perform tension tests on microsamples of steel. The main objective was to test submillimeter size regions that could not be tested by conventional tension testing. Tensile stress versus strain curves were measured, and the yield strength, ultimate strength, and elongation were calculated for each sample. Bow tie shape specimens were machined from various locations of double-V butt weld joint of HY-100 steel plates. The specimen is 3.07 mm long with a 1.73 mm reduced section, and cross-section dimension of 0.2 mm x 0.2 mm. The profile of the reduced section has a radius of curvature of 9.4 mm. The microsample test technique was able to accurately measure the yield strength and ultimate strength of the base metal when compared to results of full-size specimens. Results of microsample test showed that there was considerable variation in the properties with the location. The sample from the center of the weld was found to be the strongest. Some locations also showed significant anisotropy. Results of the tests gave the correlation between the yield strength and ultimate strength with hardness as

$$\sigma_y (\text{MPa}) = 3.15 \text{ Hr} - 168, \text{ and} \quad (2.1)$$

$$\sigma_{\text{ult}} (\text{MPa}) = 2.84 \text{ Hr} + 28 \quad (2.2)$$

where Hr is the Vickers hardness value, σ_y is the yield strength and σ_{ult} is the ultimate strength.

2.4.3 Material Modeling and Finite Element Analysis

Finite element analyses have been used frequently to study the performance of welded joints. One of the most important parameters required in the analysis is the true stress versus true strain relationship of the material. But there are considerable

differences between the true stress versus true strain relationship of the base metal, weld metal and heat-affected zone. Even within the heat-affected zone, the difference can be significant between sub-zones. However, most finite element analyses performed on the welded connections so far have not incorporated these differences. Furthermore, only limited studies have been carried out to characterize the true stress versus true strain relationship for various regions around the weld and incorporate these values in the finite element analysis.

Matic and Jolles (1987) modeled the behavior of a double-V butt welded HY-100 plate with the finite element program ABAQUS. Different true stress versus true strain data were used for the base metal, weld metal and heat-affected zone. The heat-affected zone was further divided into four sub-zones. This is shown in Figure 2.6. There was no explanation as to how the various sizes of the sub-zones were obtained. Even though different material properties were incorporated into the analysis, only true stress versus true strain data of the base metal were calculated directly from a material test. The weld metal properties were reconstructed from the load versus deformation curve of a typical weld metal and the material properties along the heat-affected zone were varied based on some assumed rates of change in ductility and yield strength. However, no justification was given for the rate chosen. The sub-zone closest to the base metal was assumed to have the lowest strength but the highest ductility. All sub-zones also have a higher yield strength and a lower ductility than the base metal. The true stress versus true strain curves of these sub-zones were assumed to be similar in shape to that of the base metal as shown in Figure 2.7. However, no experimental work was carried out to verify the numerical result.

Zuniga and Sheppard (1995) studied the variation of constitutive properties around a resistance spot weld on a 0.91 mm thick SAE 950X sheet. Tension tests were carried out on 1.90 mm wide miniature notched-bar specimens with a notch radius of 0.40 mm. These specimens were machined from various regions around the weld. A special welding technique was used to create samples with uniform microstructure that have the hardness and microstructure similar to that of the actual HAZ. The deformation over the notch region during the test was measured with an extensometer.

In this research, finite element analyses were carried out using the finite element program ABAQUS to simulate the stress versus deformation of the test in order to extract the true stress versus true strain relationship of the material. The true stress versus true strain values used in the analysis was corrected iteratively until the stress versus deformation predicted by the analysis matched that from the test. The first estimate of the true stress versus true plastic strain relationship of the material was obtained through the strain hardening function of

$$\sigma(\bar{\epsilon}^p) = \sigma_{\infty} - (\sigma_{\infty} - \sigma_0) \exp(-\delta \bar{\epsilon}^p) + H \bar{\epsilon}^p \quad (2.3)$$

where $\sigma(\bar{\epsilon}^p)$ is the flow stress, $\bar{\epsilon}^p$ is the equivalent plastic strain, σ_0 is the elastic limit stress, σ_{∞} is the saturation flow stress or asymptotic stress attained after severe deformation, δ is the saturation exponent, and H is the linear hardening coefficient. A procedure was developed to correct the true stress versus true plastic strain relationship of the material using results from the previous numerical simulation. A reasonable match of the stress versus deformation curve was achieved after only one to two cycles of corrections.

Gray et al. (2000) carried out finite element analyses to study the structural integrity of a fillet weld attachment. The model considered the variation of the yield strength across the weld, but not the true stress versus true plastic strain relationship. However finite element analyses from their study did not agree with the test results.

Figure 2.1 Types of groove weld

Figure 2.2 Types of fillet weld

Figure 2.3 Slot and plug weld

Figure 2.4 Tension connection

Figure 2.5 Variation of hardness with distance from the weld edge (modified from Karthick and Radhakrishnan, 1987)

Figure 2.6 Material zones for butt welded plates with weld crown (modified from Matic and Jolles, 1987)

Figure 2.7 Uniaxial true stress versus true plastic strain curves (modified from Matic and Jolles 1987)

Chapter 3 Experimental Program

An experimental program was developed to determine the characteristic properties around a butt weld. Non-standard small tension specimens of the weld and regions around the weld were machined and tested. The testing was conducted in the Civil and Environmental Laboratory at Carleton University. Details of the specimen and testing program are described below.

3.1 Objective

A test program with a series of small tension coupons was conducted to determine the characteristic properties of each region around the weld. Tension specimens from the weld metal, heat-affected zone and base metal were tested to study the material properties variation around the weld. The main objective of the test program is to obtain data for characterizing the true stress versus true strain relationship of the material around the weld. In addition the variation obtained in this study will also provide an indication of the extent from the weld edge where welding has altered the material properties and how different regions around the weld are affected by the welding.

3.2 Specimen Preparation

Small non-standard tension coupons were used in the study. The various processes and steps involved in the specimen preparation are described in this section.

3.2.1 Material Specification

There were a total of four plates with three different thicknesses of 15.9 mm (5/8 inch), 19.1 mm (3/4 inch) and 25.4 mm (1 inch) investigated in the study. They were designated as T5, T3 (T3A) and T1 respectively. While there was only one plate each of 15.9 mm and 25.4 mm, there were two plates for 19.1 mm (3/4 inch). Two 19.1 mm plates were considered in order to study the properties variation between plates of the same thickness after undergoing the same welding process. All plates were ASTM A572 grade 50, which is almost equivalent to CSA G40.21 350W. Some of the mechanical and chemical properties of the plates are given in Table 3.1

3.2.2 Welding

All four plates of the size 304.8 mm x 304.8 mm (12 inch x 12 inch) were cut along the center into two equal parts. The cut was parallel to the rolling direction of the plate. A gap of 22 mm was provided between the cut pieces, which was to be filled with the weld metal. The plates were butt welded using shielded metal arc welding with the E7018 electrode. E7018 electrode is the matching electrode for ASTM A572 grade 50 steel. Figure 3.1 shows the sequence of welding. An electrode of 3.175 mm (1/8 inch) was used at the start of welding to bridge the gap as indicated by direction 1 in Figure 3.1. This is followed by using a 4 mm (5/32 inch) electrode in building up the weld up to the plate thickness. Welding started at the mid-depth of the plate, and alternate between the top and bottom surfaces until the gap was filled up. This is shown as direction 2 in the figure. A voltage of 550 volts and 135 amperes was used with the 3.175 mm electrode and 155 ampere with the 4 mm electrode. The heat input was

74.25 kW with the 3.175 mm electrode and 85.25 kW with the 4 mm electrode. There was not post weld heat treatment.

Reference lines at a distance of 50 mm from the weld edge were marked on each side of the plate to help in identifying the location after welding. Welding was carried out in Science and Technology Center at Carleton University.

3.2.3 Cutting Plan

A cutting plan was devised to obtain tension coupons from the various regions around the weld. Numerous coupons from the weld metal, heat-affected zone and the base metal were machined. A 50 mm wide piece was cut from one end of the plate along the direction perpendicular to the weld to reduce the weld length (plate length) to 254.8 mm (10 inch). Reference lines marked at a distance of 50 mm from the weld edge were used to identify the location from where the coupon was obtained.

