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Friction Stir Welding of High-Strength Automotive Steel

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FRICTION STIR WELDING OF HIGH-STRENGTH AUTOMOTIVE STEEL

by

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FINAL READING APPROVAL

I have read the thesis of Eric M. Olsen in its final form and have found that (1) its format, citations and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials include figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

FRICTION STIR WELDING OF HIGH-STRENGTH AUTOMOTIVE STEEL

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The following thesis is a study on the ability to create acceptable welds in thin-plate, ultra-high-strength steels (UHSS) by way of friction stir welding (FSW). Steels are welded together to create tailor-welded blanks (TWB) for use in the automotive industry. Dual Phase (DP) 590, 780, and 980 steel as well as Transformation-Induced Plasticity (TRIP) 590 steel with thicknesses ranging from 1.2 mm to 1.8 mm were welded using friction stir welding under a variety of processing conditions, including experiments with dissimilar thicknesses.

Samples were tested under tensile loads for initial determination if an acceptable weld had been created. Acceptable welds were created in both TRIP 590 and DP 590 at speeds up to 102 centimeters-per-minute. No acceptable welds were created in the DP 780 and DP 980 materials.

A series of microhardness measurements were taken across weld samples to gain understanding as to the causes of failure. These data indicate that softening, caused by both excessive heat and insufficient heat can result in weld failure. Not enough heat causes the high concentration of martensite in these materials to temper while too much heat can cause excessive hardening in the weld, through the formation of even more martensite, which tends to promote failure mode during forming operations.

Laser welding is one of the leading methods for creating tailor-welded blank. Therefore, laser welded samples of each material were tested and compared to Friction Stir Welded samples. Lower strength and elongation are measured in weld failure while the failure location itself determines the success of a weld. In short, an acceptable weld is one that breaks outside the weld nugget and Heat Affected Zone (HAZ) and where the tensile strength (both yield and ultimate) along with the elongation are comparable to the base material. In unacceptable welds, the sample broke in the weld nugget or HAZ while strength and elongations were well below those of the base material samples.

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1.1. Background

1.1.1. Tailor Welded Blanks

Tailor-welded blanks are rapidly gaining popularity in the automotive industry as they allow materials that may be different in thickness or material properties or both, to be combined in a single pressed and stamped part in order to improve product performance. The improvement comes in many ways to both the individual parts and to the overall automobile. Initially, the main goal for tailor-welded blanks was to reduce the weight in attempts to meet fuel efficiency standards. The majority of weight savings is achieved by using thick material in locations that require the higher strength but thinner material in areas that do not, instead of thick material for the whole part. Additional benefits that result from using tailor-welded blanks include a decrease in noise from the vehicle, a reduction in material waste and decreased stamping costs. Noise is reduced as more of the car is welded together in a rigid weld rather than bolted, riveted or spot welded (Kochan, 2004). Waste is reduced by using thinner material in some areas and by not using any material in large openings. Stamping costs are reduced because fewer stamps, dies and forming operations are required for the same parts (Gerdel, 2000). Research into tailor-welded blanks found other benefits which include lower part count, improved dimensional tolerances, increased part stiffness, reduced manufacturing costs, improved corrosion resistance and reduced vehicle vibration.

1.1.2. Laser Welding Tailored Blanks

Tailor-welded blanks in the United States rely almost exclusively on laser welding. Laser welding is fast, precise, reliable and able to join a wide variety of materials, both varying in thickness and type. Typically, laser welding is able to weld from 3.4 – 4.6 meters (12 – 15 feet) per minute depending on various parameters. Laser welders are almost exclusively controlled by robot and have near 100 percent uptime (Kochan, 2004). The speed and reliability of lasers make them the current method of choice for the creation of tailor-welded blanks.

Lasers, however, are not perfect for every application. Laser welding does have some drawbacks and limitations in the creation of tailor-welded blanks. One main drawback is the required edge tolerance to create a functional weld. Laser welds are so narrow and run at such high speeds that a high level of precision is required. The edge tolerance for production welding must be within .08 mm (Rooks, 2001). Tolerances are so small in production applications that custom precision shears or other specialty tooling is required to ensure these tight tolerances. With these required tolerances the weld lines are generally restricted to linear welds. A second problem with laser welding is that the weld zone has a high hardness which is prone to brittle failure during the forming operations that tailor-welded blanks undergo. Tailor-welded blanks are press formed after welding and the location of the weld must be considered when designing the tailor-welded blank. The optimum use of materials is not realized because designers are forced to design the tailor-welded blank around each weld location. Another difficulty is that some materials are very difficult or impossible to weld by laser welding. Some high DP steels, TRIP steels, quiet steels (a sandwich of steel and plastic), and aluminums are not suited to laser welding. A final drawback is that laser welding machines are relatively expensive and only economical for very large volume production.

1.1.3. Friction Stir Welding

Friction stir welding is a relatively new technology with many potential applications. It was invented by The Welding Institute in 1990 (Cook, 2004) and patented in 1991 (Seidel, 2003). Since then many studies and real-world applications have demonstrated certain areas of high potential for the use of friction stir welding. Some of these areas include aerospace, automotive, railroad, shipbuilding, construction, electrical and pressurized gas tank industries (Cook, 2004). Despite the research taking place there is more that can be studied.

Friction stir welding is a solid state joining process in which a rapidly rotating tool stirs and forges two parts together at a seam or overlap. Friction stir welding first began in softer, lower temperature materials, namely aluminum. Lower temperature materials can be welded with tool steel, generally using H13. Since then, further research and development has made it possible to weld steels, stainless steels, and titanium. These higher temperature materials cause a high level of heat and force during welding and require different materials for the tools. It took the development of Polycrystalline Cubic Boron Nitride (PCBN) tools to allow welding in these harder materials (Sorensen, 2007). Friction stir welding produces higher quality welds with fewer defects and material properties closer to the parent material than most other welding processes. In addition, because friction stir welding is performed below the melting temperature, protection requirements are greatly reduced. The need for radiation protection is eliminated. In addition, friction stir welding is much more forgiving with regards to the edge quality when creating a functional weld. The material being welded is stirred together; therefore small gaps can often be filled. These reasons make this welding process suitable for many applications.

1.1.4. Laser versus Friction Stir Welding

Laser welding has been used effectively in the creation of tailor-welded blanks for the automotive industry. However, this industry is extremely competitive and further improvements are required to stay competitive. Although laser welding has been effective thus far it does have limitations including the required edge tolerance, poor weld properties, inability to join some materials and the cost of the machines. Improvements are forthcoming but some limitations, inherent to the process, will be very hard to overcome to create an optimum tailor-welded blank. For this reason other methods should be explored. Friction stir welding is one method that should be researched because it counters the main drawbacks exhibited in laser welding. The ability to weld some materials that cannot be laser welded appears promising for friction stir welding but must be studied on a per-material basis.

Friction stir welding, however, is not without its own limitations. Presently travel speeds are much slower than laser welding. In aluminum, a softer and more researched metal, welds can be run up to 108 cm/min (43 in/min) depending on the thickness of the material. Welds in steel are run and lower speeds. Parts also require a fairly large clamping force to withstand the torque generated during the friction stir welding process. With improvements and research these drawbacks may be reduced or eliminated. Friction stir welding machines cost a fraction of a laser welding machine allowing more flexibility and possibly a greater net welding speed per cost. For these reasons the processing feasibility of friction stir welding in the creation of tailor-welded blanks will be studied.

1.2. Problem

The problem that this study addresses is that laser welding has limitations in the creation of tailor-welded blanks, both in formability and the capacity to acceptably weld certain desired materials. Specifically Ultra-high-strength steels are difficult to weld. In addition, the reduction in ductility becomes troublesome in the forming operations for which tailor-welded blanks must undergo. Previous studies have shown promise of increased ductility in friction stir welds over laser welds. However, for friction stir welding to be a viable alternative in the creation of tailor-welded blanks it must produce a weld equal to or better than that of laser welding, in both strength and ductility, and do so within economic restraints.

1.3. Thesis Statement

This thesis will investigate whether friction stir welding can produce acceptable welds in Dual Phase (DP) 590, 780, 980, and Transformation-Induced Plasticity (TRIP) 590 steels. An acceptable weld is defined here as a weld which does not fail in the heat affected zone or in the weld nugget during transverse tension testing. Friction stir welded samples will be compared to both the base material and laser welded samples.

1.4. Significance of Study

The ever increasing competition in the automobile industry forces companies to constantly seek for improvements in design, construction and performance. Tailor-welded blanks are making a large impact on the construction of automobiles to improve overall performance. Tailor-welded blanks are currently limited to some degree by the laser welding process due to low tensile elongation of laser welds and difficulty in joining some alloys. Therefore, other options should be explored to further improve the creation and use of tailor-welded blanks. If friction stir welding is determined to be a technically feasible welding process for creating tailor-welded blanks then further improvements in the tailor-welded blank design, material options and creation might be possible.

1.5. Procedure of Study

The procedure for this study consists of four major steps repeated for the different material combinations. The first step is the preparation of the samples. This will include cutting samples to size, removing zinc coatings when necessary, and removing oxide layers. The second step is to weld the samples with the desired parameters. The third step is testing the samples. This will include tension and microhardness tests. Both tests have required preparation. The fourth step is an analysis of the test data. The test data will indicate cause for failure and maximum performance before failure. This four step process will be repeated under various processing parameters.

1.6. Delimitations

The quality and properties of the welds will be determined based on tensile and microhardness testing. The welding and testing will be performed at Brigham Young University and at Megastir Technologies. Not every possible combination of welding parameters will be tested.

The study will be limited in some ways.

1. The materials combinations studied will be limited to
    a. TRIP 590 CR, where CR designates the steel as cold rolled, to same
    b. DP 590 welded to TRIP 590 CR
    c. DP 590, 790 and 980 welded to the same material
2. Thickness will vary with the material
    a. DP 590 is 1.8, 1.6, 1.4 and 1.2 mm
    b. TRIP 590 CR is 1.6 mm
    c. DP 790 and DP 980 are 1.4 and 1.2 mm

Material properties will be tested at BYU and will include standard methods which will be discussed in Chapter 3. Actual metal stamping and press forming will not be done. In addition, no economic analysis will be performed to determine economic feasibility, only that faster travel speeds will make economic feasibility more likely. A full study of post-weld microstructure will not be performed but some limited investigation will be carried out.

2. Review of Literature

2.1. Tailor Welded Blanks

2.1.1. History

In the 1970's oil shortages put pressure on the automotive industry to improve gas mileage and reduce carbon dioxide emissions (Ashley, 1997). Recently, there has been a renewed effort to develop fuel efficient vehicles while at the same time improving passenger safety and reducing costs. The simplest solution to meeting fuel efficiency standards is through the reduction in the overall weight of the vehicle. It is estimated that a 1% reduction in vehicle weight results in a .6 – 1% reduction in fuel consumption (Pallett, 2001). Since 1970 the average weight of an automobile has decreased 1000 pounds (Ashley, 1997). Much of this weight savings was simply designing a lighter car. The automotive industry is very competitive, and with government regulations for emissions and the increasing demand for fuel efficient vehicles, further reductions in vehicle weight are being pursued. In the mid 1980's, attempts to lower vehicle weight led automotive manufactures to look for other ways to reduce weight. The two main options to reducing weight were by either using lighter materials or simply using less of the same material. Two applications of these attempts include implementing aluminum in place of steel and through the use of Tailor-Welded Blanks (TWB). Of these two, tailor-welded blank have found the most use in the automotive industry.

When tailor-welded blanks were first used in production is somewhat unclear. In 1967 Honda tried to use a tailor-welded blank for a body side ring but the creation of tailor-welded blanks were too costly with available welding processes at the time. One source stated that full production of tailor-welded blanks started in 1985 in Germany for the Audi 100 (Rooks, 2001). Another source indicates that in the early 1980's tailor-welded blanks were used in the Audi 80 (Pallett, 2001).

The tailor-welded blank industry is growing at an ever increasing rate. In 1993 usage in Europe was about 3 million blanks, reaching 50 million by 2000 (Pallett, 2001). One estimate puts the worldwide use of tailor-welded blanks at 150 million blanks per year by 2007 (Kubel, 1997). Another states a usage of 15 million in 1997 and estimates 40-60 million by 2000 (Das, 2000). A fourth source indicated 50 million were used in Europe in 2000 and could reach 80 million by 2001. It was also stated that usage in the United States was 30 million in 2000 (Rooks, 2001). A final source listed usage in North America at 20 million in 1999 and projected use at 90 million by 2005 (Auto/Steel Partnership, 2005). One source listed that in the year 2000 GM had 20 body parts made from tailor-welded blank while DaimlerChrysler had 18 and Ford had 10 (Gerdel, 2000). Another listed these figures for the same year at 65 and 50 for General Motors and DaimlerChrysler, respectively (Auto/Steel Partnership, 2005). The cause for this difference is not apparent. Figure 2-1 illustrates a sample of automotive part that can be created using tailor-welded blanks instead of single gauge stamping.

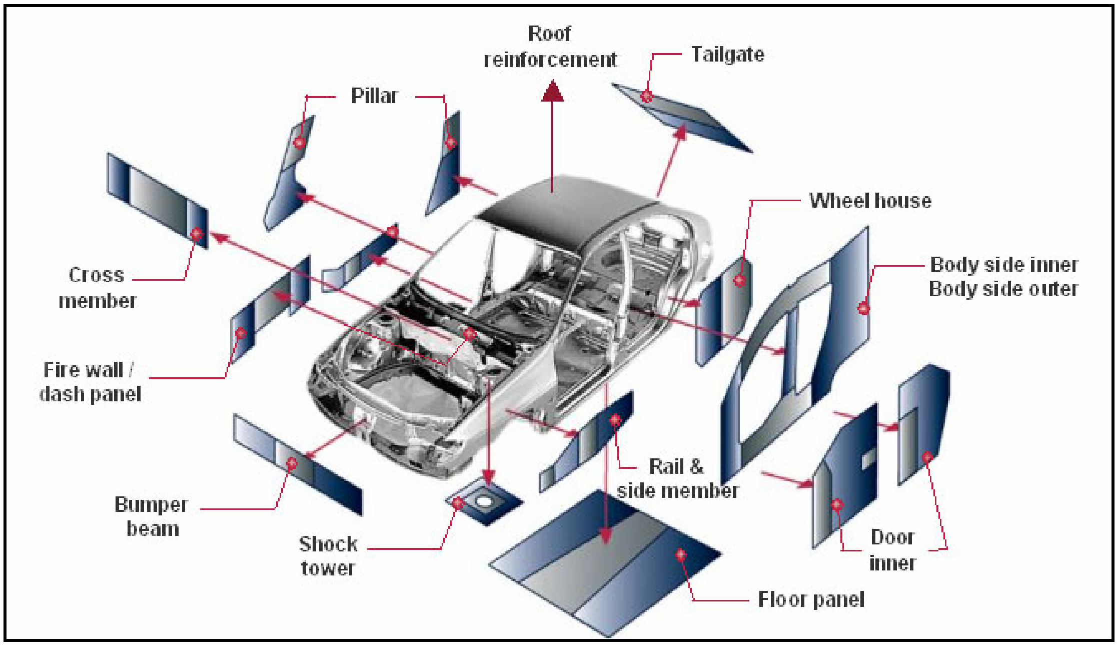

Figure 2-1 Automotive part applications for tailor-welded blanks (Tailor Steel)

2.1.2. Process

In the automotive industry many parts were traditionally formed by taking a single type and thickness of sheet steel and then press forming and stamping that sheet into the desired shape. In fact, 78% of the structural parts were made by this process (Schurter 2002). This process works but is not optimal. This process is limited by the variety of material properties available in a single part. In many instances different material properties were more advantageous for separate areas. This could only be achieved by using multiple parts that were later assembled or through compromises in part efficiency. Often, materials with the greatest strength were used even if large areas of the same part did not require those demanding properties. In the case of reducing vehicle weight, the biggest waste is using a thicker gauge material for a whole part when only small areas need the strength which that gauge provides.

Tailor-welded blanks offer a solution. A tailor-welded blank is formed by welding two or more sheets of materials that differ by gauge, coating, strength or other material properties into a single sheet. These sheets are then press formed and stamped into the desired part. The welding is currently done by either laser or mash seam welding. Laser welding is dominant in the United States while mash seam welding is more popular in Europe. These tailor-welded blank parts can make up much of the Body In White (BIW), the main structure and body of an automobile.

2.1.3. Benefits

There are several benefits for implementing tailor-welded blanks. These include reduced weight, reduced scrap, lower part count, improved dimensional tolerances, increased stiffness, reduced manufacturing costs, improved corrosion resistance, reduced vehicle vibration and more. Each of these benefits improves the overall performance and quality of the vehicle. These benefits can be magnified through the use of non-linear weld lines when designing the blanks (Kochan, 2001). Currently this is difficult because the precision required in the parts to be welded is much harder to achieve in non-linear cutting.

- **Reduced weight** - Reduced weight was the main motivation for using tailor-welded blanks. Initially, tailor-welded blanks mainly targeted parts that required strength in some locations but not in others, such as doors. The doors require much more strength at the hinges and latches than in other areas. These were targeted by tailor-welded blanks because the manufacturers can allocate thicker or stronger material near the hinges and latches, but thinner material for the rest of the part. As mentioned above, a

1% reduction in weight allows a .6-1% improvement in fuel efficiency (Pallett, 2001). Another source estimated that every pound or weight reduction provided either a savings of $2 or allowed break-even manufacturing costs to increase by $2 (Auto/Steel Partnership, 2005).

- **Reduced scrap –** Scrap can be reduced when the tailor-welded blank is welded together leaving open spaces (e.g. a window). If cut from a standard rolled sheet these open spaces would be scrap. Also, improved part tolerances (due to elimination of tolerance stack up) reduce the number of scrapped parts.
- **Reduced part count –** The total number of parts is reduced as multiple parts can be combined that include a variety of material properties into a single part. Lower part count often reduces assembly time and material handling costs.
- **Improved dimensional tolerances –** Tolerances are improved through combining parts so tolerance stack-up is reduced and part stiffness is improved.
- **Improved vehicle stiffness –** This improvement is achieved as a side effect from fewer parts, tighter tolerances and stronger parts. In 1997 the Ultra Lite Steel Auto Body (ULSAB) partnership estimated that using tailor-welded blank could improve torsional rigidity by up to 65% (Kubel, 1997).
- **Reduction in overall manufacturing costs –** This reduction is possible due to less material usage, less scrap (reducing material costs), reduced

part count (reduced assembly and material handling costs) and improved dimensional tolerance (reduced assembly and scrap rates). General Motors estimated that they saved between $4.9 and $6.3 million on a tailor-welded inner door panel (Kinsey, 2000). Other manufacturing cost reductions can be achieved by reducing the number of stamping dies that are required to be designed and built (Gerdel, 2000).

- **Improved corrosion resistance –** Corrosion resistance is achieved through the elimination of lap joints (prone to corrosion) and the ability to target areas that require corrosion resistance with material providing that property.
- **Reduced vehicle vibration –** Overall vehicle vibration is reduced through a combination of reduced part count, eliminating some spot welds, and the improved stiffness of the overall vehicle due to lower part count and better material properties. In the same statement from ULSAB, they estimated a possible 35% improvement in vibration behavior (Kubel, 1997). This lower body vibration can also eliminate the need for sound reduction pads which further lowers cost and part count (Rooks, 2001).
- **Improved safety –** A stronger and more rigid BIW improves overall safety (Krizan, 2003) and crash durability through increased stiffness (Jiang, 2004).
- **Improved styling options –** With fewer parts and surface interruptions there is an opportunity to improve the aesthetic design of the car (Jiang, 2004).

- **Reduced design effort –** Fewer parts equals fewer dies that need to be designed and built. Although design time for the larger part increases it is generally lower than the sum of the many parts that it replaced (Jiang, 2004).

2.1.4. Ultra Light Steel Auto Body

The Ultra Light Steel Auto Body (ULSAB) consortium consists of 35 steel companies from 18 countries. Its goal has been to reduce the weight and improve the safety of the Body in White (BIW). The $22 million project achieved dramatic results. When compared to the average of 32 comparable cars, ULSAB was able to achieve a 25% reduction in weight, an 80% increase in torsional rigidity, and a 52% increase in bending resistance. The estimated cost to make the ULSAB BIW was $947 compared to $1116 for a traditional BIW. These improvements were achieved by using HSS, UHSS, steel sandwich, tailor-welded blanks and hydroforming. Over half of the mass of the BIW was made out of tailor-welded blanks (World Auto Steel, 2005).

2.1.5. Drawbacks and Limitations

The many benefits of tailor-welded blank are not without some problems or limitations. Currently laser welding is the main method for creating tailor-welded blank. The main problem with laser welding comes in the forming operations. Forming limitations subsequently increase the time and cost for designing both the tailor-welded blank as well as reducing the efficiency of the design. Cost is a concern in all manufacturing operations and reductions of cost are always desired. These main drawbacks and other secondary ones are discussed below.

- **Forming failures –** Due to differing material properties between the weld and the base material, problems, such as weld line movement and failure in the weld nugget or accompanying heat affected zone (HAZ), may arise. Weld line movement results when the thicker and usually stronger material does not stretch as much as the thinner material. This can cause tearing or wrinkling in the thinner material (Kinsey, 2000). One study showed, by use of dome tests, that the formability of tailor-welded blanks are reduced 8-22% compared to base materials (Kinsey 2004).
- **Along-weld stretching –** Forming operations that stretch the weld along the weld line are especially problematic because the changes in the material properties are magnified for the whole length of the weld instead of a small transverse area. Elongation along the weld line can be reduced to half of that of the base material (Kinsey, 2000).
- **Design consideration –** Special consideration must be designed into the tailor-welded blank and the forming operations to ensure quality parts are produced. The change in the base material properties, due to the laser welding process, limits the advantage of a tailor-welded blank (Kinsey, 2000). The design of the tailor-welded blank requires time and money and the design is not fully optimized due to the forming limitations. If blank design can be further optimized, larger improvements can be achieved. In most applications, simple linear welds are employed which use excess thick material when thinner material would suffice. Curved welds would be better but are more difficult to implement.

- **Design optimization –** Using curved welds is difficult due to the required edge tolerances of laser welding. Cutting the pieces to match before welding is very difficult and costly. Since curved welds are difficult, linear welds are usually employed but do not optimize material usage. In addition, the weld itself not optimally placed because the weld cannot undergo the forming operations without failure and is therefore placed in a location of lower strain. There is much room for improvement if curved welds can be used and located more optimally. Thyssen Fügetechnik GmbH in Germany has been making Thyssen Engineered Blanks which are essentially tailor-welded blanks with curved laser welds instead of straight line welds. This allows the engineers to create better blanks because they have more control over material placement and weld positioning. They reported that some components have a much higher weight savings potential with Thyssen Engineered Blanks than with tailor-welded blanks. One example was a door panel which achieved a 34% weight savings with a Thyssen Engineered Blanks while only 18% with a tailor-welded blank. Thyssen estimates that 25 to 30% of tailor-welded blanks used in the future will be of the TEB variety (Benedyk, 2000).

These drawbacks are not inherent to tailor-welded blanks but to the process used to make them. One method to improve the benefits of tailor-welded blank is to reduce the difference between the base material properties and those of the weld and HAZ. This would provide better forming properties and allow more optimized tailor-welded blanks to be designed.

2.1.6. Tailor-Welded Blank Failure Modes

The closer the material properties of a weld are to those of the base material the better. Comparable ductility, sheet flatness, narrow weld zone and fatigue endurance are attributes of a good weld (Draugelates, 2000). The failures of tailor-welded blanks occur by necking, tearing or wrinkling in the formed part. In almost all cases the failure occurs in the thinner of the two materials (Meinders, 2000). Necking and tearing are caused from reduced strength and ductility of the weld or HAZ. The weld zone is often the site for cracking due to lower plasticity than the base metal (Jiang, 2004). Weld line movement is an indicator that the blank is nearing failure (Kinsey, 2004). Weld line movement is caused by the stronger material not stretching as much as the thinner material. Springback or non-permanent shape change is also a failure mode in the tailor-welded blank (Jiang, 2004). Desired weld attributes, simply stated, are to maintain as much of the base material properties as possible (Ono, 2002).

2.1.7. Testing Methods

Tension, limiting dome height and microhardness tests are good tools to determine the quality and formability of a material or welded sample. Tensile tests are a simple check to determine the tensile and yield strength and elongation of a material while determining where a material will fail. Microhardness tests determine the hardness of the sample and can often explain the forming characteristics or reason for weld failure. In this case the material is tested across the weld zone to determine the hardness at different points and compare them to the base material. Large changes in hardness can be the cause for failure during forming operations.

2.2. Material Considerations

An attempt to reduce the weight of an automobile is very much dependent upon material selection. Steel has widely been the material of choice in auto body parts due to its cost, strength, joinability and the extensive experience in forming it. Another benefit is that steel is easy to recycle (Lee, 2003). Aluminum has been used to some extent due to its low density, but at much lower production volumes than steel.

2.2.1. Steel Overview

Steel has been the material of choice due to low material cost and relative ease of forming. Rolled steel is the least expensive structural metal costing $.77 per kilogram ($.33 per pound) compared to $3.30 per kilogram ($1.50 per pound) for aluminum (Ashley, 1997). High Strength, Ultra High Strength, Dual Phase and Transformation Induced Plasticity steels are providing the best benefits in this use as the increased strength allows thinner material to be used. Specifically, DP and TRIP steels have increased formability over traditional steels. Forming operations for steel have a long history and are fairly well understood. Welding steel is relatively simple compared to most other metals. The welding operation and requirements are generally well known. These include the operating parameters, material preparation requirements and other conditions.

2.2.2. Steel Phase Change

Steel has many possible microstructures which determine its properties. There are many different steel alloys and each has a distinct phase diagram. These diagrams indicate the temperatures and times that will form certain microstructures in the metal.

Those microstructures not only are produced when first forming the metal but are modified at any time if the temperature is high enough. In welding the temperature is high enough to cause changes in the material. Depending on how high the temperature gets and how long it remains elevated, different microstructures can form. When temperature is raised high enough, in a material with a carbon equivalent greater than 0.1 percent, martensite will form. One of the most common microstructures in a steel weld is martensite. Martensite is harder and less ductile than most base materials. This is good for creating a strong joint but can be detrimental because of the low ductility if the weld undergoes strain during a forming operation.

2.2.3. Steel Classes and Nomenclature

Over 2000 different types of steels have been formulated. These are based on different alloying, forging parameters and material properties (Prange, 2003). How to designate steels and some of the more common steels used in tailor-welded blank are as follows:

- **NOMENCLATURE –** The designation for a type of steel is as follows: XX-AAA-BBB. Where XX is the type (DP, TRIP, Mild, IF, etc), AAA is the minimum yield strength, BBB is the minimum UTS in MPa (Flaxa, 2002). For this experiment, the minimum yield strength is not noted.
- **High Strength Steels (HSS) –** These steels have ultimate tensile strengths (UTS) from 220-550 MPa (Hartley, 2002)
- **Ultra-high-strength steels (UHSS)** – These steels have UTS greater than 550 MPa (Flaxa, 2002).

- **Dual Phase (DP) Steels –** DP steels are gaining popularity for use in tailor-welded blanks. They consist of mostly soft ferrite and hard martensite phases. They have UTS ratings from 450-1000 MPa (Hartley, 2002).
- **Transformation-induced Plasticity (TRIP) Steels –** TRIP steels have been gaining popularity because they have better forming characteristics than DP steels due to a precise two-step heat treating (Svensson, 2003). They consist of mainly ferrite, bainite, martensite, and retained austenite formations (Cretteur, 2003).

2.2.4. Aluminum

Aluminum is heralded for it low density resulting in reduced part weight. Aluminum is more expensive than steel (Ashley, 1997) and is much harder to weld (Benedyk, 2000). These limitations have greatly limited the use of aluminum in the creation of tailor-welded blank. Part of the welding difficulty results from the high reflectivity, high melting point of the oxide coating and high thermal conductivity of aluminum (Benedyk, 2000). Aluminum will not be studied but was included here for completeness.

2.3. Mash Seam Welding

2.3.1. History and Process

Mash welding has more popularity in Europe than in the United States, but is still used less than laser welding. In 1997, about 60% of the tailor-welded blanks made in Europe were made by mash welding (Kubel, 1997). It is a resistance forge process where two sheets are overlapped 1-1.5 times their thickness and then passed through copper electrode rollers that put immense pressure, while inducing a current, on the seam causing the welding to occur (Draugelates, 2000).

2.3.2. Benefits

Mash welding has the ability to be controlled in real-time and is more cost effective than laser welding. The equipment costs a little over half as much as a laser system. It produces about 1% scrap compared to 3-4% for laser systems. It also does not require tight edge tolerances (Kubel, 1997).

2.3.3. Drawbacks and Limitations

One drawback is that the weld itself thickens from 2-30% while laser welds do not thicken to any significant degree. This is important to consider and is often a problem in the later forming processes (Draugelates 2000). The weld and HAZ is generally about 10-15 mm wide which is much larger than the 1-2 mm for laser welding (Meinders, 2000). Another problem is that the HAZ of a mash seam weld softens and decreases material properties (Ono, 2002).

2.4. Laser Welding

2.4.1. History

Laser welding became a viable welding technique in the late 1980’s and for production in the early 1990’s (Svensson, 2003). It has emerged as the leading welding process in the creation of tailor-welded blanks (Rooks, 2001).

2.4.2. Process

The laser welding process is performed by using a laser to generate the heat required to melt and join the desired materials. Currently Carbon Dioxide (CO_2) and Neodymium Doped Yttrium Aluminum Garnet (Nd:YAG or YAG) are the leaders in the laser welding industry. CO_2 has been the outright leader until recently as Nd:YAG was developed and began gaining popularity. Differences between the two include a variety of things. CO_2 lasers cost about half as much as Nd:YAG lasers. YAG lasers are able to use a flexible fiber optic delivery system where CO_2 cannot. YAG lasers have a larger beam diameter and also require less expensive shielding gas than the CO_2 variety (Kubel, 1997). CO_2 lasers are more widely available and safer (Das, 2000). In either case the two pieces of material are cut and then butted up against each other. The laser then traverses the butt joint heating both sides to a melting point, using a shielding gas to reduce oxidation and then the material solidifies to form the weld.

2.4.3. Benefits of Tailor Welded Blanks

The ability for lasers to make high quality welds at high speeds has allowed lasers to become the leader in formation of tailor-welded blank. High up-time of laser welding equipment is also a key benefit. Speeds in production range from 5-10 m/min (200-394 in/min) with a more realistic average of about 6 m/min (236 in/min) for aluminum. This is greatly improved over TIG welding that reaches only about 0.25 m/min (10 in/min) (Benedyk, 2000). These figures vary greatly due to material type, thickness and other process parameters. This range is fast for a welding process although improvements are still being sought after. There are some differences in the welding process for steel versus aluminum due to the increased difficulty of welding aluminum. In either case the process is relatively fast and reliable at creating quality parts. One source listed laser welding equipment to have an up-time of 99.99% (Kochan, 2004). Finally, laser welding creates a very narrow weld and HAZ, which is a highly desirable characteristic of a weld (Raymond, 2003).

2.4.4. Drawbacks and Limitations

Laser welding does have some drawbacks when used to fabricate tailor-welded blanks using high strength steels. These problems include reduced material properties of the weld, high required edge tolerances and the cost of welding.

The material properties of the weld cause some problem in the forming processes of a tailor-welded blank. The weld nugget and the HAZ can have vastly differing material properties than the base material. This can make the press forming process difficult and unpredictable. In the case of laser welding steel, the weld and associated HAZ exhibit an increase in hardness while the elongation decreases (Benedyk, 2000). One study showed that although ultimate strength was maintained at 100%, the elongation decreased between four and six percent (Dodd, 1998). This may not seem like much of a reduction but it must be remembered that the weld itself is only a small fraction of the pulled specimen. The elongation of the weld itself is reduced far more than the 94-96% indicates. This reduced elongation can cause problems in the press forming process. It is especially problematic when the strain is along the weld. The performance of the weld and HAZ are “significantly less desirable from a forming standpoint compared to those of the base metal.” (Jiang, 2004). In the case of aluminum, the weld and HAZ undergo a reduction in hardness (Benedyk, 2000). Tensile strength in 6xxx grade aluminum is reduced 40% due to the softening of the HAZ (Kinsey, 2000). In either case, failure at the weld site is a concern that must be designed around. This takes time and leads to designs that are often not optimal for the part. These three problems need to be overcome in order to reach optimal levels in the formation and use of tailor-welded blanks.