The plates were milled to the required width before being cut into strips. Figure 3.2 shows a sketch of a milled plate. Tungsten carbide cutters were used to cut the plate. The cutting process is shown in Figure 3.3 and the cutting blade alignment is shown in Figure 3.4. Referring to the sketch of the cutting alignment, coupons from T3A plate were cut with the cutting line aligned with the edge of the cutter, while the cutting line was aligned with the center of the cutter for plates T1, T3 and T5. All plates were supposed to have the cutting line aligned with the center of the cutter. However due to the error in the alignment during cutting, T3A was cut with an offset alignment.

A total of eleven to fifteen coupons were machined from each plate by cutting specimen strips at an interval of 4 mm. The machined coupon has a final thickness of

1.9 to 2.3 mm. All coupons had a width to thickness aspect ratio of close to 3. One important measurement taken during the test is the change in thickness of the coupon with deformation. For this reason, the coupon was not machined down to a smaller thickness in order to allow the thickness to be measured with sufficient accuracy during the test. But it is recognized that it is desirable to have a coupon as thin as possible so that the change in material properties due to welding at a specific location can be better captured in a test. Sketches of the cutting plan are shown in Figures 3.5 and 3.6.

In general, only three coupons from the right side of a plate were obtained. But for T3A, five coupons from the right side were obtained in order to study and compare the material properties variation of the plate between the left and right halves.

The designation Txx-nnn was used to identify the coupon. Txx denotes the plate as defined in Section 3.2.1, and nnn indicates the location of the coupon relative to the reference line as shown on the Figures 3.5 and 3.6. To facilitate the discussion, the following convention is adopted to identify the location where the coupon was obtained from. As indicated in Figure 3.1, the position at the weld edge is taken as zero. The region towards the base metal from the weld metal is assumed to be at a positive distance. Conversely, the region towards the centerline is assumed to be at a negative distance. For example, specimen T1-R1.5 is located on the right side of the plate at a distance of -8.0 mm from the weld edge. It has the same distance from the reference line as the mid-point of T1-1 and T1-2 from the left side of the plate. Also note that in Figure 3.6 (b), specimen T1-R3.5 straddles the weld edge and has the distance of zero. Coupons were marked from 1 to 11, with 1 being the first coupon from the middle of the weld.

Coupons 10 and 11 were obtained from the base metal. Due to the size of the weld, only one of either Txx-1 or Txx-R1.5 can be machined.

3.2.4 Test Specimens

A total of forty seven coupons were prepared from four plates. All specimens were rectangular in cross-section. The profile of the tension coupon is shown in Figure 3.7. An approximate 84 mm long segment was provided at each end to allow for a proper grip of the machine jaw. The transition radius of the specimen was 20 mm and the reduced section was 6 mm wide. Specimens were cut and polished to get a smooth finish.

The reduced section was 62 mm long in order to allow room for a 50 mm gage extensometer with the actual gage being 57.2 mm. This ensures that up to the peak load, the stress is uniform along almost the full length of the reduced section.

3.3 Test Setup and Instrumentation

The specimens were loaded in tension by the machine. The load versus deformation data were measured during the test. In a standard tension test, only the longitudinal deformation was measured with an extensometer. However studies by Khoo et al. (2000) showed that the longitudinal deformation-load relationship after the peak load was sensitive to any slight geometric imperfection, while the transverse deformation-load relationship was found to be rather insensitive. For this reason, the transverse deformation of the specimen was also measured with a caliper and a micrometer. The digital caliper and the digital micrometer have a resolution of 0.01 mm

and 0.001 mm respectively. The test setup and the testing machine are shown in Figure 3.8.

3.3.1 Test Procedure

Testing was carried out using INSTRON universal testing machine with a capacity of 100 kN (20 kips). All readings were routed through a data acquisition system. Stroke control was employed in all tests. The specimen was tested until fracture with regular stoppages during the test to take static readings. All specimens were monotonically loaded.

Displacement rates of 0.25 mm per minute to 0.5 mm per minute was maintained during the test. The objective of the test is to measure the static response of the specimen. For this reason, the loading rate was kept reasonably low.

3.4 Measurement Procedures

3.4.1 Initial Measurements

Each coupon was marked and labeled. The initial width and thickness of each coupon were measured prior to testing.

The testing machine and the data acquisition system were calibrated prior to the start of the testing program. Since the specimen is small, the tension force induced when clamping the specimen to the testing machine can be significant compared to its ultimate load. Thus, this pretension force was recorded for each test and added to the force recorded by the data acquisition system. The data acquisition system was initialized to

zero only after the specimen has been clamped to the testing machine. The initial strain due to the pretension force was calculated based an assumed elastic modulus of 200 GPa.

3.4.2 Measurement during Testing

As shown in Figure 3.9, a typical engineering stress versus engineering strain curve for ductile steel can be divided into four distinct stages. Slightly different loading rates and data acquisition schemes were used for each of this region.

a) Elastic Region

In the initial straight line region, a displacement rate of 0.25 mm/min was used and the electronic recording was taken at every 4 sec interval. There was no static reading nor manual measurement taken.

b) Yield Plateau

At the yield plateau, there is no change in the stress with strain. For this region, the displacement rate is maintained at 0.25 mm/min and the electronic recording was taken at a 4 sec interval. Three to four static readings were taken in this region.

c) Strain Hardening until Peak Load

After the yield plateau, the material starts to strain harden. In this region, the displacement rate was increased from 0.25 mm/min to 0.5 mm/min. The electronic recording was taken at every 6 sec interval and seven to ten static readings were taken. Manual measurements of the width and thickness were taken with a digital caliper

d) Post Peak

Once the point of maximum load or peak load is reached, the change in cross-section is localized to as small region and the load continues to fall with

deformation. The specimen also starts to neck. In this region, the displacement rate of the machine was reduced to 0.25 mm/min to allow for a better control of the loading and the frequency in taking the static and manual measurements. After the peak load, the extensometer was removed so that measurements can be made with the micrometer. Thus only the machine stroke and the load were recorded electronically after the peak load. The machine stroke and the load were recorded at a 12 sec interval. There were also ten to twelve static and manual readings taken in this region. The manual measurements of the minimum and maximum width and thickness at the necked region were taken with the digital caliper and the digital micrometer.

Figure 3.2 Milled plate

Figure 3.3 Cutting process

- a) Cutting line aligned with the edge of the cutter for T3A

- b) Cutting line is centered about the cutter for T1, T3 and T5

Figure 3.4 The alignment of the cutter

Figure 3.5 Cutting plan for left half of all plates (shown for T1)

a) Cutting plan for right half of T3A

b) Cutting plan for right half of T1, T3 and T5 (shown for T1)

Figure 3.6 Cutting plan for right half of plates

Figure 3.7 Tension coupons profile

a) Test setup

b) Testing machine with the data acquisition system

Figure 3.8 Test setup and testing machine

Figure 3.9 Typical stress versus strain curve for ductile steel

Chapter 4 Test Results and Discussions

Based on the test results, the variation of the material properties across a butt weld are presented and discussed in this chapter. Procedures used in calculating some of these properties are also presented.

There were a total of forty seven coupons fabricated for the study. Out of these, only results of thirty four coupons could be used in their entirety. Table 4.1 lists coupons with some results not included in the discussion along with reasons for not including them.

4.1 Test Results Calculation

Material properties vary from the weld metal through the HAZ to the base metal. Thus, an accurate characterization of these variations would improve the numerical modeling and analyses of welded joints. The ultimate strength and ductility are two important properties that affect the capacity of a welded connection. Another factor that affects the capacity is the stress versus strain relationship of the material, especially if the stress is not uniform across the connection. In this section, calculations of ultimate strength, ductility, engineering stress versus deformation (change in cross-section area) relationship across regions around the weld will be discussed.

The first step in the calculation is to determine the exact location of each coupon relative to the weld edge. The weld edge is taken as the interface of weld metal and base metal as shown in Figure 3.1. For the convenience of plotting, the distance of 35 mm is

used in the graph and tables for the base metal coupons Txx-10 and Txx-11 instead of the actual distance.

4.1.1 Ultimate Strength

The calculation of ultimate strength is straight forward. It is given by

$$\sigma_{ult} = \frac{F_{max}}{A_o} \quad (4.1)$$

where F_{max} is the maximum static load and A_o is the original or undeformed cross-section area of the coupon.