An additional problem is the required edge tolerance for the materials that are to be joined. Gaps between the two parts must be kept at 0.1 mm or below in slower operations and below 0.05 mm in higher speed operations (Pallett, 2001). Another source stated that 0.1 mm tolerance was the maximum possible to ensure a quality weld (Kubel, 1997). This often requires precision sheers for cutting or additional processing to attain this tolerance. This is especially difficult in large parts where long edges are harder to keep within those tight tolerances. One suggested solution for this was through high speed milling machines that run from 20 to 80 meters per minute can provide the required edge tolerance and have the ability to mill both linear and curved edges (Kubel, 1997).

Some materials are very difficult, if not impossible, to weld via laser welding. Some types of aluminum (2xxx and 7xxx series), quiet steels and the high end of DP and TRIP steels are very hard to laser weld. Also some combinations such as steel to aluminum cannot be done with a laser (Prange, 2003).

Cost is another limitation. A laser welding machine is very expensive as far as welding equipment goes. A laser welding machine can cost five times as much as a friction stir welding machine. Along with the cost of the machine is the cost of running the machine. One factory stated that 150 YAG lasers on the production line required 47 MW to run between generating the laser and the accompanying cooling systems (Kochan, 2004). Another source listed a single YAG laser requiring 350-400 kWatts for operations (Haake, 2004). Shielding gas is also costly in some applications for laser welding but is reduced in friction stir welding. In a comparison of YAG versus CO_2 the YAG costs more to operate by about 50% but does not require the expensive shielding gas. The YAG process is a little faster and it is estimated that after everything is taken into account the YAG process costs about 25% less than CO_2 (Dodd, 1997). Average costs for welding either steel or aluminum are estimated at $2.00 per meter ($.05/inch) for linear welds and $3.00 per meter ($.075/inch) for contoured welds (Das, 2000). Another source estimated the welding cost to be £2.00 per meter ($.08/inch) (Pallett, 2001).

2.5. Friction Stir Welding

2.5.1. History and Process

Friction stir welding (FSW) was patented in 1991 by The Welding Institute (TWI) (Seidel, 2003). Friction stir welding is a solid state joining process in which a rapidly rotating tool stirs and forges two parts together at a seam by a combination of heating and mechanical work. In thinner materials the majority of the heating comes from the friction of the shoulder on the part. As thickness increases more of the heat is generated by the probe that adds mechanical work to the material (Thomas, 2003).

Friction stir welding first started in softer, lower melting point materials like aluminum, but further research and development has made it possible to weld higher melting point materials including a variety of steels, including high strength steels, magnesium, titanium, copper and 2xxx and 7xxx grade aluminums that are impossible to weld by laser welding (Klein, 2003). Figure 2-2 shows a brief explanation of the friction stir welding process.

For welding softer materials, such as aluminum, the non-consumable tool can be made of HS steels. For welding HS steels and other harder materials, Polycrystalline Cubic Boron Nitride (PCBN) tools were developed in 1998 (Sorensen, 2007).

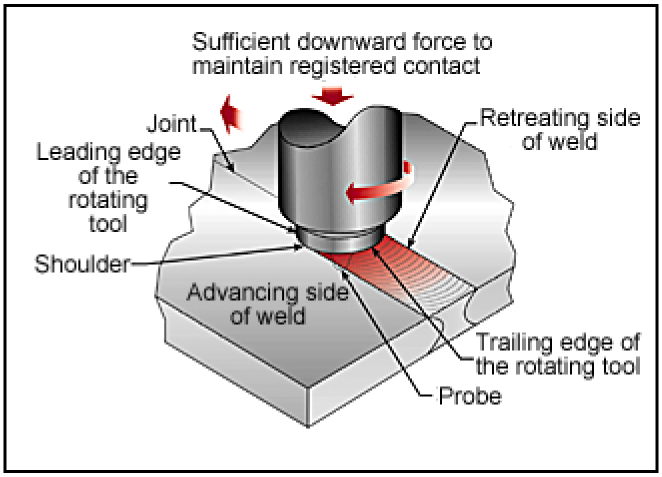

Figure 2-2 Explanation of friction stir welding process

Friction stir welding has potential use in many industries. The number of licensed users of friction stir welding grew from 20 to about 96 between 1998 and 2003 (Klein, 2003). Possible uses include aerospace, automotive, railroad, shipbuilding, construction, electrical and pressurized gas tank industries (Cook, 2004).

2.5.2. Benefits for use in Tailor Welded Blanks

Friction stir welding has many desirable features that could be beneficial in the creation of tailor-welded blank. The benefits and advantages over laser welding include:

- Better material properties in the weld and HAZ – As the joining of the materials is performed below the melting temperature the material properties are better maintained.

- Fewer defects in the weld
- Able to weld materials hard to weld in other processes – 2xxx and 7xxx aluminums cannot be welded by laser welding. The high end DP and TRIP steels (above 900 or so) are difficult to weld with laser welding.
- Low distortion and shrinkage – As the material is not heated as much as other welding processes the material does not undergo as much expansion and subsequent contraction as other welding processes.
- No fume
- Low porosity
- No Spatter
- Use in any position – Gravity does not have an effect on the process, while some other welding processes are affected by gravity (Smith, 2003).
- Fewer variables – The rotational speed, travel speed and downward force are controlled. This makes the process easier to control and determine optimum operating conditions.
- Fatigue life is improved – Studies have shown that fatigue life of a friction stir welding can be twice as long as laser welding of the same materials (Klein, 2003).
- Less stringent edge tolerances – As a friction stir weld is much wider than a laser weld the edge tolerance required is not nearly as small as laser welding.
- Lower machine cost – A friction stir welding machine costs about 1/5th to 1/10th of a laser welding machine.

These reasons make friction stir welding suitable for many applications. Friction stir welding may be especially useful in the formation of tailor-welded blank due to the benefits or improvements over laser welding.

2.5.3. Drawbacks and Limitations

There are currently some drawbacks to friction stir welding. As a relatively new process it has not been tested and optimized for all applications. Friction stir welding is currently very slow compared to laser welding. Welding rates for similar thicknesses of materials are far faster in laser welding. As mentioned, the rates for laser welding in aluminum or steel for the standard tailor-welded blank thicknesses are in the 254-762 m/min (100-300 in/min) rate. Friction stir welding on the other hand has rates of 51-76 m/min (20-30 in/min) for aluminum (Benedyk, 2000) and 20-25 m/min (8-10 in/min) for steel. The lower cost of the friction stir welding machines may provide the flexibility and combined speed to reach a comparable cost to laser welding, especially if optimization can increase the current speed of the friction stir welding process.

3. Methodology

3.1. Overview

This study was carried out to determine if friction stir welding could be used to create acceptable welds in certain alloys, namely high strength DP and TRIP steels. Three combinations were initially looked at: DP 590 to DP 590, DP 590 to TRIP 590 and TRIP 590 to TRIP 590. Laser samples from Mittal Steel were tensile and hardness tested. These were compared to friction stir welding samples that were run under a variety of variables to determine favorable operating conditions. Initial tests were not as universally successful as expected based on previous research. At this time a new tool shape was devised by Megastir Technologies which exhibited superior welding capabilities. Therefore, this new stepped-spiral convex tool was used to repeat those initial experiments. The new tool was then used for all future experiments including the higher strength DP 780 and DP 980 to see if those alloys could be acceptably welded.

3.2. Materials

Several different steels in different combinations were studied. All materials were provided by Mittal Steel. The steels provided and studied are ultra-high-strength steels that are of particular interest in the automobile industry. A further description is given below.

3.2.1. Dual Phase Steel

Dual phase steels are high strength steels with UTS from 450 to 1000 MPa. The grain structure is mainly ferrite and martensite while varying process parameters controls the strength and other properties. The DP 590, 780 and 980 used have 20, 40 and 60 percent martensite microstructure, respectively. DP steels can be up to three times stronger than the mild steels that once dominated automobile production. They are less expensive and easier to weld than some other high strength steels such as TRIP steels. The particular DP steels used for this research were DP 590, 780 and 980 with thicknesses between 1.2 mm and 1.8 mm. The chemical compositions of these steels, provided by Mittol Steel, are show in Table 3-1.

Table 3-1 Chemical Composition of DP Steels

Material	C	Mn	P	S	Si	Cr	Al
TRIP 590	0.200%	1.500%	-	-	-	-	2.000%
DP 590	0.110%	1.900%	0.012%	0.008%	0.250%	0.020%	0.040%
DP 780	0.110%	0.990%	0.011%	0.006%	0.330%	0.020%	0.037%
DP 990	0.150%	1.440%	0.011%	0.007%	0.320%	0.020%	-

3.2.2. Transformation-Induced Plasticity Steel

TRIP steels are also high strength steels that are gaining popularity for use in tailor-welded blanks due to better forming characteristics than comparable strength DP steels. The grain structure of TRIP steels is a combination of ferrite, bainite, martensite and retained austenite. TRIP steels, currently, are more difficult to weld and more expensive than similar strength DP steels. The TRIP steel used for research was TRIP 590 CR. The designation indicates an ultimate tensile strength of 590 MPa. The CR indicates that the sheet was cold rolled. The thickness of the TRIP sheet steel was 1.6 mm (.063 in).

3.3. Welding Procedure

3.3.1. Material Preparation

A few steps were necessary to prepare the metal for friction stir welding. The metal was received in large sheets measuring up to about two meters in both length and width. These were sheared into 12.7 cm. (five in.) wide sheets. The length varied based upon original sheet size and ranged from 30-60 cm. (12-24 in.) long. Some of the sheets were received with galvanization. These sheets of material had the zinc coating removed prior to welding, to prevent zinc from entering the weld. This may or may not be an issue that will need to be resolved when zinc coated steels are friction stir welded, but for this study the effect of the zinc coating was not studied and therefore removed by dipping the sheet into a 37% hydrochloric acid solution. The sheet is then washed to remove any excess acid and dried to avoid corrosion. Laser welding does not require this step as the laser vaporizes the zinc coating (Miles, 2006). Final preparation before welding requires the removal of any residual oxidation. This is done shortly before welding using a sanding disc. After brief sanding, methanol is used to wash and remove any excess particles.

3.3.2. Welding Equipment and Tooling

The machines used to perform the friction stir welding were two identical 1957 Kearney and Trecker milling machines that were retrofitted for friction stir welding. One of them is shown in Figure 3-1. Machines at both Brigham Young University and Megastir Technologies were used. The machines have been equipped with digital numerical control on three axes. The mills had also been equipped with shrouds to direct shielding gas (argon in this case) into the welding zone to limit oxidation in the weld.

Figure 3-1 friction stir welding machine at Brigham Young University

The tools used for experimentation are made from a polycrystalline cubic boron nitride (PCBN) inserted into a steel shank. The tools were designed and produced by Megastir Technologies. The tool profiles for both tools are shown in Figures 3-2 and 3-3.

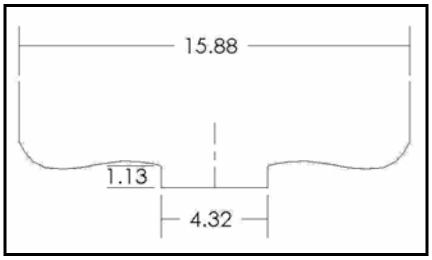

Figure 3-2 the first tool: Concave

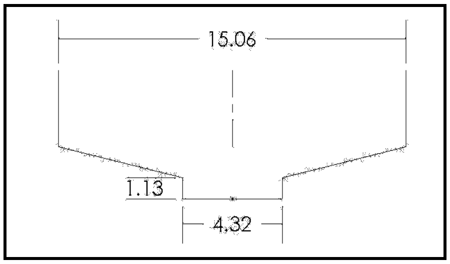

Figure 3-3 the second tool: Convex, stepped spiraled

The first tool was concave and had a shoulder diameter of 1.59 cm (0.625 in), a tool tip diameter of 0.43 cm (0.170 in), and a tip depth of 0.113 cm (0.044 in). It was used for preliminary experiments. The second tool was convex and had a shoulder diameter of 1.51 cm (0.593 in), a tool tip diameter of 0.43 cm (0.170 in), and a tip depth of 0.113 cm (0.044 in). It was used for the bulk of the experimentation. The first tool required a three degree head tilt while the second requires a zero degree head tilt.

Friction stir welding has three main parameters to control. These are the rotational speed, travel speed, and downward force. In all experiments the rotational speed and travel speed were specified while the downward force was adjusted as needed based upon experience. For the first set of experiments two rotational speeds ,700 and 800 rpm, and two travel speeds, 15 and 20 centimeters-per-minute (cm/min) (6 and 8 inches-per-minutes (in/min)), were used. This provided four distinct experiments for the three combinations (DP 590 to self, DP 590 to TRIP 590, and TRIP 590 to self). Downward force was generally set at 772 kg (1700 lbs) with the first tool but was increased when necessary to provide full penetration of the weld. The design of the second tool requires more downward force and was set closer to 908 kg (2000 lbs). As travel speed increases more downward force is required to achieve the heat needed for welding. Later experiments were run up to 152 cm/min (60 in/min) while the majority of tests were run between 51 and 102 cm/min (20 and 40 in/min). The butt-welding was run along the length of the prepared sheets, joining them into a welded sample 25.4 cm (10 in) wide and 30-60 cm (12 to 24 in) in length.

3.4. Testing Procedure

3.4.1. Tensile Test

Tensile tests were used to determine yield strength, ultimate tensile strength, and elongation before failure. Tensile testing is a two step process. First, the test specimen must be cut from the base material. For these tests a waterjet cutting machine was used to cut the ASTM E-8 samples from the welded sheets. A cut sheet is illustrated in Figure 3-4. The major dimensions for the ASTM E-8 are shown in Figure 3-5. The samples were cut with the weld running transversely across the sample, leaving a visible weld about 1.3 cm (0.5 in) wide. The weld was located as close to the center of the E-8 sample as possible.

Figure 3-4 Welded sheet with tensile and hardness samples removed.

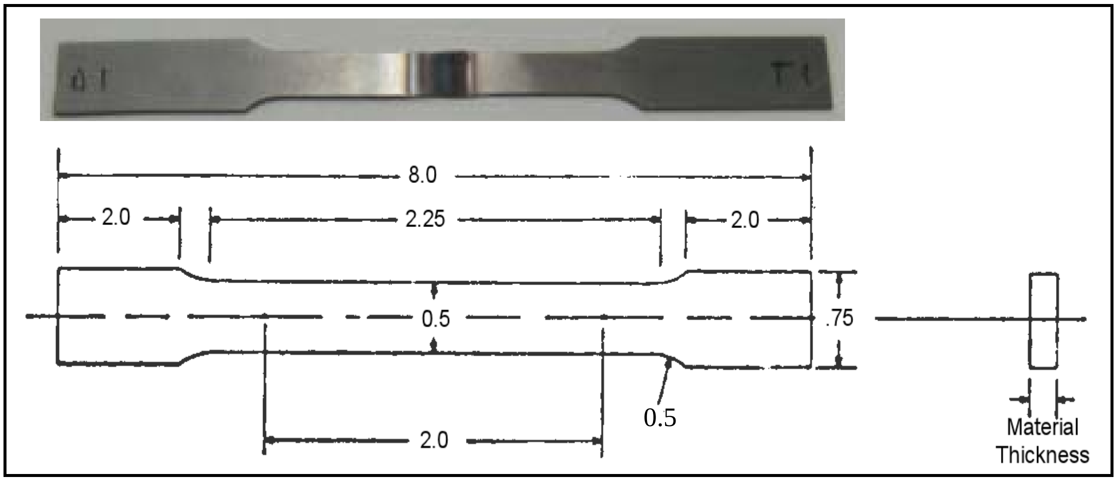

Figure 3-5 ASTM: E-8 dimensions. All units inches. Outline sketch courtesy of ASTM handbook.

After the test samples were cut they were tested. This was performed on a 4204 Instron tensile testing machine, pictured in Figure 3-6. The samples were mounted in the jaws and then pulled until broken. Sensors output force and displacement data to an Excel file on the computer. These data were then interpreted and analyzed. The force is reported in pounds and displacement in inches. Elongation is calculated as the change the length compared to the original length. In the case of differing-gauge tests the original length was only measured on the thinner side. The strain rate used for the tests was set initially at 2.5 cm/min (0.10 in/min) with the first tool. This was increased to 6.4 cm/min (0.25 in/min) without a change in result. This faster speed was then used for the second tool and the remainder of the experiments.

The tensile test results indicate a few main things. The first is a qualitative result and is defined by the location of the break. Breaks outside the weld nugget and HAZ indicate that the weld is not the weak point and is a quick determination of an acceptable weld. Breaks in the weld zone or HAZ indicate a weak point in the weld and therefore have not provided an acceptable weld. In either case the data were compared to that of the base material. E-8 samples from the base metal were cut and tested with the same methods

Figure 3-6 Instron tensile testing machine.

3.4.2. Microhardness Test

Microhardness tests are used to determine the hardness of a material. In this case, the hardness has a strong inverse correlation with formability of a material. The hardness change across a weld indicates the change in material properties in the weld and heat affected zone.

The procedure for the Vickers microhardness testing requires four steps. First, a sample specimen is cut from the welded part. Next, the sample is mounted for polishing. The samples are placed in a mold and held in place by hardened Bakelite, shown in Figure 3-7. After they are mounted in the Bakelite the samples can then be polished. This is done using abrasive pads beginning at 300 grit and progressing through 600, 800, 1200 coarse, 1200 fine, 6 micron, and 3 micron levels until a mirror finish is achieved. Finally, the test sample is placed in the Leco LM 100 AT microhardness tester, shown in Figure 3-8. This machine, coupled with a computer is able to layout testing patterns. Then the computer finely focuses on the sample surface, indents the sample and optically measures the size of the indentation to determine the hardness of the material. The indentations made by the machine used a 300 gram weight and a 9 second dwell time. Data are recorded on the computer and are available for export and analysis. The software used for the procedure is AMH43 version 1.43.

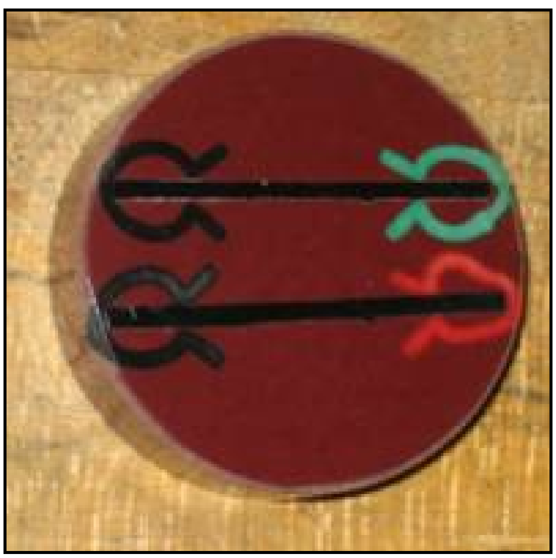

Figure 3-7 Two samples mounted in Bakelite.

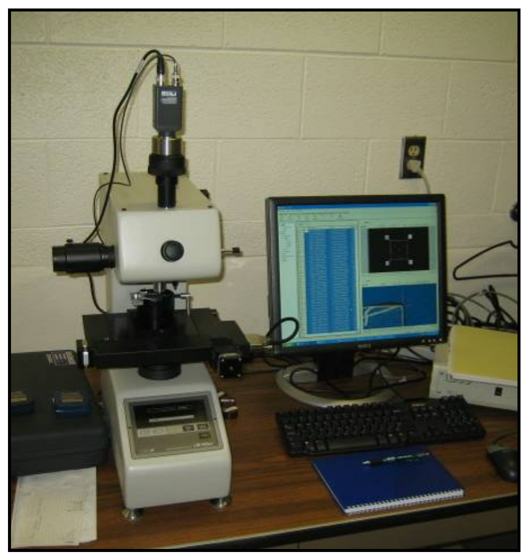

Figure 3-8 Leco microhardness tester.

3.4.3. Test Series Performed

Several test series were performed to determine weldability of these steels. A summary is given in Table 3-2, omitting material thickness. The shaded portions were groupings run attempting to determine differences caused by rotational and travel speed. A list of parameters, differentiated by gauge, is listed immediately following Table 3-2.

Table 3-2 list of weld parameters

	Travel Speed in cm/min										
RPM	15	20	25	38	51	76	89	102	114	127	152
324			7	7	7						
436			7	7	7						
600			7,9	7,9	7,9			5,7,9			
700	T,DT,5	T,DT,5									
800	T,DT,5	T,DT,5	7,9	7,9	7,9	5,7,9	5,7,9	5,7,9	9	5,9	5
1000								5,7,9			
1200								5			
	T=TRIP 590				7=DP 780			5=DP 590			
	DT=DP 590 to TRIP 590				9=DP 980						

- TRIP 590 to TRIP 590 – 1.6 mm to 1.6 mm – 15 and 20 cm/min (6 and 8 in/min) at 700 and 800 rpm.
- DP 590 to TRIP 590 – 1.8 mm to 1.6 mm and 1.6 mm to 1.6 mm - 15 and 20 cm/min (6 and 8 in/min) at 700 and 800 rpm.
- DP 590 to DP 590 – 1.8 mm to 1.8 mm and 1.6 mm to 1.6 mm - 15 and 20 cm/min (6 and 8 in/min) at 700 and 800 rpm.
- DP 590 to DP 590 – 1.4 mm to 1.2 mm – 102 cm/min (40 in/min) at 1200 rpm.
- DP 590 to DP 590 – 1.4 mm to 1.4 mm – 76, 89, 102, 127, & 152 cm/min (30, 35, 40, 50 & 60 in/min) at 800 rpm.

- DP 590 to DP 590 – 1.4 mm to 1.4 mm – 102 cm/min (40 in/min) at 600, 800, & 1000 rpm.
- DP 780 to DP 780 – 1.4 mm to 1.4 mm – 25, 38, & 51 cm/min (10, 15, & 20 in/min) at 324, 436, 600 & 800 rpm.
- DP 780 to DP 780 – 1.4 mm to 1.4 mm & 1.4 mm to 1.2 mm – 76, 89, & 102 cm/min (30, 35 & 40 in/min) at 800 rpm.
- DP 780 to DP 780 – 1.4 mm to 1.4 mm & 1.4 mm to 1.2 mm – 102 cm/min (40 in/min) at 600, 800, & 1000 rpm.
- DP 980 to DP 980 – 1.4 mm to 1.4 mm – 25, 38, & 51 cm/min (10, 15, & 20 in/min) at 600 & 800 rpm.
- DP 980 to DP 980 – 1.4 mm to 1.4 mm – 76, 89, 102, 114, & 127 cm/min (30, 35, 40, 45 & 50 in/min) at 800 rpm.
- DP 980 to DP 980 – 1.4 mm to 1.4 mm – 102 cm/min (40 in/min) at 600, 800 & 1000 rpm.
- DP 980 to DP 980 – 1.4 mm to 1.2 mm – 76, 89, & 102 cm/min (30, 35 & 40 in/min) at 800 rpm.
- DP 980 to DP 980 – 1.4 mm to 1.2 mm – 102 cm/min (40 in/min) at 600, 800 & 1000 rpm.

4. Results

4.1. Overview

The test used to determine an acceptable weld was the transverse tensile test. A weld was considered acceptable if the tensile test results in a failure away from weld nugget and heat affected zone. The tensile test also determines the strength and elongation of the sample which was compared to the base material and samples from laser welding. A microhardness test was also used as a follow-up to the tensile test, to help determine why the weld failed where it did. The test determines the hardness of the material at predetermined locations across the weld. These results are discussed in terms of determining the processing feasibility of using friction stir welding to weld these high strength steels. Testing on the base materials provided comparison. The results for the base materials are shown in Table 4-1.

Table 4-1 Testing Results on Base Materials

Testing Results on Base Materials				
Material	YS (Mpa)	UTS (MPa)	Elongation	Microhardness
TRIP 590	443	627	31%	210
DP 590	370	630	24%	220
DP 780	503	793	17%	270
DP 980	703	1009	16%	330

4.2. Tensile Test Results

Numerous experiments yielded a variety of tensile test results. Breaks occurred in the weld joint, the HAZ and in the base material. Ultimate tensile strengths (UTS) recorded varied from under 20% to above that of the base material. Elongations also varied from about 10% of the base material to above that of the base steel. Table 4-2 shows the best results for each material, as compared to the parent material. Detailed results will be shown further below and full results can be found in the Appendix. The percentages in Table 4-2 are an average of all of the samples included in that listed parameter. A minimum of three samples were tested from each weld. The numbers of samples vary based upon the number or samples tested for each parameter and the number of parameter grouped together.

Table 4-2 Best tensile results in each material.

Best results for each material or combination					
Material	Thickness (mm)	Travel Speed (cm/min)	Acceptable welds	UTS vs. base	Elongation vs. base
TRIP 590	1.6	15-20	20/20	99%	83%
DP 590 - TRIP 590	1.6	15	9/9	98%	98%
DP 590 - TRIP 590	1.8 - 1.6	15	10/10	102%	120%
DP 590	1.4 - 1.2	102	4/4	93%	127%
DP 590	1.8 - 1.4	89-102	5/6	95%	139%
DP 780	1.4	76-102	0/15	78%	37%
DP 980	1.4	76-127	0/15	74%	36%

As Table 4-1 illustrates acceptable welds were achieved in some materials while not in others. This does not mean that it is impossible to achieve an acceptable weld with these materials only that the parameters used did not yield acceptable welds. In a few cases, almost exclusively when welding dissimilar thickness samples, values over 100% of the base were recorded. As shown above there are three samples with values over 100%. The 102% UTS is not outside the realm of minor variation while those over 120% elongation compared to the base are not. The cause for this is that in the calculation for elongation the original length was measured only on one side of the weld as it was assumed that all elongation would occur on the thinner side. The data indicates that the thinner side does account for the majority of the elongation but after work hardening to some extent the thicker side also experiences some elongation. The data show a correlation between the ratio of difference in thickness and how much elongation occurs on each side.

4.2.1. Dual Phase 590

The dual phase 590 steel was welded from 15 to 152 cm/min (6 to 60 in/min) and from 700 to 1200 rpm. Different thicknesses were welded, in a few combinations ranging from 1.2 to 1.8 mm. Table 4-3 shows some of the significant weld results using DP 590.

Table 4-3 Selected weld results in DP 590

DP 590						
Thickness (mm)	Feed (cm/min)	Speed (rpm)	Z-force (kg)	Acceptable welds	UTS vs. base	Elongation vs. base
1.8 - 1.4	76	800	2943	0/3	92%	79%
1.8 - 1.4	89	800	2043	2/3	97%	143%
1.8 - 1.4	102	800	2043	3/3	93%	135%
1.4 - 1.2	102	1200	2406	4/4	93%	127%
1.6 - 1.6	20	800	772	0/3	89%	26%
1.6 - 1.6	20	700	772	0/3	66%	17%
1.6 - 1.6	15	800	772	0/5	111%	83%
1.6 - 1.6	15	700	772	0/3	47%	83%

As shown above, the only acceptable welds were obtained in different thickness welds, either in 1.8 – 1.4 mm or 1.4 – 1.2 mm. Also of note is that even unacceptable welds can have UTS above 90% of the base material. The big difference is in the elongation which in unacceptable welds is often under 50% but did reach as high as 83% of the base in these experiments. One last note is the extremely high elongation in the thick-to-thin materials. As mentioned, in all of these experiments the elongation was calculated based on elongation only coming from the thinner side of the sample. However, the research indicates that both sides will deform to some extent, though not equally, under most loads.

4.2.2. Transformation-induced Plasticity 590

Attempts were made to weld TRIP 590 to itself and to DP 590. TRIP to TRIP was welded at 15 or 20 cm/min (6 or 8 in/min) and at 700 or 800 rpm. These first attempts yielded acceptable welds and are shown in Table 4-4

Table 4-4 Selected weld results in TRIP 590

TRIP 590						
Thickness (mm)	Feed (cm/min)	Speed (rpm)	Z-force (kg)	Acceptable welds	UTS vs. base	Elongation vs. base
1.6 - 1.6	20	800	772	5/5	99%	75%
1.6 - 1.6	20	700	772	5/5	100%	87%
1.6 - 1.6	15	800	772	5/5	99%	85%
1.6 - 1.6	15	700	772	5/5	99%	85%

All the welds were acceptable and maintained UTS virtually identical to the base material. The elongation in each sample was lower than the parent. This is most likely caused by some hardening that extended further than the visually measured weld.

4.2.3. Dual Phase 590 to TRIP 590

The DP 590 was welded to TRIP 590 at the same 15 and 20 cm/min (6 and 8 in/min) and 700 and 800 rpm as the TRIP 590 to itself was welded. Specimens were welded both in 1.8 to 1.6 mm and in 1.6 to 1.6 mm. The results are shown in Table 4-5.

Table 4-5 Selected weld results in DP 590 to TRIP 590

DP 590 to TRIP 590						
Thickness (mm)	Feed (cm/min)	Speed (rpm)	Z-force (kg)	Acceptable welds	UTS vs. base	Elongation vs. base
1.8 - 1.6	20	800	772	0/5	97%	87%
1.8 - 1.6	20	700	772	1/5	100%	103%
1.8 - 1.6	15	800	772	5/5	102%	121%
1.8 - 1.6	15	700	772	5/5	102%	119%
1.6 - 1.6	20	800	772	0/3	79%	27%
1.6 - 1.6	20	700	772	0/3	47%	12%
1.6 - 1.6	15	800	772	5/5	105%	97%
1.6 - 1.6	15	700	772	4/4	101%	99%

Overall, in both sets, the 15 cm/min (6 in/min) samples were acceptable while the 20 cm/min (8 in/min) samples were not. However, in the 1.8 to 1.6 mm run at 20 cm/min (8 in/min) and 700 rpm there was one acceptable weld out of the five while UTS was 100% of the base UTS and elongation was above that of the base material. As noted above in the DP 590 section, the elongation of dissimilar thickness samples often goes above 100% due to calculating elongation based on a one sided sample.

4.2.4. Dual Phase 780

With satisfactory results in the DP and TRIP 590 and interests to try friction stir welding with higher strength materials, which are harder to laser weld, focus proceeded to DP 780 and 980. DP 780 was welded to itself both in 1.4 mm to 1.4 mm and to 1.2 mm gauges. Parameters varied from 25 to 102 cm/min (10 to 40 in/min) and from 600 to 1000 rpm. These results are summarized in Table 4-6.

Table 4-6 Selected weld results in DP 780

DP 780						
Thickness (mm)	Feed (cm/min)	Speed (rpm)	Z-force (kg)	Acceptable welds	UTS vs. base	Elongation vs. base
1.4 - 1.4	25	600	1589	0/3	77%	36%
1.4 - 1.4	38	600	1589	0/3	88%	44%
1.4 - 1.4	51	600	1589	0/3	90%	49%
1.4 - 1.4	25	800	1589	0/3	76%	33%
1.4 - 1.4	38	800	1589	0/3	78%	35%
1.4 - 1.4	51	800	1589	0/3	85%	34%
1.4 - 1.4	76	800	2043	0/3	92%	43%
1.4 - 1.4	89	800	2043	0/3	71%	22%
1.4 - 1.4	102	800	2270	0/3	95%	54%
1.4 - 1.4	102	600	2270	0/3	47%	24%
1.4 - 1.4	102	1000	2270	0/3	83%	41%
1.4 - 1.2	76	800	2043	0/3	79%	41%
1.4 - 1.2	89	800	2043	0/3	72%	31%
1.4 - 1.2	102	800	2043	0/3	81%	38%
1.4 - 1.2	102	600	2043	0/3	83%	33%
1.4 - 1.2	102	1000	2043	0/3	76%	38%

Although no acceptable welds were created in DP 780, the relatively high UTS and elongation of the samples is promising. As the table above shows UTS were, with one exception, above 70% of the base. Elongations, with two exceptions, were above 30% of the base. Although 30-50% elongation is not very high it should be kept in mind that a few percent increase in UTS equates to a much larger percent increase in elongation. This is due to the nature of steel after crossing the yield point. In almost all instances the yield strength of these samples was similar to the base material. Finally, all of the welds shown above failed in the HAZ, not the weld nugget. Possible reasons for these failures will be discussed in Section 4.3 below.