4.1.2 Ductility

Ductility characterizes the extent a material can deform before fracture occurs. A measure of the material ductility can be taken as the ratio of the original cross-section area A_o over the mean cross-section area at fracture A_{mf} as

$$\frac{A_o}{A_{mf}}, \text{ and} \quad (4.2)$$

$$A_m = \frac{A_{max} + A_{min}}{2} \quad (4.3)$$

where A_m is the mean cross-section area, A_{max} is the cross-section area based on the maximum width and thickness, and A_{min} is the cross-section area based on the minimum width and thickness. Referring to Figure 4.1,

$$A_{max} = W_{max} \times T_{max}, \text{ and} \quad (4.4)$$

$$A_{min} = W_{min} \times T_{min} \quad (4.5)$$

where $W_{\max}$ is the maximum width, $T_{\max}$ is the maximum thickness, $W_{\min}$ is the minimum width and $T_{\min}$ is the minimum thickness.

The mean value of the area is used because the cross-section is no longer rectangular once necking starts. The natural logarithm of the ratio, $\ln(A_o/A_{mf})$, gives an approximate value of the true strain at fracture.

In the test, the machine stroke and testing load were recorded at a greater frequency than the cross-section dimension. There were three to four stroke readings recorded for every cross-section measurement. Thus the last cross-section measurement was always never taken at the instance of fracture. Usually two to three stroke readings may have been taken after the last cross-section measurement before fracture occurred. Thus the mean cross-section area at fracture (A_{mf}) was linearly projected from the final two mean cross-section area measurements based on the stroke recorded before fracture.

4.1.3 Engineering Stress Versus Deformation

Engineering stress versus deformation (change in cross-section area) relationship was established for each coupon across the weld. Khoo et al. (2000) found that axial deformation-load relationship is sensitive to any slight geometric imperfection while the transverse deformation-load relationship is much less sensitive. For this reason, the engineering stress versus change in cross-section area ($1-A_m/A_o$) is used in characterizing the load versus deformation relationship of the coupon. $1-A_m/A_o$ represents the change in cross-section area at the location of necking, with A_m being the current mean cross-section area calculated using (4.3) and A_o being the original undeformed cross-section area.

The deformation of the coupon profile is uniform until the peak load is reached. Thus by assuming that the deformation is completely plastic, the axial deformation and transverse deformation until the peak load is related by

$$A_m L = L_o A_o \quad \text{or} \quad (4.6)$$

$$\frac{A_m}{A_o} = \frac{L_o}{L} \quad (4.7)$$

where L_o is the original gage length and L is the current length of the gage. In the test, L was measured with an axial extensometer. The magnitude of the extensometer axial deformation measured with the extensometer was larger than transverse deformation of the coupon up until the peak load. For this reason, the cross-section area change was calculated using extensometer data until the peak load with (4.7). After the peak load, the cross-section area change was obtained directly from the manual cross-section measurements because the coupon profile is no longer uniform. As a result, the stress versus cross-section area change relationship was established using a combined axial and transverse deformation data.

4.2 Discussions

Material properties calculated from the test data were plotted and analyzed. Discussions of these material properties are presented in the following sections. The effect of welding on different thickness can not be quantified because all plates have different chemical compositions.

4.2.1 Ultimate Strength

The ultimate strength and the ultimate strength as a ratio of the base metal strength across the weld for each plate thickness are given in Tables 4.2 to 4.5 and Figures 4.2 to 4.7. These plots show that the ultimate strength varies for different regions around the weld. There is an overall similarity in terms of shape and trend for these plots for all plate thicknesses. However at the weld and close to the weld edge, there is a greater variability in the strength because welding is a non-homogeneous process. Begini et al (2001) also found that the variability of the ultimate strength is greater at the heat-affected zone and at the weld.

In general, there is a gradual increase in the ultimate strength as the location moves closer to the weld edge. The ultimate strength is highest at the interfacial zone between the weld and the base metal, which is at around the weld edge as shown in Figures 4.6 and 4.7. For specimens in this study, the ultimate strength was 20% higher than that of the base metal for T3 (3/4 inch) plates, and 10% for T1 (1 inch) and T5 (5/8 inch) plates. As can be seen in Table 4.4, and Figures 4.4 and 4.5, the ultimate strength of T3-3 and T3-4, which located at -2 and 2 mm from the weld edge, are respectively 582 MPa and 606 MPa. These translate to an increase of almost 20% in the ultimate strength when compared to T3-10 base metal coupon, which has an ultimate strength of 514 MPa. Figure 4.7 shows that the ratio of the ultimate strength to base metal strength is close to unity at distance greater 6 mm. This indicated that welding only affect a small region that is about 6 mm from the weld edge. In Figure 4.4 and 4.5 for T3 and T3A plates, the ultimate strength varies close to linearly from the base metal to the weld metal

through the HAZ. But for T1 and T5, there are too few data points available to make any conclusion similar to that for T3 and T3A.

From test results, it can be observed that the effect of welding produced by the process in this test program is quite consistent for plates with same thickness. It can be seen in Figures 4.4 and 4.5, the ultimate strength for plates T3 and T3A varies smoothly from the base metal until close to the weld edge. From the Table 4.4, T3-5 at 6 mm has an ultimate strength of 527 MPa. This coupon is located at a distance from the weld edge that is between T3A-R4.5 at 4.75 mm and T3A-5 at 6.75 mm. As shown in Table 4.5, both these coupons have ultimate strengths of 536 MPa and 519 MPa respectively.

Table 4.5 also shows that the effect of welding from the welding process in this test program is quite consistent for the right and left halves of the plate. As coupons moving closer to the weld edge, alternate between the right and left side from T3A-R5.5 to T3A-4, there is also a consistent gradual increase in the ultimate strength.

4.2.2 Ductility

The ductility of a material allows the stress to redistribute when there is stress concentration in a connection. This effectively increases the capacity of a connection. Thus, it greatly affects the performance of a connection.

The ratio of A_0/A_{mf} against the distance from the weld edge are given in Tables 4.6 to 4.9 and in Figures 4.8 to 4.10. These figures show that there is a greater scatter in the A_0/A_{mf} ratio as compared to the ultimate strength. One of the reasons is due to the thin specimen used in the test. There is a greater relative error in the measuring the change in thickness of a thin specimen than a thick specimen. Another

reason is that the last reading is not exactly right before fracture. As a result, the final mean cross-section area A_{mf} is less accurate and shows a greater scatter.

Overall there is a reduction in ductility closer to the weld edge and at the weld metal. This trend is not clear for T5. But for T3 and T3A in Figure 4.9, and T1 in Figure 4.8, the ductility can be seen to reduce going from the base metal to the weld edge. However, most of the specimens have a ratio of close to 2.5 to 3.0, which indicate a high level of ductility. The base metal has a minimum ratio of 2.7, but the ratio is as low as 2.1 at the HAZ and as low as 1.5 at the weld metal.

4.2.3 Engineering Stress Versus Cross-Section Change

Engineering stress versus cross-section change curves for coupons from various regions for all plate thicknesses are plotted and compared in Figures 4.11 to 4.19.

The plots for coupons T1-R1.5 and T1-2 from the weld metal, which are located at a distance of -8 mm and -6 mm from the weld edge respectively, are shown in Figure 4.11. The two curves have a rather flat curvature in the strain hardening region. The ultimate strength is only slightly higher than the yield strength, which is less than 20% higher. Similar characteristic is observed for weld metal coupons of other plate thicknesses in the study, as can be seen for T3-3 in Figure 4.14, T3A-3 in Figure 4.16 and T5-2 in Figure 4.18.

The engineering stress versus cross-section change curves for some T1 coupons are shown in Figures 4.12 and 4.13. There is little change in the material properties beyond 6 mm away from the weld edge as indicated by the almost identical stress-deformation curves of the base metal coupon T1-11 coupon and the coupon T1-5,

which is at 6 mm from the weld edge. This clearly shows that welding has a little effect on the material properties at a distance further away than about 6 mm from the weld edge. The similar trend in engineering stress versus cross-section area relationship is observed in Figures 4.14 and 4.16 for T3 and T3A plates. For T3 and T3A, the distance is slightly further than 6 mm as can be seen in Figures 4.15 and 4.17. However for T5 plate, results of the base metal coupons cannot be used due to the error in testing and the error in recording the clamping force. Since T5-7 is the coupon furthest away from the weld edge that has the reliable engineering stress versus deformation data, it is assumed to be the base metal in the discussion. The trend shown in Figure 4.19 for T5 is similar to T3.

The coupon T1-R3.5 in Figure 4.12, which straddles the weld edge (interfacial region of weld metal and base metal), has a same yield strength but with a higher ultimate stress than the weld metal coupon T1-2. Curves for coupons T1-2, T1-R3.5, and T1-4 at the weld metal and the interfacial zone, located closer than 6 mm from the weld edge, are also significantly different from that of the base metal.