4.2.5. Dual Phase 980

Again, with the satisfactory results from the lower strength steels, focus was put on DP 780 and 980. Preliminary results achieving acceptable welds at 102 cm/min (40 in/min) in DP 590 and some indication that faster travel would input less heat into the weld pushed experiments towards faster travel speeds. As with DP 780, DP 980 was welded from 1.4 mm to both 1.4 mm and 1.2 mm. The parameters were also the same at with DP 780 but increasing the maximum travel speed to 127 cm/min (50 in/min). Some of the more significant data from these experiments are displayed in Table 4-7.

Table 4-7 Selected weld results in DP 980

DP 980						
Thickness (mm)	Feed (cm/min)	Speed (rpm)	Z-force (kg)	Acceptable welds	UTS vs. base	Elongation vs. base
1.4 - 1.4	25	600	1589	0/3	74%	37%
1.4 - 1.4	38	600	1362	0/3	71%	36%
1.4 - 1.4	51	600	1589	0/3	77%	46%
1.4 - 1.4	25	800	908	0/3	76%	41%
1.4 - 1.4	38	800	908	0/3	73%	41%
1.4 - 1.4	51	800	1362	0/3	72%	38%
1.4 - 1.4	76	800	2043	0/3	72%	28%
1.4 - 1.4	89	800	2043	0/3	81%	48%
1.4 - 1.4	102	800	2497	0/3	77%	38%
1.4 - 1.4	114	800	2497	0/3	78%	39%
1.4 - 1.4	127	800	2497	0/3	64%	27%
1.4 - 1.2	76	800	2043	0/3	80%	35%
1.4 - 1.2	89	800	2043	0/3	83%	41%
1.4 - 1.2	102	800	2043	0/3	81%	44%
1.4 - 1.2	102	600	2043	0/3	51%	22%
1.4 - 1.2	102	1000	2043	0/3	84%	36%

As with the DP 780, no acceptable welds were created. Also, as with the DP 780, the UTS and elongations showed the ability to weld the DP 980 with some strength. The samples tested generally had ultimate tensile strengths in the 70 – 85% range and elongations in the 30 – 50% range. Again the UTS achieved is promising and a few percent increase would result in a much higher gain in elongation. As with the DP 780 all failures were in not in the weld nugget but the HAZ. Rational for this is explored below.

4.3. Hardness Test Results

The hardness test can give insight into why a weld failed. Excessive softening can reduce strength and total elongation of a sample while excessive hardness only reduces elongation. In most cases the weld nugget and HAZ cover a range of hardness from somewhat softer to much harder than the base metal. In general, higher hardness does not cause an unacceptable weld as determined by the transverse tensile test. An unacceptable weld is more often caused by a reduction in hardness. Figure 4-1 shows a summary of the maximum, minimum and base metal hardness for the different steels tested. This is given to show general trends in hardness, more discussion can be found the under sections for each material.

Figure 4-1 shows the DP 980 and 780 showed significant softening in the HAZ while the weld nugget was close to that of the base material. Both the TRIP and DP 590 welded at slow speeds, under 25 cm/min (10 in/min), showed very limited softening in the HAZ but significant hardening of the weld nugget. When the DP 590 was welded at faster speeds, up to 102 cm/min (40 in/min), they showed significantly more softening in the HAZ and less hardening in the weld nugget. Reasons for this difference are explored in the DP 590 section below.

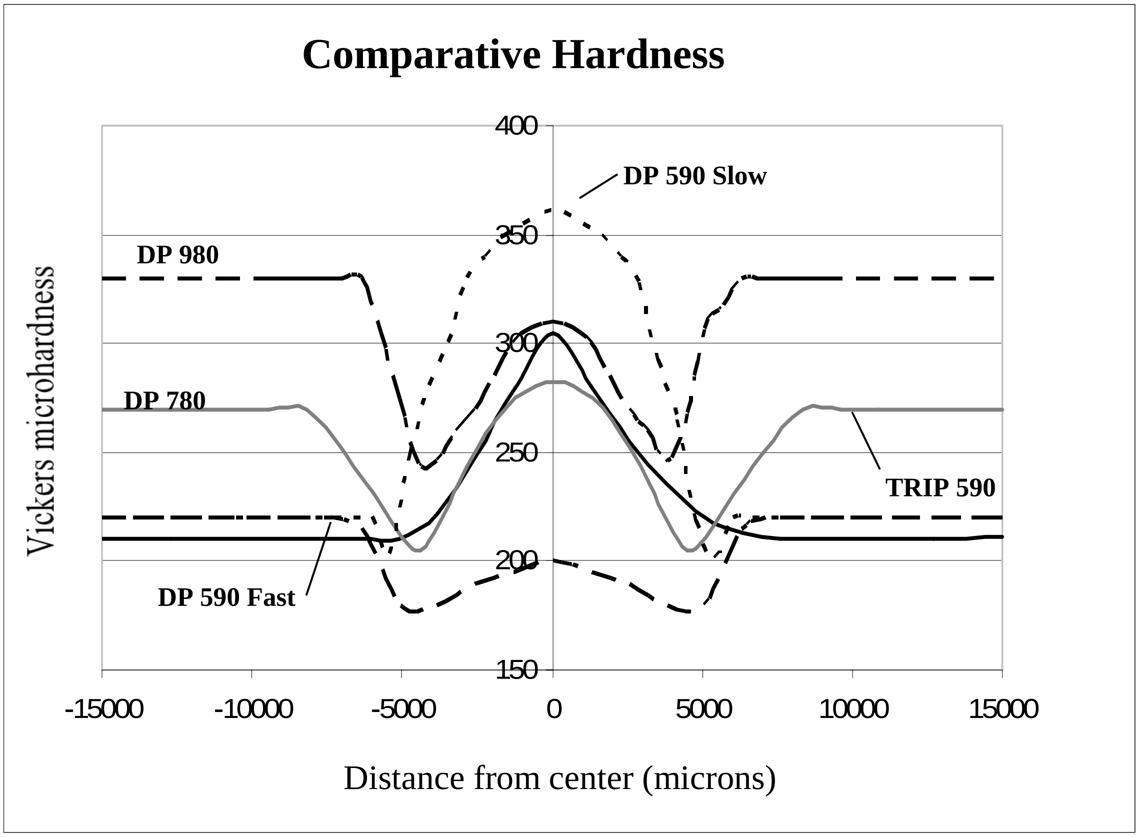

Figure 4-1 Comparative hardness of welded samples based on material.

4.3.1. Dual Phase 590

Acceptable welds were created in DP 590. Hardness tests of both acceptable and unacceptable welds provide useful results for study. The hardness profiles of two different series of welds in DP 590 are shown in Figure 4-2.

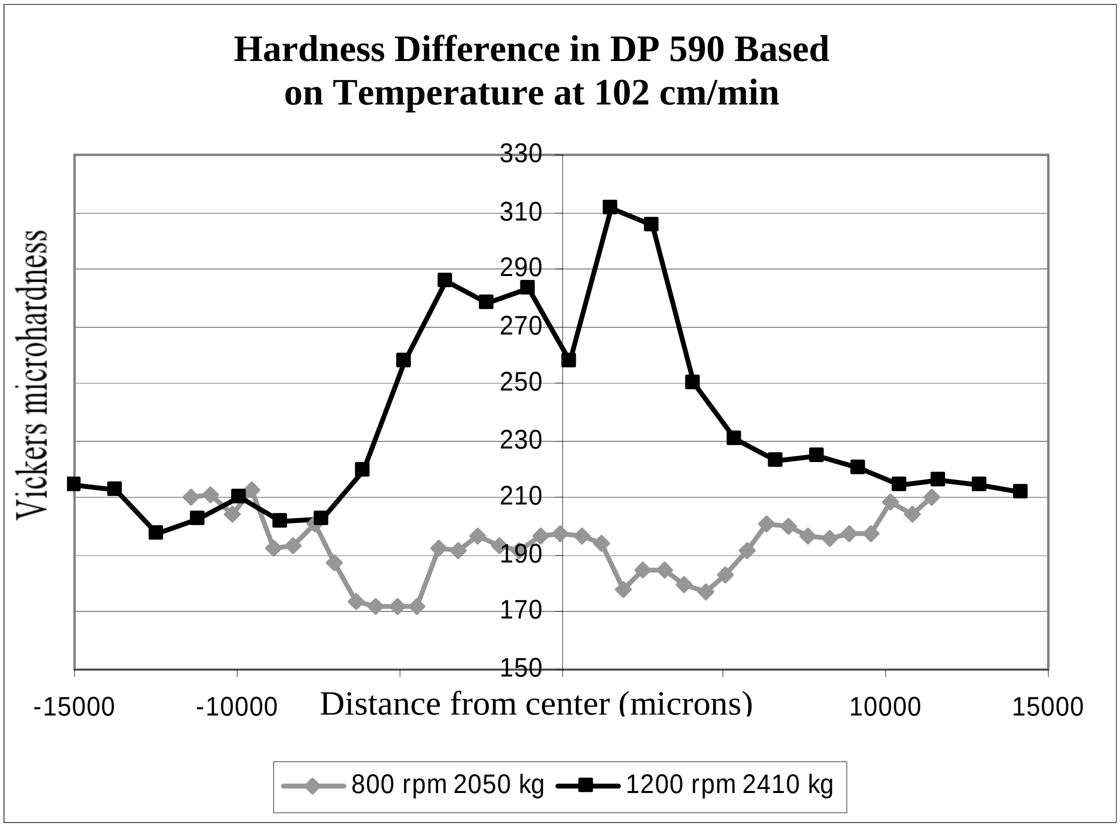

Figure 4-2 Difference in the hardness of DP 590 based on temperature

As Figure 4-2 shows, temperature has a large impact on final hardness. Although temperature was not measured the 50% increase in RPM and extra 364 kg (800 pounds), with the same feed rate (102 cm/min (40 in/min)), results in a higher temperature. Similar results were measured at slower speeds where a significant change in hardness correlated with parameters that would result in lower temperatures.

4.3.2. Transformation-Induced Plasticity 590

Acceptable welds were produced in the TRIP 590. Therefore, hardness tests were performed to provide insights into what happens to the base material during the welding process. The hardness results are shown in Figure 4-3.

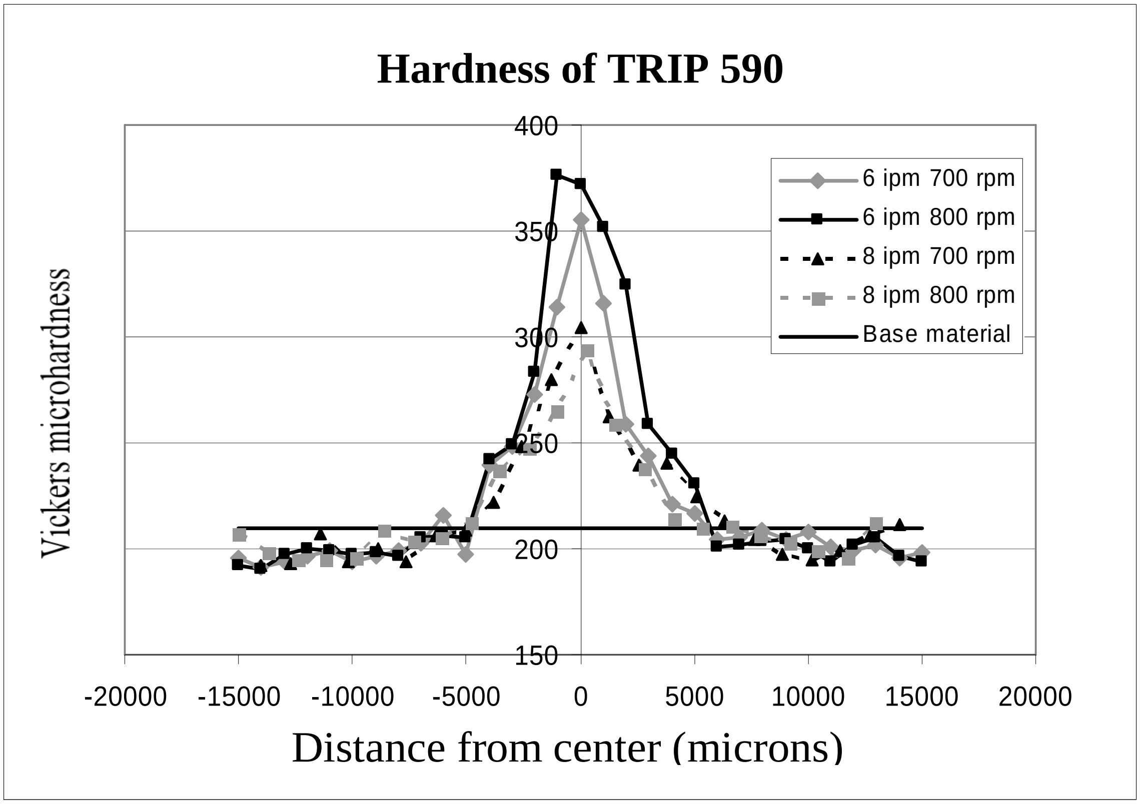

Figure 4-3 Microhardness values from TRIP 590

There is significant hardening in the weld nugget and virtually no softening in the HAZ of the samples. In addition, the welds performed at 15 cm/min (6 in/min) showed significantly more hardening (74%) than the samples welded at 20 cm/min (8 in/min) (42%). With rotational speed and downward force held constant an increase in travel speed will decrease the temperature of the weld. Figure 4-3 shows that a lower temperatures result in a lower hardness. It should be kept in mind that although excessive hardening has minimal negative effect during tensile test it can be detrimental in forming operations. A desire to keep hardening low and prove feasible manufacturing speeds drove further experiments to be run at higher speeds.

4.3.3. Dual Phase 780

Attempts to create acceptable welds in DP 780 failed. Hardness tests were performed to try to explain why. The microhardness values of two representative samples are shown in Figure 4-4.

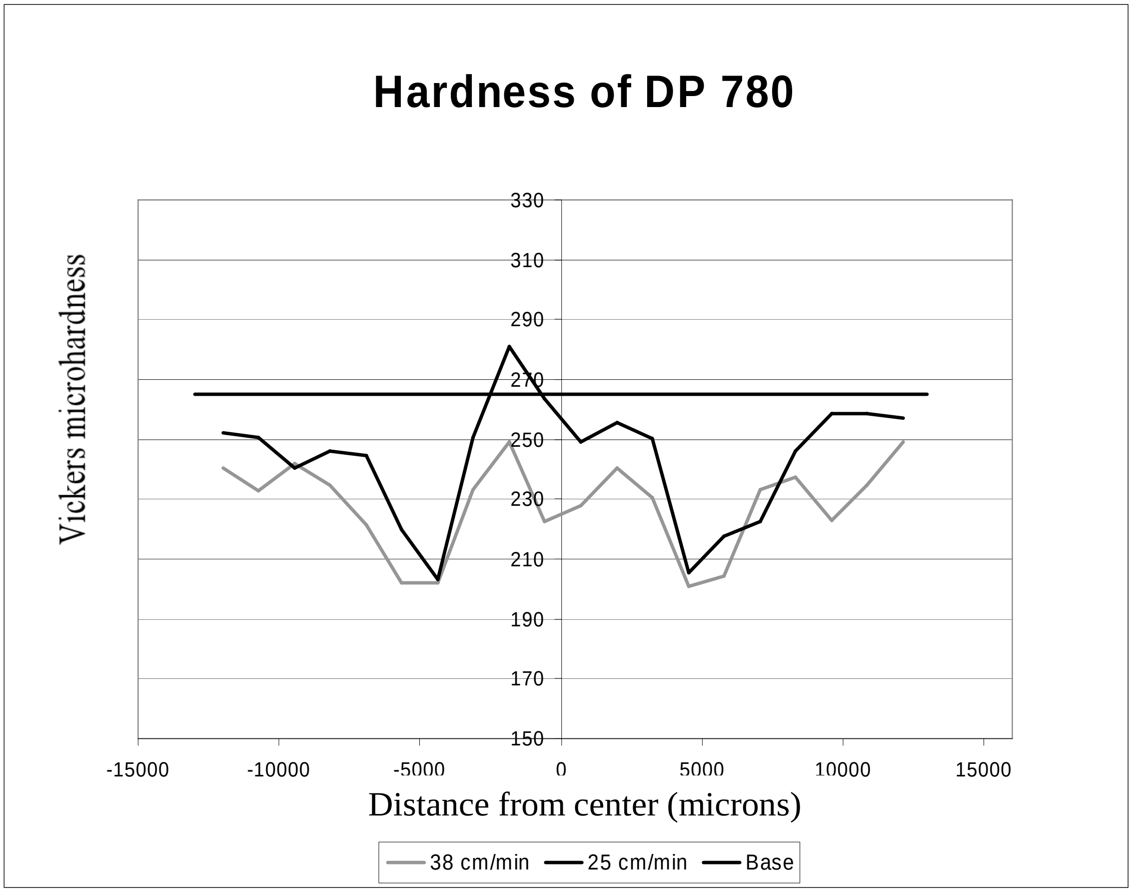

Figure 4-4 Microhardness in DP 780 samples.

The two tested samples in Figure 4-4 illustrates the pattern of softening in the HAZ (about 5000 microns to each side of center) while maintaining hardness in the weld nugget. This softening, most likely caused by tempering martensite, averages 26% which is a very likely cause for failure during the tensile tests. In addition, these two samples show the correlation between temperature and hardness in the weld. Both of these samples were run at 800 rpm and 2272 kg. The only difference is in the travel speed. One sample was run at 38 cm/in (15 in/min) while the other was run at 25 cm/in (10 in/min). The faster travel speed equates to a shorter amount of time that heat enters the weld for a given point. This lower heat is shown to lower the overall hardness in the weld nugget and HAZ.

4.3.4. Dual Phase 980

The DP 980 is again very similar to the DP 780 as to the hardness test. The results in Figure 4-5 show the same trend for softening in about 5000 microns from the center of the weld in the HAZ.

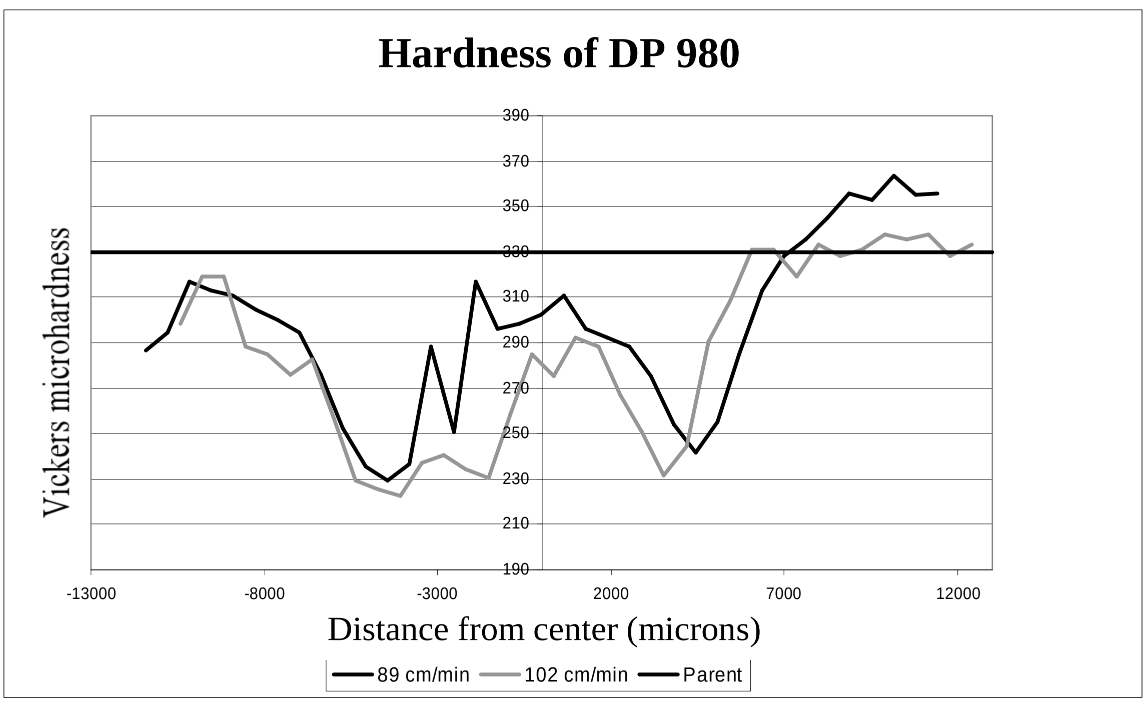

Figure 4-5 Microhardness in DP 980 samples. Welds performed at 800 rpm and 2045 kg.

Just as in the DP 780, the DP 980 exhibited softening in the HAZ with hardness close to the base material in the weld nugget. Again that softening (30%) was approximately 5000 microns from the center of the weld. The weld nugget was about 10% softer than the base metal. As with the DP 780 this significant softening, again by tempering martensite, is a very likely candidate for failure of the sample during tensile tests. The samples in Figure 4-5 show the correlation between temperature and hardness. These two samples were run with the same rotational speed (800 rpm) and downward force (2045kg) but different travel speeds (89 and 102 cm/min (35 and 40 in/min)). This difference in travel speed limits the heat entering the weld which causes more softening in the weld.

4.4. Additional Hardness Investigation

One theory for the cause for softening was that some amount of austenite was not transformed to martensite upon cooling. An experiment was set up taking pictures and performing microhardness tests of samples before and after quenching in liquid nitrogen. This quenching will convert any of the retained austenite into martensite. This experiment was performed in DP 590, DP 780 and DP 980 in samples that showed significant softening in the HAZ. The hardness tests and photographs indicate that very little if any retained austenite was converted to martensite, thus eliminating this theory. The hardness and photos for DP 980 are shown in Figure 4-6 and Figure 4-7, respectively. Although the photographs are not high enough resolution to prove conclusively that no retained austenite was transformed to martensite, the combination of the photographs and hardness tests are enough to indicate that very little if any was transformed.

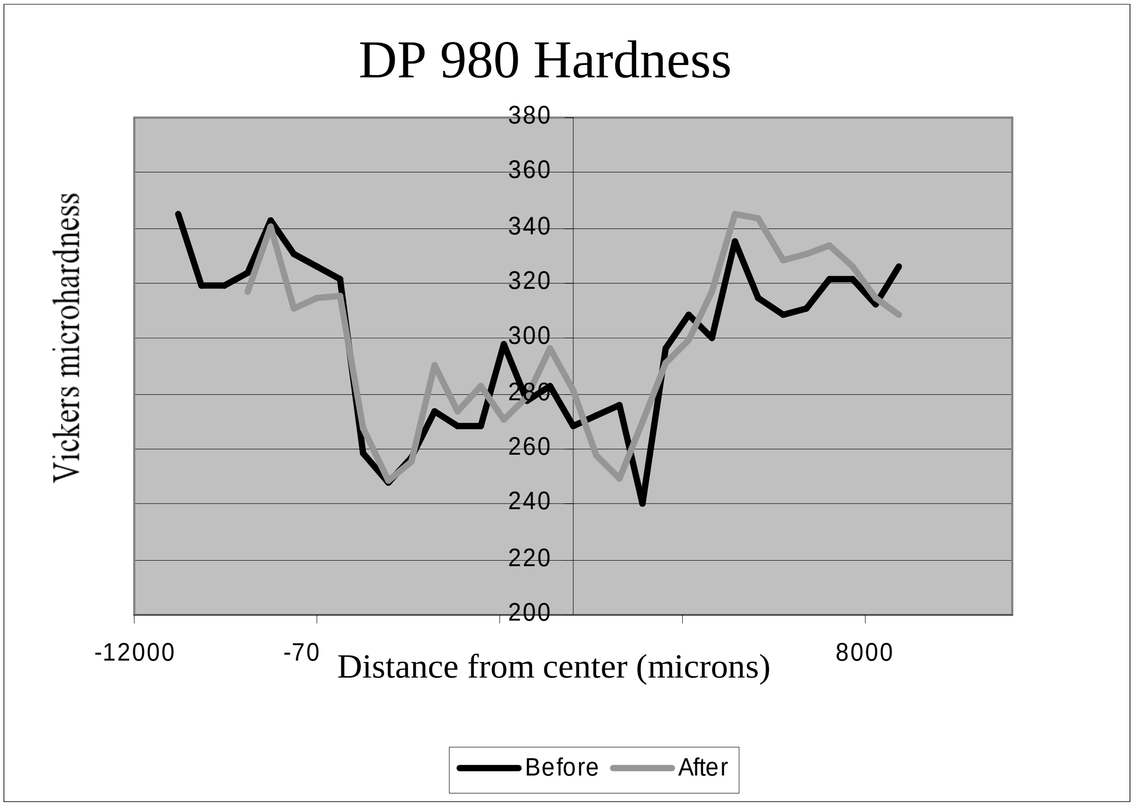

Figure 4-6 Hardness before and after liquid nitrogen quench

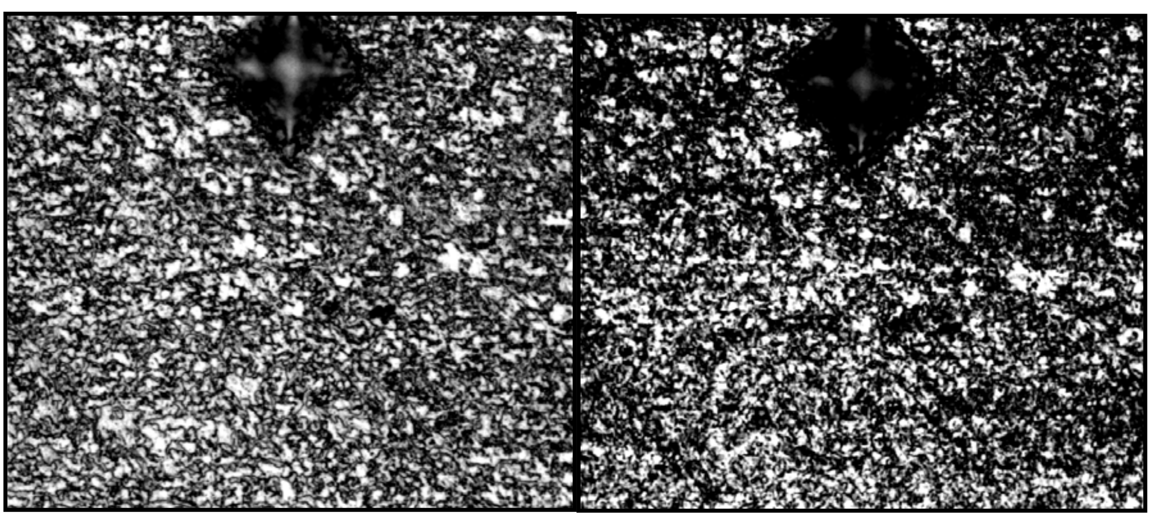

Figure 4-7 Microstructure at 500x in DP 980 before (left) and after (right) quenching

Investigations into Temperature-Time Transition curves for these Dual Phase steels indicate that there is considerable time allowed to cool to cause the formation of martensite. The curves for DP 590, 780 and 980 are combined on one chart shown in Figure 4-8. Briefly, if the weld can cool from peak temperature to below about 450 Celsius in under 10-12 seconds then virtually all of the austenite will form martensite. In this case the samples are thin plate on a large backing plate so cooling rate is sufficient for a virtually complete martensite formation.

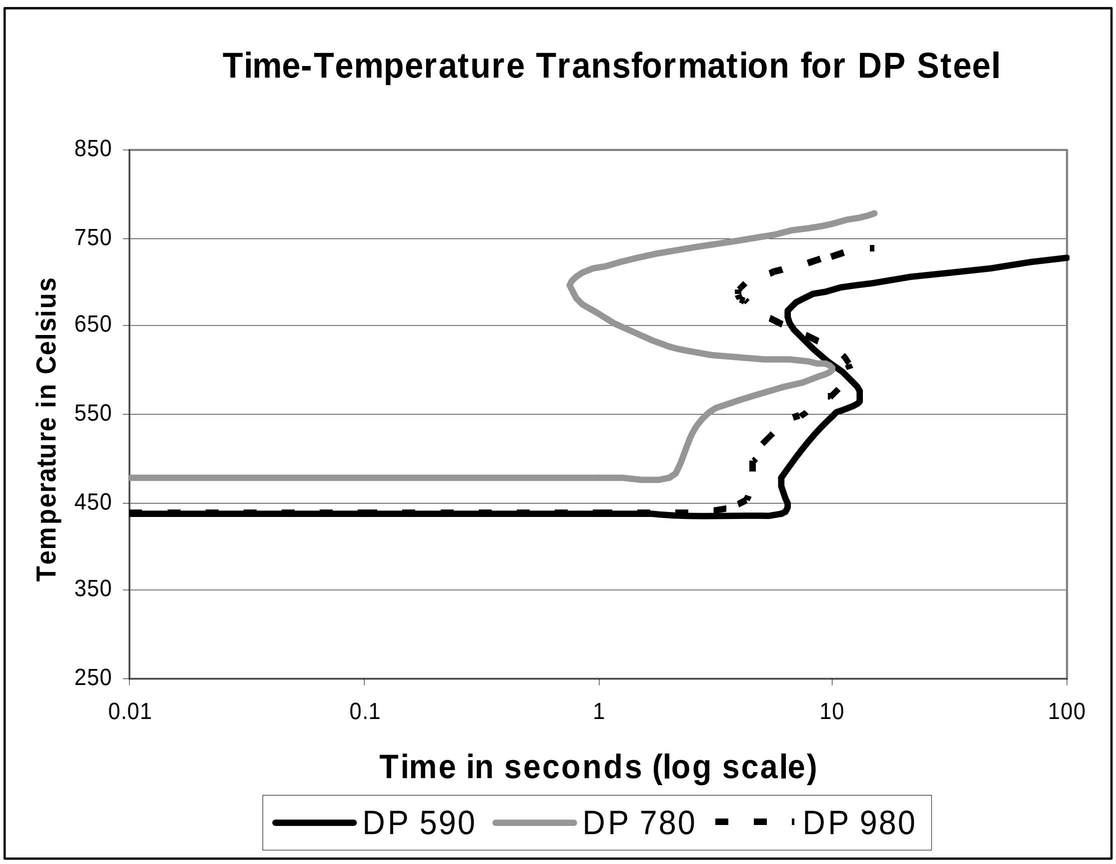

Figure 4-8 Time-Temperature Transformation curve for DP steel

4.5. Comparison to Laser Welding

Laser welding is the main method for creating tailor-welded blanks. The tensile and hardness results from the base material were compared to laser welded and friction stir welding samples. These results are discussed in detail in the respective sections below.

4.5.1. Dual Phase 590

DP 590 is one of the easiest, of the materials tested, to be laser welded. Acceptable welds were also created using the friction stir welding process. Table 4-8 shows the comparison between laser and a few friction stir welding samples.

Table 4-8 Laser vs. friction stir welding in DP 590

Laser Welding vs. FSW in DP 590					
	YS in % of base	UTS in % of base	Elongation in % of base	Speed (cm/min)	Acceptable welds
Base Material	100%	100%	100%	N/A	N/A
Laser Weld	99%	94%	77%	up to 508	3/3
FSW 1.8 - 1.4	95%	93%	134%	102	3/3
FSW 1.4 - 1.2	100%	93%	127%	102	4/4

Acceptable welds were created in DP 590 both with laser and friction stir welding. Relatively high speeds with acceptable welds were obtained with friction stir welding indicating a possible substitution for laser welding, based on tensile test results.

4.5.2. TRIP 590

As with the DP 590 the TRIP 590 attained acceptable results. Table 4-9 displays the comparison between laser welding and friction stir welding for TRIP 590.