The plots for coupons T1-5, T1-6 and T1-11 (base metal) are shown in Figure 4.13. These coupons are located at 6 mm, 14 mm and 92 mm (base metal) from the weld edge. The three curves are almost identical in shape. Figures 4.15 and 4.17, and T5-5 and T5-7 in Figure 4.19, show plots of coupons of other plate thicknesses that have almost the same shape as the base metal. These coupons are all generally greater than 6 mm away from the weld edge. It can be seen that the slope of the curve for the base metal in the strain hardening region is generally steeper than weld metal. There is also greater strength increase after yielding than the weld metal and HAZ curves.

Figure 4.20 shows that the ultimate to yield strength ratio decreases going from the base metal to the weld metal. The reduction starts at about 10 mm for T3 and T3A, and 6 mm for T1. For T1, T3 and T3A, there is close to a linear decrease from a ratio of 1.5 at the base metal to 1.1 at the weld edge. There is also a similar reduction for T5. But the reduction is not as well defined as other plates.

In general, the weld metal and the region close to the weld edge do not strengthen as much after yielding as compared to the base metal. Similarly, these regions also have a slower rate of strength increase with strain hardening. There is also a gradual transition of the stress versus deformation curve from the base metal to the weld edge. This can be seen in Figures 4.12, 4.14, 4.16 and 4.19. The yield strength also increases going from the base metal towards the weld metal and weld edge. Figure 4.21 shows the variation of the yield strength across the weld region. The trend is similar to that of the ultimate to yield strength ratio except that the ultimate to yield strength ratio decreases.

Table 4.1 Coupons not used in the study

Coupon	Distance from the weld edge	Results not used			Comment
		Ultimate strength	Ductility	Stress-deformation relationship	
T1-R2.5	-4.000	Ignored	Ignored	Ignored	Holes in the specimen
T1-10	92.000	Ignored		Ignored	Incorrect clamping force
T3-2	-6.000	Ignored	Ignored	Ignored	Holes in the specimen
T3-R2.5	-4.000			Ignored	Insufficient manual measurements
T3-R3.5	0.000	Ignored		Ignored	Failure close to profile transition
T3-11	96.000	Ignored	Ignored	Ignored	Trial testing
T3A-1	-10.750	Ignored	Ignored	Ignored	Deep cuts in the profile
T3A-2	-6.750			Ignored	Insufficient manual measurements
T3A-R2.5	-3.250	Ignored	Ignored	Ignored	Holes in the specimen
T3A-11	96.750	Ignored	Ignored	Ignored	Trial testing
T5-6	10.000	Ignored		Ignored	Incorrect clamping force
T5-10	92.000	Ignored	Ignored	Ignored	Error in testing
T5-11	96.000	Ignored		Ignored	Incorrect clamping force

Table 4.2 Ultimate strength for T1 (1 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	Ultimate load kN	Ultimate strength σ_{ult} MPa	Ultimate strength ratio $\sigma_{ult}/\sigma_{ult \text{ base}}$
T1-R1.5	13.417	-8.00	7.710	574.6	1.039
T1-2	13.418	-6.00	7.631	568.7	1.028
T1-3	13.409	-2.00	7.940	592.1	1.070
T1-R3.5	13.358	0.00	7.818	585.3	1.058
T1-4	13.403	2.00	7.627	569.0	1.029
T1-5	11.596	6.00	6.328	545.7	0.987
T1-6	13.400	10.00	7.342	547.9	0.991
T1-7	13.368	14.00	7.275	544.2	0.984
T1-11	13.472	35.00	7.452	553.1	1.000

Table 4.3 Ultimate strength for T5 (5/8 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	Ultimate load kN	Ultimate strength σ_{ult} MPa	Ultimate strength ratio $\sigma_{ult}/\sigma_{ult \text{ base}}$
T5-R1.5	13.447	-8.00	7.052	524.4	1.001
T5-2	13.348	-6.00	7.549	565.6	1.080
T5-R2.5	13.452	-4.00	7.273	540.7	1.032
T5-3	13.375	-2.00	7.267	543.3	1.037
T5-R3.5	13.199	0.00	7.526	570.2	1.089
T5-4	13.382	2.00	7.199	537.9	1.027
T5-5	13.356	6.00	7.098	531.5	1.015
T5-7	13.232	14.00	6.931	523.8	1.000

Table 4.4 Ultimate strength for T3 (3/4 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	Ultimate load kN	Ultimate strength σ_{ult} MPa	Ultimate strength ratio $\sigma_{ult}/\sigma_{ult \text{ base}}$
T3-R2.5	13.366	-4.00	7.809	584.3	1.136
T3-3	13.499	-2.00	7.860	582.3	1.132
T3-4	13.350	2.00	8.100	606.7	1.180
T3-5	13.353	6.00	7.034	526.8	1.024
T3-6	13.122	10.00	6.797	518.0	1.007
T3-7	13.338	14.00	6.718	503.7	0.979
T3-10	13.391	35.00	6.888	514.4	1.000

Table 4.5 Ultimate strength for T3A (3/4 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	Ultimate load kN	Ultimate strength σ_{ult} MPa	Ultimate strength ratio $\sigma_{ult}/\sigma_{ult \text{ base}}$
T3A-2	10.892	-6.75	5.641	517.9	1.014
T3A-3	11.013	-2.75	5.908	536.4	1.050
T3A-R3.5	13.887	0.75	6.813	490.6	0.960
T3A-4	11.164	2.75	6.259	560.6	1.097
T3A-R4.5	13.385	4.75	7.175	536.0	1.049
T3A-5	11.302	6.75	5.862	518.7	1.015
T3A-R5.5	13.244	8.75	6.799	513.4	1.005
T3A-6	11.349	10.75	5.825	513.3	1.005
T3A-R6.5	13.444	12.75	6.785	504.7	0.988
T3A-7	13.370	14.75	6.872	514.0	1.006
T3A-8	13.319	18.75	6.795	510.2	0.999
T3A-10	13.333	35.00	6.811	510.8	1.000

Table 4.6 Ductility of T1 (1 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	A_{mf} mm^2	A_o/A_{mf}
T1-R1.5	13.417	-8.00	5.400	2.485
T1-2	13.418	-6.00	5.153	2.604
T1-3	13.409	-2.00	5.600	2.395
T1-R3.5	13.358	0.00	5.081	2.629
T1-4	13.403	2.00	5.432	2.467
T1-5	11.596	6.00	3.895	2.977
T1-6	13.400	10.00	4.255	2.973
T1-7	13.368	14.00	4.935	2.902
T1-10	13.485	35.00	4.345	3.104
T1-11	13.472	35.00	4.947	2.723

Table 4.7 Ductility of T5 (5/8 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	A_{mf} mm^2	A_o/A_{mf}
T5-R1.5	13.447	-8.00	4.970	2.706
T5-2	13.348	-6.00	4.822	2.768
T5-R2.5	13.452	-4.00	4.477	3.005
T5-3	13.375	-2.00	4.691	2.851
T5-R3.5	13.199	0.00	4.651	2.837
T5-4	13.382	2.00	3.938	3.398
T5-5	13.356	6.00	4.407	3.031
T5-6	13.386	10.00	4.469	2.995
T5-7	13.232	14.00	4.740	2.791
T5-11	11.451	35.00	4.092	2.798

Table 4.8 Ductility of T3 (3/4 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	A_{mf} mm^2	A_o/A_{mf}
T3-R2.5	13.366	-4.00	4.398	3.039
T3-3	13.499	-2.00	4.783	2.822
T3-R3.5	13.544	0.00	4.670	2.900
T3-4	13.350	2.00	6.260	2.133
T3-5	13.353	6.00	4.386	3.045
T3-6	13.122	10.00	4.102	3.199
T3-7	13.338	14.00	4.631	2.880
T3-10	13.391	35.00	4.554	2.941

Table 4.9 Ductility of T3A (3/4 inch) plate

Coupon	Original area A_o mm^2	Distance from weld edge mm	A_{mf} mm^2	A_o/A_{mf}
T3A-2	10.892	-6.75	7.471	1.458
T3A-3	11.013	-2.75	4.038	2.727
T3A-R3.5	13.887	0.75	4.885	2.843
T3A-4	11.164	2.75	4.576	2.440
T3A-R4.5	13.385	4.75	4.936	2.712
T3A-5	11.302	6.75	4.304	2.626
T3A-R5.5	13.244	8.75	4.370	3.031
T3A-6	11.349	10.75	4.209	2.696
T3A-R6.5	13.444	12.75	4.645	2.894
T3A-7	13.370	14.75	4.283	3.122
T3A-8	13.319	18.75	4.750	2.804
T3A-10	13.333	35.00	4.577	2.913