Table 4-9 Laser vs. friction stir welding in TRIP 590

Laser Welding vs. FSW in TRIP 590					
	YS in % of base	UTS in % of base	Elongation in % of base	Speed (cm/min)	Passing Welds
Base Material	100%	100%	100%	N/A	N/A
Laser Weld	100%	102%	95%	up to 508	4/4
FSW 1.6 - 1.6	97%	95%	85%	15 or 20	20/20

These results were obtained on first runs and therefore were not studied further. Additional tests would have to be run at faster travel speeds to be appropriately compared to laser welding.

4.5.3. Dual Phase 780

Although DP 780 did not yield any acceptable welds there is still some useful comparison to the laser welded samples. These comparisons are shown in Table 4-10.

Table 4-10 Laser vs. friction stir welding in DP 780

Laser Welding vs. FSW in DP 780					
	YS in % of base	UTS in % of base	Elongation in % of base	Speed (cm/min)	Passing Welds
Base Material	100%	100%	100%	N/A	N/A
Laser Weld	110%	105%	82%	up to 508	1/3
FSW 1.4 - 1.4	104%	83%	42%	76-102	0/9
FSW 1.4 - 1.2	105%	75%	34%	76-102	0/9

The speeds at which the DP 780 was welded are promising but not a replacement for laser welding, based on unacceptable welds. However, as mentioned earlier, UHSS are hard to weld, even with laser welding. Two of the three laser welded samples were deemed unacceptable by the tensile tests. The most apparent reason for this is the softening in the HAZ shown in Figure 4-9, which shows the microhardness results of laser and friction stir welding samples.

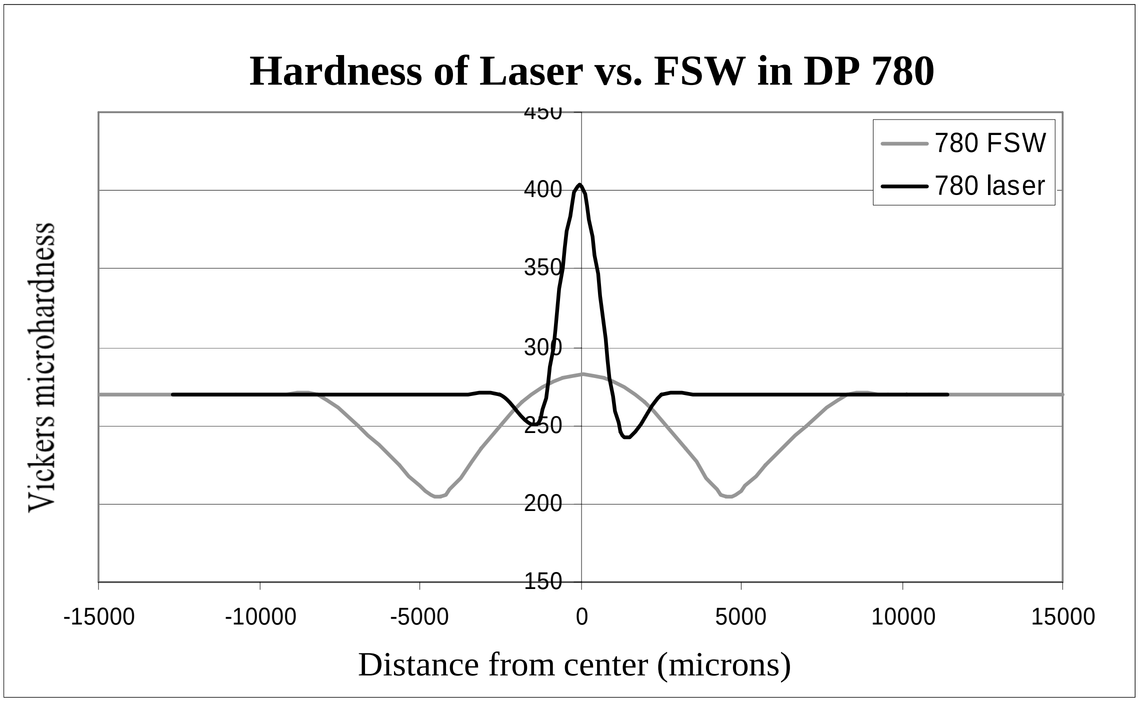

Figure 4-9 Hardness profiles of laser and friction stir welding samples in DP 780

As Figure 4-7 shows the laser welding has extreme hardening (48%) in the weld and some softening (9%) in the HAZ. Though the softening is not as significant as that exhibited in the friction stir welding samples it is the cause of failure during the tensile test. This hardness data can be used in making projections as to how a sample will perform during various forming test.

4.5.4. Dual Phase 980

No acceptable welds were created using friction stir welding in the DP 980. However, the comparison between friction stir welding and laser welding is worth reporting. The comparison is shown in Table 4-11.

Table 4-11 Laser vs. friction stir welding in DP 980

Laser Welding vs. FSW in DP 980					
	YS in % of base	UTS in % of base	Elongation in % of base	Speed (cm/min)	Passing Welds
Base Material	100%	100%	100%	N/A	N/A
Laser Weld	104%	105%	78%	up to 508	2/3
FSW 1.4 - 1.4	91%	75%	37%	76-127	0/18
FSW 1.4 - 1.2	95%	77%	37%	76-102	0/18

Again, similar to the DP 780 the welding speeds are promising but the lack of acceptable welds prohibits friction stir welding to be a substitute for laser welding, according to these results. Also, as with the DP 780, the laser welds were not universally acceptable. In this case, one of the three samples failed in the HAZ. Again the most likely reason for this is illustrated by the microhardness tests. Figure 4-10 shows the comparison between friction stir welding and laser welding in a hardness test. Again the softening in the HAZ for both the friction stir welded and laser welded samples is the reason for failure. The laser welds softened (21%) in the HAZ and hardened (50%). The failure of laser welding, caused by softening in the HAZ, and the indication of possible poor results in forming tests does leave room for friction stir welding to be a viable replacement for laser welding. This will require further development, especially in the process parameters for friction stir welding. It appears that more heat, rather than less, is needed to reduce the softening seen in the heat affected zone.

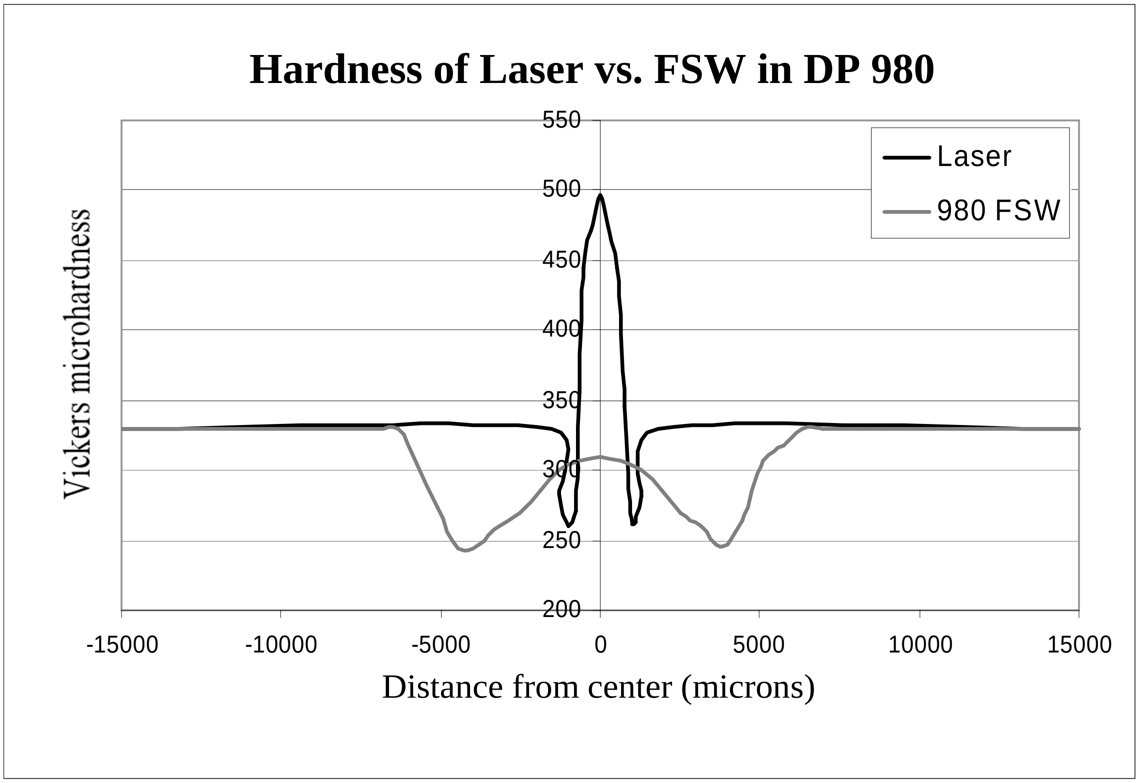

Figure 4-10 Hardness profiles of laser and friction stir welding samples in DP 980

5. Discussion of Results

5.1. Conclusions

Some conclusions can be made from this study. First, some of these UHSS automotive sheets investigated can be acceptably welded using friction stir welding. Second, limiting the hardening and especially the softening of the weld nugget and HAZ is essential to the creating acceptable welds. Generating the required heat during welding, by controlling feeds, speeds and vertical force, should provide a temperature during welding to create acceptable welds.

5.1.1. Weldability

The results from this study show that DP 590 and TRIP 590 steels were acceptably welded. Specifically, the following combinations yielded acceptable welds in this experiment:

- DP 590 to DP 590 in dissimilar thicknesses at 15, 20, 89, and 102 cm/min (6, 8, 35, and 40 in/min). Ultimate tensile strength and elongation were similar to the base material.
- DP 590 to TRIP 590 in similar and dissimilar thicknesses at 15 and 20 cm/min (6 and 8 in/min). Ultimate tensile strength and elongation were similar to the base material.

- TRIP 590 to TRIP 590 in similar thicknesses at 15 and 20 cm/min (6 and 8 in/min). Ultimate tensile strength and elongation were similar to the base material.

The following are those materials did not yield acceptable welds:

- DP 780 to DP 780 in similar and dissimilar thicknesses at speeds from 25 to 102 cm/min (10 to 40 in/min). The UTS of these unacceptable samples reached 78% of the base material. Elongation only reached 37% of base.
- DP 980 to DP 980 in similar and dissimilar thicknesses at speeds from 25 to 127 cm/min (10 to 50 in/min). The UTS of these unacceptable samples reached 74% of the base material. Elongation only reached 36% of base.

Although acceptable welds were not proven in all materials the study suggests that it is possible under other processing conditions. The high percentage of UTS that was measured in the friction stir welded samples of DP 780 and 980 indicate this possibility. The cause of failure in the DP 780 and 980 samples was softening in the HAZ. The data suggests the solution to this problem is increasing the heat during welding. This should increase the overall hardness of the weld nugget and HAZ. When comparing the results of DP 780 and 980 to the current method of laser welding, the failure of half of the laser welded samples in the HAZ demonstrates the limitations of laser welding these steels.

5.1.2. Feasibility

The feasibility of using friction stir welding for high strength steels in a production environment requires both acceptable welds and sufficient speed to make the operation economically feasible. Acceptable welds were created at 102 cm/min (40 in/min) in DP 590, which is only about a quarter as fast as laser welding can achieve, but this speed is fast compared to what has been performed before. The faster the travel speed the more likely it can be an economically viable solution.

5.1.3. Heat versus Hardness

The more interesting conclusions come from the hardness testing of welded samples. Nearly all welded samples that failed did so in the HAZ, not the weld nugget. Heat is generated in the weld as the tool rotates and pushes on the material. Higher rotational speed and more pressure increase the rate of heating. Travel speed determines how long the tool inputs heat on a given area and therefore the temperature which that area reaches. The TRIP 590 welded at 15-20 cm/min (6-8 in/min) resulted in hardening in the weld nugget from the base material of 200 to 360 in the 15 cm/min sample but only to about 300 in the 20 cm/min samples. Faster travel speeds at a given rotational speed and downward force will have less heat added and therefore lower final temperature. DP 590 samples run at the same travel speed but different rotational speeds and downward forces showed even more significant results. At 102 cm/min (40 in/min) there was hardening in the nugget from the base of 210 to 310 with insignificant softening in the HAZ when using 1200 rpm and 2410 kg (5300 lb). When running at 800 rpm and 2050 kg (4500 lb) extensive softening from 210 to 170 in the HAZ and peaking at 200 in the weld nugget. These two examples show that temperature has a significant role in the final microstructure, measured by microhardness tests. Hardness data in DP 780 and DP 980 support this conclusion. Further support can be seen in the phase diagram for steel, shown in Figure 5-1. These low carbon steels maintain the majority of their microstructure until approximately 723 degree Celsius where austenite begins to form. The diagram indicates phases present, at equilibrium for a given temperature, but can still be used to support this conclusion. As temperature increases through the two phase austenite/ferrite region, more of the material changes phase to austenite. Between 1150 and 1500 degree Celsius, depending on the alloy, all of the material has changed to austenite. Again, this is only true if held at this temperature long enough to reach equilibrium. The percentage of austenite formed will be converted to martensite when cooled at a sufficient rate. As indicated earlier these DP steels have been alloyed to provide a larger window to cool and form martensite. All welded samples were thin plate on a large steel backing plate, therefore the cooling rate is sufficient to convert virtually all of the austenite to martensite.

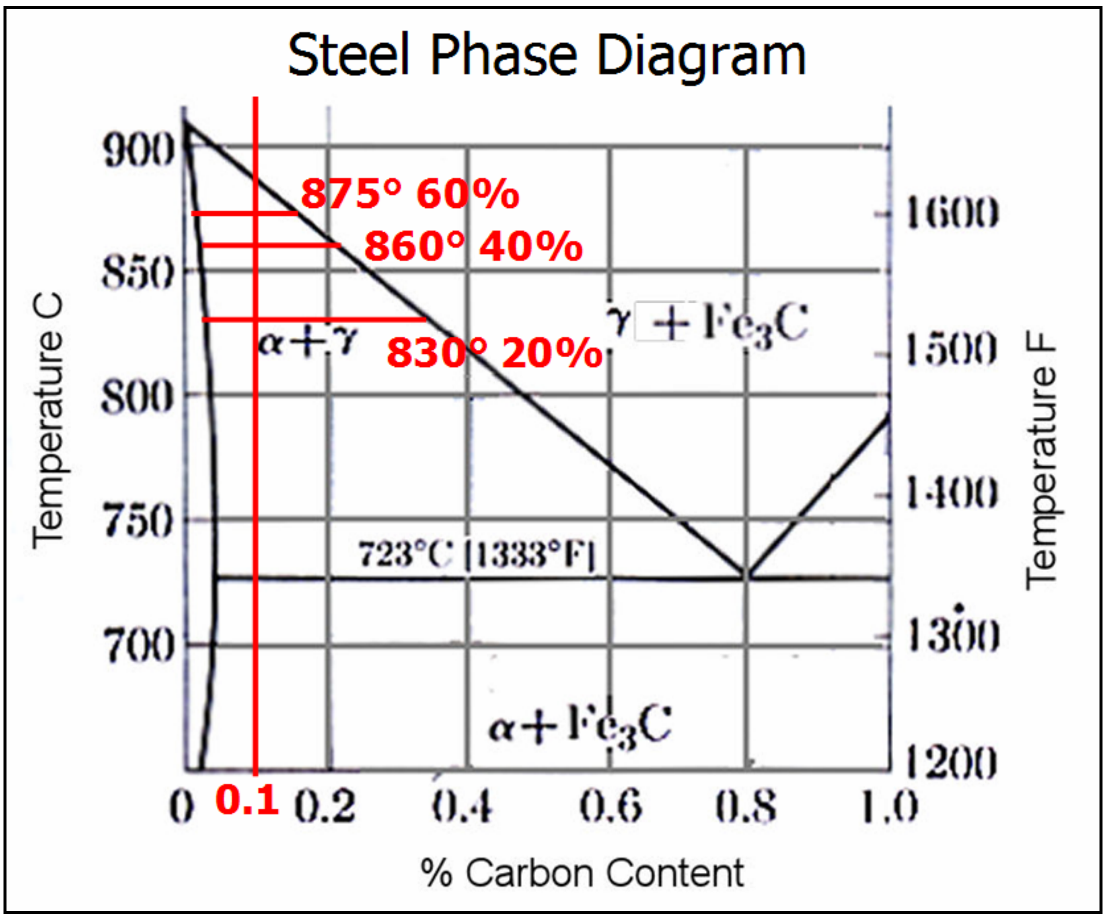

Figure 5-1 Steel Phase Diagram

The phase diagram can be used for an important calculation. This is to determine what temperature, at equilibrium, would be required to form a certain amount of austenite, which could then form martensite. Using the lever rule and known carbon content approximate temperatures can be devised per material. Given approximately 0.1% carbon content, a temperature of about 830 degree Celsius would form 20% austenite which would lead to 20% martensite upon cooling. This is the percent of martensite found in unaltered DP 590. Raising the required martensite to reach the 40% and 60% of DP 780 and 980 requires raising the temperature to about 860 and 875 degrees Celsius, respectively. Again, these temperatures are equilibrium states and that temperatures not held to equilibrium will not attain these percentages. It is possible that increasing the temperature beyond these calculated temperatures for time less that required for equilibrium may yield the same final percentage.