Figure 4.1 Cross-section of rectangular coupon close to fracture

Figure 4.2 Ultimate strength across the weld for T1 and T5 plates

Figure 4.3 Ultimate strength as a ratio of base metal strength across the weld region for T1 and T5 plates

Figure 4.4 Ultimate strength across the weld for T3 and T3A plates

Figure 4.5 Ultimate strength as a ratio of base metal strength across the weld region for T3 and T3A plates

Figure 4.6 Ultimate strength of, T1, T3, T3A and T5 plates

Figure 4.7 Ultimate strength as a ratio of base metal strength for T1, T3, T3A and T5 plates

Figure 4.8 Variation of ductility across the weld for T1 and T5 plates

Figure 4.9 Variation of ductility across the weld for T3 and T3A plates

Figure 4.10 Variation of ductility across the weld for T1, T3, T3A and T5 plates

Figure 4.11 Engineering stress versus deformation relationship for T1-R1.5 and T1-2 weld metal coupons

Figure 4.12 Engineering stress versus deformation relationship of the material at various locations for plate T1 (1 inch)

Figure 4.13 Engineering stress versus deformation relationship for T1-5, T1-6 and T1-11 base metal coupons

Figure 4.14 Engineering stress versus deformation relationship of the material at various locations for plate T3 (3/4 inch)

Figure 4.15 Engineering stress versus deformation relationship for T3-6, T3-7 and T1-10

Figure 4.16 Engineering stress versus deformation relationship of the material at various locations for plate T3A

Figure 4.17 Engineering stress versus deformation relationship for T3A-R5.5, T3A-6, T3A-7, T3A-8 and T3A-10

Figure 4.18 Engineering stress versus deformation relationship for T5-R1.5, T5-2 and T5-R2.5 weld metal coupons

Figure 4.19 Engineering stress versus deformation relationship for T5 plate

Figure 4.20 Ultimate to yield strength ratio of T1, T3, T3A and T5 plates

Figure 4.21 Yield strength of T1, T3, T3A and T5 plates

Chapter 5 Numerical Modeling and Analysis

The true stress versus true strain relationship of the material is required in a finite element analysis of a steel structure that experiences large strains. While the true stress versus true strain relationship until the peak load can be established from results of a tension test, there is no direct method for determining this relationship after the peak load. Thus, numerical modeling and analyses were carried out to study and determine the true stress versus true strain relationship of the material around the butt weld. The numerical analysis was carried out using the commercial finite element software ABAQUS (2002).

5.1 True Stress Versus True Strain Relationship

The true stress versus true strain relationship of the plate varies from the base metal, through the HAZ to the weld metal. A simple function is proposed to assist in the process of determining this relationship for these different regions.

5.1.1 True Stress Versus True Strain Relationship up to Peak Load

In a tension coupon test, the uniform uniaxial state of stress exists in the reduced region of the coupon up to the initiation of necking, which is at a point corresponding to the peak load. Thus by assuming the deformation is completely plastic, the true stress versus true strain relationship can be estimated from the longitudinal engineering strain versus engineering stress up to the peak load from the tension test. Since there is no

change in the material volume in plastic deformation according to the incremental flow theory of plasticity, it follows that

$$AL = A_0L_0, \text{ which leads to} \quad (5.1)$$

$$\frac{A_0}{A} = \frac{L}{L_0} = 1 + \epsilon^e \text{ and} \quad (5.2)$$

$$\frac{A_0}{A} = \left(\frac{d_0}{d} \right)^2 = 1 + \epsilon^e \quad (5.3)$$

where ϵ^e is the engineering strain in the longitudinal direction, A is the current cross-section area, L is the current length of the gauge, A_0 is the original undeformed cross-section area, L_0 is the original gauge length, d_0 is the original undeformed diameter of the coupon and d is the current diameter of the coupon. The true stress versus true strain relationship can be calculated from the longitudinal engineering strain versus engineering stress through

$$F = A\sigma^t = A_0\sigma^e, \text{ which gives} \quad (5.4)$$

$$\sigma^t = \sigma^e \frac{A_0}{A} = \sigma^e (1 + \epsilon^e), \quad (5.5)$$

$$\epsilon^t = \ln \left(\frac{L}{L_0} \right) = \ln (1 + \epsilon^e) = \ln \left(\frac{A_0}{A} \right), \text{ and} \quad (5.6)$$

$$\epsilon^p = \epsilon^t - \frac{\sigma^t}{E} \quad (5.7)$$

where F is the load on the tension coupon, σ^t is the true stress, ϵ^t is the true strain, σ^e is the engineering stress, ϵ^p is the true plastic strain and E is the elastic modulus. Equation 5.7 assumes that the elastic modulus does not change with deformation.

However after the peak load, the state of stress changes from uniaxial state to multiaxial due to necking. So (5.5) and (5.6) are not longer valid after the peak load.

5.1.2 Proposed True Stress Versus True Strain Function

Matic and Jolles (1987) and Khoo et al. (2000) determined the true stress versus true strain relationship after the peak load by trial and error method. The true stress versus true strain relationship was adjusted until the numerical simulation agrees with the load-deformation data of the tension test.

As it is not possible to directly calculate the true stress versus true strain relationship after the peak load from the tension data, a proposed function based on power law stress-strain relationship is used instead in generating the complete true stress versus true strain relationship. The proposed function is applicable after the start of strain hardening and is expressed as

$$\epsilon^p = C \left[\left(\frac{\sigma^t}{\sigma_o^t} \right)^n - 1 \right] + \epsilon_o^p \text{ for } \sigma^t \geq \sigma_o^t \quad (5.8)$$

where ϵ_o^p is the true plastic strain at the start of the strain hardening or the end of yield plateau with the true stress σ_o^t , C and n are parameters to be determined by curve fitting. This function automatically goes through the point at the start of strain hardening. Thus by forcing the function to also pass through the point at peak load, the relationship between parameters C and n is established and can be expressed as

$$\varepsilon_f^p = C \left[\left(\frac{\sigma_f^t}{\sigma_o^t} \right)^n - 1 \right] + \varepsilon_o^p, \text{ and} \quad (5.9)$$

$$C = \frac{\varepsilon_f^p - \varepsilon_o^p}{\left(\frac{\sigma_f^t}{\sigma_o^t} \right)^n - 1} \quad (5.10)$$

where ε_f^p and σ_f^t are respectively the true plastic strain and true stress at the peak load. Consequently, C and n are not independent. The parameter n can be determined by trial and error, or by some error minimizing techniques until the true stress versus true plastic strain relationship generated by (5.8) with the selected n closely matches that from the test data up to the peak load or 90% peak load.

5.1.3 Procedure for Using the Function

The steps in calculating the true stress versus true plastic strain relationship using the function are described below.

- a) True stress versus true plastic strain for the tension coupons were calculated until the peak load or 90% peak load from the experimental data using the (5.5) and (5.7). After the peak load, the true stress and true strain were calculated using the term A_o/A in (5.5) and (5.7), while replacing A replaces with the mean area A_m .
- b) The true stress σ_o^t and true plastic strain ε_o^p is the point at the start of strain hardening or the end of yield plateau, and the true stress σ_f^t and true plastic strain ε_f^p is the point at the peak load. These points were identified from test data. The

point at around 90% peak load is on the descending branch of the load-deformation curve. For the discussion, $(\varepsilon_o^p, \sigma_o^t)$ is referred to as the initial point.

- c) The parameter n was determined by some error minimizing techniques until the true stress versus true plastic strain relationship generated by (5.8) closely matches that from the test until the peak load or around 90% peak load. This is illustrated in Figure 5.1. In this study, the least square error of the true stress is minimized to obtain n .
- d) The parameter C was then calculated using (5.10) after n was determined.
- e) The true stress versus true plastic strain relationship for the material was then calculated using (5.8) with values from (b), (c) and (d).

5.2 Numerical Simulations

Numerical simulations of the test specimens were carried out to study the validity of the proposed function in characterizing the true stress versus true plastic strain relationship of the material. Even though the specimen is rectangular, the simulation was carried out using axisymmetric element by assuming the specimen is circular. This reduces the computing effort significantly, and the justification for modeling the test specimen with a circular specimen is provided in the following section.

5.2.1 Finite Element Model for the Circular Specimen

The finite element model for the circular specimen was developed based on the profile of the tension specimen AS1g50r5 by Khoo et al. (2000). The reduced region of

the specimen was approximately 50 mm long and 14 mm in diameter. Thus, the reduced region is sufficiently long so that this region will have close to a uniform uniaxial stress up to the peak load. The exact length of the reduced region is not important since the load versus transverse deformation is used in the comparison.

The mesh study was carried out using the true stress versus true strain data for AS material by Khoo et al. (2000) and T1-2 coupon. The procedure employed in calculating the true stress versus true plastic strain data for T1-2 will be discussed in the subsequent section. All numerical analyses were carried out using the axisymmetric element CAX8R and the non-linear geometry option of ABAQUS (2002). CAX8R is an eight-node biquadratic element with a reduced integration. The specimen is assumed to be symmetric about the mid-length of the reduced region where necking occurs. Thus only half of the specimen is modeled. The elastic modulus E was assumed to be 200,000 MPa and the Poisson's ratio to be 0.3.

The two meshes used in the study are shown in Figure 5.2. The element size for the fine mesh scheme at the mid-length is half that of the coarse scheme. Comparisons in Figure 5.3 shows that there is no significant difference in the engineering stress versus cross-section deformation for both schemes. However, no further mesh study was carried out because the time required to complete one simulation using both schemes is not long. For this reason, the fine mesh scheme is adopted in the numerical simulations of the test coupons in the subsequent sections. Figure 5.4 shows the undeformed and deformed meshes of the finite element model used in the numerical modeling.

5.2.2 Effect of Cross-Section Shape

Khoo et al. (2004) showed that there is little difference in the load versus cross-section deformation curve between circular specimen and a rectangular specimen with a width to thickness ratio of up to six. The cross-section deformation is taken as $(1-A/A_0)$ for a circular specimen and $(1-A_m/A_0)$ for a rectangular specimen. A is the current cross-section area, A_0 is the original cross-section area, and A_m is the mean cross-section area as defined in Section 4.2.2.

Numerical simulations of a rectangular specimen with a width to thickness ratio of three and a circular specimen were carried out to illustrate the good agreement of the load versus cross-section deformation results.

The rectangular coupon was modeled with C3D20R, a three-dimensional tri-quadratic twenty-node solid elements with reduced integration. The length of the reduced region is around 60.0 mm and the width is 12.4 mm. The undeformed and deformed finite element meshes of the rectangular specimen are shown in Figure 5.5. Numerical simulations were carried out for both the true stress versus true plastic strain data by Khoo et al. (2000) of AS material and T1-2 coupon. The time required to complete a numerical simulation of a rectangular coupon is 10 times that of a circular coupon.

Figures 5.6 shows the comparison of the predicted engineering stress versus cross-section deformation results for the rectangular and the circular models for both AS material and material properties of T1-2 respectively. The good agreement found allows a circular model to be used to model the rectangular coupon from the test.

5.3 Suitability of the Proposed Function

The study on the suitability of the proposed function and procedure for calculating the true stress versus true strain relationship was carried out using the test data. In addition to the data from the test program, data from Khoo et al (2000) were also used in the study.

5.3.1 Tension Tests from Khoo et al.

Three round test specimens with different material properties from tests carried out by Khoo et al (2000) were used in the study. They were designated as AS, AN and NM following Khoo et al. Figure 5.7 shows the comparison of the true stress versus true plastic strain relationship up to the peak load from both the test and (5.8) for all three materials, and the projection of the curve beyond the peak load point. The calibration of n was carried with data up to the peak load. The true stress versus true plastic strain relationship used in the numerical simulation was completely generated using the proposed function. Parameters of the function for these three materials are shown in Table 5.1. Figure 5.8 shows that there is a good agreement between the numerical simulation and test results. For these three materials, the proposed function is able to closely approximate the true stress versus true plastic strain relationship that is to be used in the finite element analysis.

5.3.2 Tension Tests from the Present Study

Numerical simulations were carried out to simulate the engineering stress versus change in cross-section area relationship for coupons across the weld region.

5.3.2.1 Comparison between Matching until Peak Stress and 90% Peak Stress

As mentioned in Section 5.1.3, the value of n used in (5.8) is determined by matching the true stress versus true plastic strain relationship generated by (5.8) with that from the test until either the peak stress or 90% peak stress. Parameters used in generating the true stress versus true plastic strain by (5.8) when matched until the peak load and 90% peak load for T1-5 and T3A-R3.5 are listed in Tables 5.2 and 5.3. Figures 5.9 and 5.10 show the engineering stress versus deformation relationship for T1-5 and T3A-R3.5 from numerical simulations and tests. As shown in these figures, the predicted engineering stress versus deformation by matching until 90% peak stress gives a better prediction as compared to that by matching until peak stress. Even though the numerical simulations by matching until peak stress gives a good prediction of the engineering stress versus deformation for specimens by Khoo et al. (2000), it does not work that well against the coupons from the present study. Thus for this reason, the calibration of n in the present study will be carried against data up to 90% peak stress for generating the true stress versus true plastic strain data for all coupons.

However there is an advantage by matching up to the peak stress to generate the true stress versus true plastic strain data. The test data for matching until the peak stress can be directly obtained from extensometer readings. But beyond the peak load, the extensometer reading no longer represents the actual transverse deformation as a result of necking. Therefore, matching up to 90% peak stress requires additional manual measurements of the cross-section change at the region of necking after the peak load.

5.3.2.2 Test and Simulated Results

Comparison of engineering stress versus deformation relationship from tests and numerical simulations are shown in Figures 5.11 to 5.15 for T1 plate. The numerical simulation was carried out using the true stress versus true plastic strain relationship generated from the function by matching up to 90% peak stress.

In general, the numerical simulation overpredicts the stress after the peak load. The agreement is good for some cases such as T1-7 in Figure 5.15. But overall, there is a reasonably good agreement between test and predicted results for all cases. Thus, the proposed function was used in determining and characterizing the true stress versus true plastic strain relationship of test coupons.

5.4 Parameters Characterizing the True Stress Versus True Plastic Strain Relationship

Parameters for (5.8) used in developing the true stress versus true plastic strain across the weld region are listed in Tables 5.4 to 5.7. They are calibrated by matching up to 90% peak stress of test data.

5.4.1 Variation of n and C Parameters across the Weld

The n value in the function is associated with the slope of the curve and hardening rate during strain hardening. A higher n implies a slow rate of strength increase. Figure 5.16 shows the value of n across the weld region. The value of n is higher for weld metal and HAZ coupons, which is associated with flatter slope and lower rate of strength increase during strain hardening when compared to base metal. Overall, the

value of n ranges between 4.3 to 5.5. The parameter n is around 4.5 at the base metal and 5 at the weld metal. There is a considerable scatter in n even at around the base metal for T3 and T3A, as shown in Table 5.5 and 5.6. It varies from 4.3 to 4.9 for coupons greater than 10 mm from the weld edge. This range is large when compared to the overall range of n . Figure 5.17 also shows that n decreases with a higher ultimate to yield strength ratio. This is expected since lower n is associated with a higher rate of strength increase. Again, there is a significant scatter in n with respect to its overall range. However by fitting a linear line through the data, the following relationship for n and the ultimate to yield strength ratio,

$$n = -1.6188(\sigma_r) + 6.9356 \quad (5.11)$$

is obtained, where σ_r is the ultimate to yield strength ratio. This line is also plotted in Figure 5.17. It should be noted that there is a significant scatter of n away from the line. Thus a sensitivity study should be carried out to investigate the effect of small changes in n from the value given by the line. This sensitivity study is outside the scope of this thesis.

The parameter C also affects the hardening rate. This parameter is closely associated with the ultimate to yield strength ratio because the variable in the proposed function (5.8) is in term of the ratio of yield strength. A larger C implies a lower rate of hardening. Figure 5.18 shows the variation of C across the weld region.

The parameter C increases towards HAZ and weld metal as the ultimate to yield strength ratio, as shown in Figure 4.20, decreases moving away from the base metal. The value of C is around 0.02 at the base metal and 0.055 at the weld metal. It can be seen in Figure 5.19 that C clearly decreases with a higher ultimate to yield strength ratio. There

is also a strong correlation between C and the ultimate to yield strength ratio. Based on the results, the relationship

$$C = \frac{0.00952}{(\sigma_r - 1)^{0.7895}} - 0.00128 \quad (5.12)$$

is derived. This equation is also plotted against test data in Figure 5.19. In this study, the parameter C varies from 0.017 at an ultimate to yield strength ratio of 1.5 to 0.06 at a ratio of 1.1. Figure 5.20 shows the relationship of n and C. Overall C increases with n. But there is too much scatter to arrive at any reliable equation to characterize the relationship between C and n.

While the variation of n and C with the location differs among different plates, relationship of parameters n and C versus ultimate to yield strength ratio however do not show the dependency on the plate. Thus (5.11) and (5.12) may be employed together with the measured yield and ultimate strengths to obtain parameters C and n required in generating the true stress versus true strain curve across the weld region. The yield and ultimate strengths may be measured indirectly with a hardness test.

5.5 True Stress Versus True Strain Relationship

The true stress versus true plastic strain curves generated by the function for T1, T3, T3A and T5 are shown in Figure 5.21 to 5.24. Only curves for a few coupons of each plate are shown to illustrate the variation across the weld region. Coupons greater than 6 mm from the weld edge in each plate have almost an identical true stress versus true plastic strain curve. This is consistent with the conclusion drawn in Chapter 4 on the extent from the weld edge where welding has altered the material properties. For T3 and T3A in Figures 5.22 and 5.23, the curves have almost the same shape but undergoes an

upward or downward shift depending on the location of the coupon. Figure 5.23 for T3 shows that there is an upward shift from the base metal towards the weld edge and weld metal. This is consistent with the increase in the ultimate strength moving towards the weld edge and weld metal.

For T5 in Figures 5.24, the shape is not maintained for curves. But for T5-R3.5, the shape is the same as that for the base metal T5-7. The curve for T5-R3.5 at the weld edge is also the highest, which is consistent with T5-R3.5 having the highest ultimate strength for T5 plate. There is also a gradual upward shift in the early segment of the curve going from the base metal to the weld metal. But the trend for T1 is not as clear when compared to other plates. Overall, no definitive conclusion can be made regarding the similarity of the shape of the true stress versus true plastic strain curve across the weld region. But there is a general upward shift of the curve going towards the weld edge, even though the shape may not be maintained.

Table 5.1 Parameters for AS, AN and NM materials

Coupon	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
AS	0.0204	368.31	0.1515	602.93	6.28	0.00623
AN	0.0236	352.90	0.1779	592.55	5.64	0.00877
NM	0.0001	280.39	0.1045	650.02	6.51	0.00477

Table 5.2 Parameters for T1-5 and T3A-R3.5 matching until peak stress

Coupon	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
T1-5	0.0112	391.21	0.1675	647.29	3.91	0.0254
T3A-R3.5	0.0455	431.68	0.2300	612.62	4.63	0.0456

Table 5.3 Parameters for T1-5 and T3A-R3.5 matching 90% peak stress

Coupon	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
T1-5	0.0112	391.21	0.1675	647.29	4.53	0.0178
T3A-R3.5	0.0455	431.68	0.2300	612.62	5.04	0.0381

Table 5.4 Parameters for plate T1

Coupon	Distance from weld edge mm	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
T1-R1.5	-8.00	0.0370	544.42	0.1243	652.81	5.25	0.0547
T1-2	-6.00	0.0386	548.79	0.1302	649.90	5.33	0.0625
T1-3	-2.00	0.0132	533.64	0.1327	678.96	5.50	0.0433
T1-R3.5	0.00	0.0399	558.83	0.1684	693.30	5.20	0.0621
T1-4	2.00	0.0060	446.99	0.1302	650.25	4.99	0.0203
T1-5	6.00	0.0112	391.21	0.1675	647.29	4.53	0.0178
T1-6	10.00	0.0143	376.44	0.2090	677.58	4.54	0.0145
T1-7	14.00	0.0154	376.74	0.2317	688.50	4.57	0.0147
T1-11	Base metal	0.0198	396.61	0.2043	680.80	4.54	0.0173

Table 5.5 Parameters for plate T3A

Coupon	Distance from weld edge mm	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
T3A-3	-2.75	0.0355	504.81	0.1056	598.99	5.31	0.0473
T3A-R3.5	-0.75	0.0455	431.68	0.2300	612.62	5.04	0.0381
T3A-4	2.75	0.0170	482.87	0.1090	627.15	5.01	0.0367
T3A-R4.5	4.75	0.0203	420.83	0.1932	626.86	5.03	0.0320
T3A-5	6.75	0.0169	400.50	0.1482	603.30	4.90	0.0204
T3A-R5.5	8.75	0.0094	379.29	0.1623	605.64	4.80	0.0181
T3A-6	10.75	0.0103	366.71	0.1452	595.44	4.68	0.0156
T3A-R6.5	12.75	0.0031	350.42	0.1363	580.06	4.70	0.0137
T3A-7	14.75	0.0145	363.08	0.2161	640.03	4.39	0.0177
T3A-8	18.75	0.0226	371.23	0.2104	631.66	4.37	0.0205
T3A-10	Base metal	0.0120	369.49	0.2332	647.06	4.37	0.0210

Table 5.6 Parameters for plate T3

Coupon	Distance from weld edge mm	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
T3-3	-2.00	0.0490	540.58	0.1532	680.96	4.84	0.0506
T3-4	2.00	0.0355	548.28	0.1129	678.43	4.79	0.0437
T3-5	6.00	0.0131	409.42	0.1662	623.95	4.77	0.0238
T3-6	10.00	0.0139	363.84	0.1597	603.90	4.78	0.0142
T3-7	14.00	0.0138	358.99	0.1979	615.82	4.78	0.0151
T3-10	Base metal	0.0212	374.44	0.2173	641.27	4.75	0.0159

Table 5.7 Parameters for plate T5

Coupon	Distance from weld edge mm	Initial strain ϵ_o^p	Initial stress σ_o^t MPa	Peak strain ϵ_f^p	Peak stress σ_f^t MPa	n	C
T5-R1.5	-8.00	0.0368	496.37	0.1800	650.00	4.95	0.0511
T5-2	-6.00	0.0339	507.60	0.1743	675.52	4.92	0.0470
T5-R2.5	-4.00	0.0409	506.44	0.2346	685.99	4.84	0.0579
T5-3	-2.00	0.0112	435.77	0.1953	662.67	4.93	0.0267
T5-R3.5	0.00	0.0519	535.53	0.2791	756.60	4.90	0.0258
T5-4	2.00	0.0202	403.29	0.1854	649.62	4.94	0.0173
T5-5	6.00	0.0162	376.91	0.1756	633.73	4.74	0.0148
T5-7	14.00	0.0119	368.05	0.2052	639.12	4.27	0.0205

Figure 5.1 Procedure for using the proposed function

a) coarse mesh scheme

b) Fine mesh scheme

Figure 5.2 Finite element mesh for circular specimen

Figure 5.3 Comparison of coarse and refined mesh results

Figure 5.4 Undeformed and deformed mesh of finite element model for circular specimen

Figure 5.5 Undeformed and deformed mesh of the finite element model for a quarter rectangular coupon

Figure 5.6 Comparison between rectangular and circular model

Figure 5.7 True stress versus true plastic train relationship for AS, AN and NM

Figure 5.8 Test and analytical stress versus cross-section change for AS, AN and NM

Figure 5.9 Comparison between simulated results using peak stress and 90% peak stress as the end point for T1-5

Figure 5.10 Comparison between simulated results using peak stress and 90% peak stress as end point for T3A-R3.5

Figure 5.11 Test and simulated results for T1-R1.5 and T1-2

Figure 5.12 Test and simulated results for T1-2 and T1-3

Figure 5.13 Test and simulated results for T1-R3.5 and T1-4

Figure 5.14 Test and simulated results for T1-5 and T1-6

Figure 5.15 Test and simulated results for T1-7 and T1-11

Figure 5.16 Variation of n across the weld region

Figure 5.17 n versus ultimate to yield strength ratio

Figure 5.18 Variation of C across the weld region

Figure 5.19 C versus ultimate to yield strength ratio

Figure 5.20 n and C relationship

Figure 5.21 True stress versus true plastic strain relationship of the material for T1 plate

Figure 5.22 True stress versus true plastic strain relationship of the material for T3A plate

Figure 5.23 True stress versus true plastic strain relationship of the material for T3 plate

Figure 5.24 True stress versus true plastic strain relationship of the material for T5 plate

Chapter 6 Summary, Conclusions and Recommendations

6.1 Summary

The research in material modeling and behavior studies of weld and regions around the weld are reviewed in Chapter 2. Various factors affecting the material properties of the weld region were also discussed. However, in most of the studies reviewed, the main focus was on the determination and variation of yield strength, ultimate strength and hardness of the weld and regions around the weld. There are very few studies carried out to establish the true stress versus true strain relationship of the material across a weld.

This research study looked at the variation of ultimate strength, ductility and stress versus deformation relationship. But the main focus of the research is on the true stress versus true strain relationship across a butt weld. The material properties and their variation across the weld region were investigated by testing small tension coupons.

Coupons of 5.9 mm to 6.0 mm in width and 1.9 mm to 2.25 mm in thickness were fabricated from 15.9 mm, 19.1 mm and 25.4 mm thick butt welded plates. These coupons represent regions around the weld. There were a total of forty seven coupons used in the study. Tests were carried out with regular stoppage for measuring static readings. The cross-section change was measured manually during testing with a digital caliper and digital micrometer.

Test results of each coupon were plotted against the distance from the weld edge in order to see the variation in material properties. Results were discussed and comparisons were made for different regions around the weld.

Numerical modeling and simulations of round specimen using the axisymmetric element were carried out with commercial finite element software ABAQUS (2002). A simple function that was able to generate the true stress versus true plastic strain relationship of the material directly using tension test results was proposed and discussed.

Studies on the finite element mesh and cross-section shape effect were carried out. The cross-section shape effect study showed that modeling can be carried out with a round specimen instead of a rectangular specimen. Comparisons were made between the measured engineering stress versus change in cross-section area data with that from the numerical simulation using the true stress versus true plastic strain relationship from the proposed function. The variation of the parameters for the function and the true stress versus true plastic strain relationship were also discussed.

6.2 Conclusions

A number of significant conclusions have been drawn from the test results and numerical studies.

- 1) Overall, the study shows that welding has an effect on the material properties of only a small region around the weld, which is about 6 mm from the weld edge in this study. There is greater variability in the material properties for the weld metal and heat-affected zone than the base metal.
- 2) Test results show that the ultimate strength is not constant across the weld region. There is an increase in the ultimate strength at the heat-affected zone due to the intense heat generated during welding and the uneven cooling. The ultimate and

yield strength increases going from the base metal to the weld metal, but the ultimate to yield strength ratio decreases.

- 3) In the present study, there is a general decrease in ductility at the heat-affected zone and at the weld compared to the base metal. Overall, the ductility is relatively high at all regions.
- 4) There is a slower increase in strength during strain hardening for weld metal and heat-affected zone compared to the base metal.
- 5) The proposed simple function is able to approximate the true stress versus true plastic strain relationship with reasonable accuracy when calibrated against test data until the peak stress. However, the approximation of the true stress versus true plastic strain relationship can be further improved by calibrating the function against test data up to 90% of the peak load point beyond the peak.
- 6) The value of n is close to 5 for weld metal and heat-affected zone and around 4.5 for the base metal. The parameter C varies from 0.02 at the base metal to 0.055 at the weld metal. A higher n and C at the weld metal indicates a slower rate of strength increase in strain hardening compared to the base metal. Two equations were developed to relate parameters C and n to the ultimate to yield strength ratio.

6.3 Recommendations

- 1) The present study only looks at butt weld. More studies should be carried for different material, weld configurations and sizes.
- 2) The accuracy and resolution of the cross-section dimension measurement should be improved so that smaller coupons can be tested. A smaller coupon will allow

for more specimens to be fabricated and will be able to better capture the variation of material properties across the weld.

- 3) More tests should be conducted on coupons close to the weld edge so that the variation at the heat-affected zone can be better quantified.
- 4) Plates with the same chemical composition should be used to study the thickness factor. Plates of different thicknesses should be milled from the same plate.
- 5) More studies should be carried out to characterize the variation of the true stress versus true plastic strain relationship including the parameters for the proposed function.
- 6) The procedure in calibrating parameters for the proposed function should be modified to improve the approximation of the true stress versus true plastic strain relationship. The current procedure generally approximates a true stress versus true plastic strain relationship that overestimate the stress after the peak load in the stress versus deformation curve. Sensitivity studies should also be carried out for parameters C and n .
- 7) Material properties also vary through the thickness. This aspect of properties variation needs to be investigated.
- 8) Numerical analyses of welded connections incorporating the variation of material properties around the weld should be carried out and compare to the test results.

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Appendix A-Yield and Ultimate to Yield Strength Ratio

Table A.1 Yield and ultimate to yield strength ratio of T1 plate

Coupon	Distance from weld edge mm	Ultimate strength σ_{ult} MPa	Yield strength σ_y MPa	Ultimate / Yield strength ratio σ_{ult}/σ_y
T1-R1.5	-8.00	574.6	520.0	1.1051
T1-2	-6.00	568.7	525.4	1.0826
T1-3	-2.00	592.1	525.2	1.1274
T1-R3.5	0.00	585.3	535.3	1.0934
T1-4	2.00	569.0	443.3	1.2836
T1-5	6.00	545.7	373.3	1.4618
T1-6	10.00	547.9	370.4	1.4793
T1-7	14.00	544.2	366.6	1.4847
T1-11	Base metal	553.1	387.9	1.4259

Table A.2 Yield and ultimate to yield strength ratio of T5 plate

Coupon	Distance from weld edge mm	Ultimate strength σ_{ult} MPa	Yield strength σ_y MPa	Ultimate / Yield strength ratio σ_{ult}/σ_y
T5-R1.5	-8.00	524.4	476.8	1.0998
T5-2	-6.00	565.6	489.7	1.1548
T5-R2.5	-4.00	540.7	468.5	1.1541
T5-3	-2.00	543.3	425.6	1.2765
T5-R3.5	0.00	570.2	486.2	1.1726
T5-4	2.00	537.9	395.5	1.3601
T5-5	6.00	531.5	369.4	1.4386
T5-7	14.00	523.8	363.0	1.4429

Table A.3 Yield and ultimate to yield strength ratio of T3 plate

Coupon	Distance from weld edge mm	Ultimate strength σ_{ult} MPa	Yield strength σ_y MPa	Ultimate / Yield strength ratio σ_{ult}/σ_y
T3-R25	-4.00	584.3	526.9	1.1088
T3-3	-2.00	582.3	513.3	1.1344
T3-4	2.00	606.7	527.7	1.1498
T3-5	6.00	526.8	404.1	1.3036
T3-6	10.00	518.0	358.8	1.4436
T3-7	14.00	503.7	353.4	1.4251
T3-10	35.00	514.4	366.6	1.4031

Table A.4 Yield and ultimate to yield strength ratio of T3A plate

Coupon	Distance from weld edge mm	Ultimate strength σ_{ult} MPa	Yield strength σ_y MPa	Ultimate / Yield strength ratio σ_{ult}/σ_y
T3A-2	-6.75	517.9	451.8	1.1463
T3A-3	-2.75	536.4	477.7	1.1230
T3A-R35	0.75	490.6	410.7	1.1945
T3A-4	2.75	560.6	473.7	1.1836
T3A-R45	4.75	536.0	400.3	1.3391
T3A-5	6.75	518.7	391.1	1.3262
T3A-R55	8.75	513.4	373.1	1.3760
T3A-6	10.75	513.3	362.3	1.4168
T3A-R65	12.75	504.7	348.7	1.4473
T3A-7	14.75	514.0	356.6	1.4413
T3A-8	18.75	510.2	349.7	1.4588
T3A-10	Base metal	510.8	363.0	1.4072

Appendix B-Stress Versus Deformation Graphs

Figure B.1 Engineering stress versus deformation relationship for T3-5 and T3A-5 coupons

Figure B.2 Engineering stress versus deformation relationship for T3-6 and T3A-6 coupons

Figure B.3 Engineering stress versus deformation relationship T1-R1.5 to T1-4

Figure B.4 Engineering stress versus deformation relationship T1-5 to T1-11

Figure B.5 Engineering stress versus deformation relationship T3A-3 to T3A-R4.5

Figure B.6 Engineering stress versus deformation relationship T3A-5 to T3A-R6.5

Figure B.7 Engineering stress versus deformation relationship T3A-7 to T3A-10

Figure B.8 Engineering stress versus deformation relationship T5-R1.5 to T5-3

Figure B.9 Engineering stress versus deformation relationship T5-R3.5 to T5-7

Figure B.10 Engineering stress versus deformation relationship T3-R2.5 to T3-5

Figure B.11 Engineering stress versus deformation relationship T3-6 to T3-10