One theory for softening was that there was some amount of retained austenite in the microstructure instead of forming martensite. This was investigated through both microhardness tests and microstructure photos before and after quenching in liquid nitrogen. Between these tests and Time-Temperature Transition diagram it is concluded that very little if any retained austenite was formed in the welded samples.

Areas of the weld, including the HAZ, that do not transform to austenite during welding, either due to insufficient temperature or time at that temperature, exhibit tempering of the base martensite, which increases ductility but decreases hardness. Although temperature was not recorded for the tests, examination of the microhardness tests and microstructure images provide a reasonable explanation for the degree of hardening and softening in the various areas of the weld.

5.2. Recommendations

5.2.1. Other Material Combinations

Although four different UHSS were studied there are others that should be studied. In addition, further study into welding of unequal gauge materials or dissimilar alloys would provide a more thorough understanding of the capabilities of friction stir welding and possible applications for use. The temperature needs for each different material will be important to consider when welding dissimilar alloys.

5.2.2. Temperature and Phase Change

One of the biggest areas for further study, both for general understanding and specifically to help determine welding parameters to create acceptable welds, should be in the area of how the microstructures is altered through welding at sub-melting temperatures. Initial concerns about too much heat in the weld pushed toward reducing heat in the weld. Final results indicate that there is a minimum temperature required to reform the original microstructure, therefore maintaining the material properties of the original steel. Determining the time and temperature required to reform the original microstructure should be studied for these and other UHSS.

In addition, further study should be done to determine how to best achieve a desired temperature in a weld. Increasing rotational speed or downward force will increase heat input but the magnitude of each and which is better to increase to generate the necessary heat in friction stir welding is not known. This should be studied along with investigations to determine the necessary temperature for a given material and speed. Finally, to correctly control temperature in the weld, the temperature in must be measured accurately. Currently thermocouples mounted in the tool can be used to measure temperature. This may be accurate and responsive enough for the FSW process but should be investigated and compared to other options.

REFERENCES

Ashley, S. (1997). "Steel cars face a weighty decision." *Mechanical Engineering*, 199 (2), 56-61.

Auto/Steel Partnership "Tailor welded blank application and manufacturing." http://www.a-sp.org/database/custom/twb/TWBApp.pdf. Internet. Accessed April 8, 2005.

Benedyk, J. C. (2000). "Tailored aluminum blanks for automotive applications: Continuous improvement and new concepts." *Light Metal Age*, 58 (11-12), 73-78.

Cook, G., Crawford, R., Clark, D., & Strauss, A. (2004). "Robotic friction stir welding." *Industrial Robot: An international Journal*, 31 (1), 55-63.

Cretteur, L., Koruk, A. I., & Tosal-Martinez, L. (2002). "Improvement of weldability of TRIP steels by use of in-situ pre- and post-heat treatments." *Steel Research*, 73 (6-7), 314-319.

Das, S. (2000). "Aluminum tailor welded blanks." *Advanced Material & Processes*, 157 (3), 41-42.

Dodd, A. (1998). "Laser welded blanks gain ground." *Manufacturing Engineering*, 121 (5), 76-79.

Draugelates, U., Bouaifi, B., & Daniel, S. (2000). "Effect of the post-weld treatment on the weld properties of mach-seam-welded and laser-beam-welded sheets." *Welding Research Abroad*, 46 (12), 27-32.

Flaxa, V., Shaw, J. (2002) "Material Applications in ULSAB-AVC." *SAE Technical Paper Series*, 2002-01-2074.

Gerdel, T. (2000). "Tailored to fit welded blanks gain ground laser process impress design, performance, automakers say." *The Plain Dealer*, August 29, 1C.

Haake, J. M., & Zediker, M. S. (2004). "High power direct diode laser successes." *Proceedings of SPIE - The International Society for Optical Engineering*, 5336, 107-115.

Hartley, B., & Ono, M. (2002). "Laser Weldability of Dual Phase Steels in Tailored Blank Applications." *SAE Technical Paper Series*, 2002-01-0150.

Jiang, H. M., Li, S. H., Wu, H., & Chen, X.P. (2004). "Numerical simulation and experimental verification in the use of tailor-welded blanks in the multi-stage stamping process." *Journal of Material Processing Technology*, 151 (1-3), 316-320.

Kinsey, B., Krishnan, N., & Cao, J. (2004). "A methodology to reduce and quantify wrinkling in tailor welded blank forming." *International Journal of Materials and Product Technology*, 21 (1-3). 154-168.

Kinsey, B., Liu, Z., & Cao, J. (2000). "A novel forming technology for tailor-welded blanks." *Journal of Materials Processing Technology*, 99, 145-153.

Klein, A. (2003). "The Sky Is Not the Limit for friction stir welding – Its' Space." *Formaing & Fabricating.* 10 (7).

Kochan, A. (2001). Laser welding adapts to non-linear tailored blanks. *Assembly Automation*, 21 (1), 48-50.

Kochan, A. (2004). "Volkswagen makes a success with lasers." *Assembly Automation*, 24 (4), 357-360.

Krizan, D., Waterschoot, T., Koruk, A. I., & Cooman, B. C. (2003). "Bake hardening of laser welded dual phase steel." *Steel Research*, 74 (10), 639-645.

Kubel, E. (1997). "Manufacturers want more tailored blanks." *Manufacturing Engineering,* 119 (5), 38-44.

Lee, K., Jung, S., Song, S., Yoo, Y., & Par, G. (2003). "Automotive door design using structural optimization and design of experiments." *Proceedings Institution of Mechanical Engineer.* 217 (D), 855-865.

Meinders, T., van den Berg, A., & Huetink, J. (2000). "Deep drawing simulations of Tailored Blanks and experimental verification." *Journal of Materials Processing Technology*, 103, 65-73.

Miles, M. Pew, J., Nelson, T., & Li, M. (2006). "Comparison of formability of friction stir welded and laser welded dual phase 590 steel sheets." *Science and Technology of Weldind and Joining, 11 (4), 384*

Nagasaka, A. (2001). "Press formability of YAG laser welded TRIP steel sheets." *Acta Metallurgigca Sinica* (English Letters), 15 (1), 21-25.

Ono, M., Yoshaitake, A., & Ohmura, M. (2002). "Laser weldability of high strength steel sheets in fabrication of tailor welded blanks." *NKK Technical Review*, 86, 13-18.

Pallett, R. J., & Lark, R. J. (2001). "The use of tailored blanks in the manufacture of construction components." *Journal of Materials Processing Technology*. 117. 249-254.

Prange, W., & Wonneberger, I. (2003). "Laser-A Tool for Light Weight Steel Solutions for the Automotive Industry." *Proceeding of SPIE.* 4831, 363-368.

Raymond, S. D., Wild, P. M., & Bayley, C. J. (2003). "On modeling of the weld line in finite element analyses of tailor-welded blank forming operations." *Journal of Material Processing Technology*, 147 (1), 28-37.

Rooks, B. (2001). "Tailor-welded blanks bring multiple benefits to car design." *Assembly Automation*, 21 (4). 323-328.

Seidel, T. U., & Reynolds, A. P. (2003). "Two-dimensional friction stir welding process model based on fluid mechanics." *Science and Technology of Welding and Joining*, 8 (3), 175-183.

Schurter, P. (2002). "ULSAB-Advanced Vehicle Concepts – Manufacturing and Processes." *SAE Technical Paper Series.* 2002-01-0039.

Smith, C.B., Hinrichs, J.F., Crusan, W.A., & Leverett, J. (2003). "Friction stir welding Stirs Up Welding Process Competition." *Forming & Fabricating.* 10 (2).

Sorensen, C. & Nelson, T. (2001). "Friction stir welding of ferrous and nickel alloys." *Friction stir welding and processing*, ed.Mishra, R., & Mahoney, M. (ASM International, 2007), 111.

Svensson, L., & Larsson, J. (2003). "Welding and Joining of high-performance car bodies." *6th International Trends in Welding Research Conference Proceedings,* 787-792.

Tailor Steel. Home Page. http://www.tailorsteelamerica.com/. Internet. Accessed May 11, 2007.

Thomas, W., & Dolby, R. (2003) "Friction Stir Welding Developments." *6th International Trends in Welding Research Conference Proceedings,* 203-211.

World Auto Steel. "ULSAB Executive Summary." http://www.ulsab.org/ulsab/ OverviewReport/ULSAB_ExecSum.pdf. Internet. Accessed April 7, 2005.

APPENDIX

Tensile test results of DP 590 to DP 590

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	YS (mPa)	as % of base	UTS (mPa)	UTS (mPa) as % of base	% Elongation	Elongation as % of base	Failures
	8	800	?	1.8	1.8			471	71.2%	19.7	76.4%	5/5
	8	700	?	1.8	1.8			493	74.5%	14.4	55.8%	3/3
	6	800	?	1.8	1.8			497	75.1%	14.3	55.4%	3/3
	6	700	?	1.8	1.8			486	73.4%	14.4	55.8%	3/3
	8	800	1700	1.6	1.6	465	123.7%	482	80.2%	3.6	16.5%	3/3
	8	600	1700	1.6	1.6	420	111.7%	438	72.9%	3.1	14.2%	3/3
	6	800	1700	1.6	1.6	475	126.3%	524	87.2%	4.9	22.5%	3/3
	6	600	1700	1.6	1.6	450	119.7%	490	81.5%	4.3	19.7%	3/3
	8	800	?	1.6	1.6	414	110.1%	537	89.4%	5.7	26.1%	3/3
	8	700	?	1.6	1.6	414	110.1%	399	66.4%	3.7	17.0%	3/3
	6	800	?	1.6	1.6	441	117.3%	667	111.0%	18.1	83.0%	5/5
	6	700	?	1.6	1.6	285	75.8%	285	47.4%	2.5	11.5%	3/3
	40	1200	5300	1.4	1.2	370	99.5%	583	93.3%	32.3	127.2%	0/4
DP 590	8	900	2000	1.4	1.4			554	88.6%	9.9	39.0%	3/3
	8	900	2000	1.4	1.4			543	86.9%	10.9	42.9%	3/3
	8	800	2000	1.4	1.4			551	88.2%	11.4	44.9%	3/3
	8	700	2000	1.4	1.4			540	86.4%	11.7	46.1%	3/3
	8	800	2000	1.4	1.4			498	79.7%	10.1	39.8%	3/3
	8	700	2000	1.4	1.4			459	73.4%	6.6	26.0%	3/3
	6	700	2000	1.4	1.4			364	58.2%	3.8	15.0%	3/3
	6	800	2000	1.4	1.4			434	69.4%	6.5	25.6%	3/3
DP 590	30	800	5000	1.4	1.4			529	84.6%	11.3	44.5%	3/3
	35	800	5000	1.4	1.4			539	86.2%	11.4	44.9%	3/3
	40	800	5000	1.4	1.4			531	85.0%	9.3	36.6%	3/3
	40	1000	4500	1.4	1.4			554	88.6%	14.3	56.3%	3/3
	40	800	4500	1.4	1.4			565	90.4%	13.9	54.7%	3/3
	40	600	4500	1.4	1.4			543	86.9%	9.2	36.2%	3/3
	40	1000	5000	1.4	1.4			526	84.2%	10.9	42.9%	3/3
	40	800	5000	1.4	1.4			544	87.0%	13.7	53.9%	3/3
DP 590	40	600	5000	1.4	1.4			533	85.3%	8.6	33.9%	3/3
	50	800	5000	1.4	1.4			353	56.5%	11.4	44.9%	3/3
	60	800	5000	1.4	1.4			536	85.8%	9.9	39.0%	3/3
	30	800	4500	1.8	1.4	388	104.3%	574	91.8%	20.0	78.7%	3/3
	35	800	4500	1.8	1.4	368	98.9%	607	97.1%	36.5	143.7%	1/3
	40	800	4500	1.8	1.4	356	95.7%	583	93.3%	34.2	134.6%	0/3
	N/A	N/A	N/A	1.8	N/A	360	N/A	662	N/A	25.8	N/A	0/5
	N/A	N/A	N/A	1.6	N/A	376	N/A	601	N/A	21.8	N/A	0/3
DP 590	N/A	N/A	N/A	1.4	N/A	372	N/A	625	N/A	25.4	N/A	0/3
	N/A	N/A	N/A	1.4	1.4	369	99.2%	590	94.4%	19.5	76.8%	0/3

Tensile test results of DP 590 to TRIP 590 and TRIP 590 to TRIP 590

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	YS (mPa)	as % of base	UTS (mPa)	UTS (mPa) as % of base	% Elongation	Elongation as % of base	Failures
DP 590 - TRIP 590	8	800	1700	1.8	1.6	440	99.3%	607	96.8%	14.9	95.2%	5/5
	8	700	1700	1.8	1.6	435	98.2%	628	100.2%	16.1	102.9%	4/5
	6	800	1700	1.8	1.6	445	100.5%	641	102.3%	19.0	121.4%	0/5
	6	700	1700	1.8	1.6	444	100.2%	641	102.3%	18.6	118.8%	0/5
	8	800	1700	1.8	1.6			553	88.2%	16.7	106.7%	3/3
	8	700	1700	1.8	1.6			536	85.5%	10.1	64.5%	3/3
	6	800	1700	1.8	1.6			495	79.0%	8.9	56.9%	3/3
	6	700	1700	1.8	1.6			442	70.5%	8.2	52.4%	3/3
	8	800	1700	1.6	1.6	447	100.9%	496	79.1%	5.9	27.1%	3/3
	8	700	1700	1.6	1.6	295	66.6%	295	47.1%	2.6	11.9%	3/3
	6	800	1700	1.6	1.6	430	97.1%	644	102.8%	21.1	96.8%	0/5
	6	700	1700	1.6	1.6	432	97.5%	633	101.0%	21.5	98.6%	0/4
	8	800		1.4	1.6	367	98.7%	490	78.4%	10.3	40.6%	3/3
	8	700		1.4	1.6	364	97.8%	487	77.9%	9.6	37.8%	3/3
	6	800		1.4	1.6	359	96.5%	464	74.2%	8.6	33.9%	3/3
	N/A	N/A	N/A	1.4	1.6	393	105.6%	611	97.8%	31.2	122.8%	0/3
TRIP 590	8	800	1700	1.6	1.6	433	97.7%	620	98.9%	23.3	74.5%	0/5
	8	700	1700	1.6	1.6	430	97.1%	628	100.2%	27.2	87%	0/5
	6	800	1700	1.6	1.6	435	98.2%	622	99.3%	26.6	85%	0/5
	6	700	1700	1.6	1.6	414	93.5%	623	99.4%	26.6	85%	0/5
	8	800		1.6	1.6							0/3
	8	700		1.6	1.6							0/3
	6	800		1.6	1.6							3/3
	6	700		1.6	1.6							0/3
	N/A	N/A	N/A	1.6	N/A	443	N/A	627	N/A	31.3	N/A	0/5
	N/A	N/A	N/A	1.6	1.6	441	99.5%	636	101.5%	29.8	95.2%	0/4

Tensile test results of DP 780 to DP 780

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	YS (mPa)	as % of base	UTS (mPa)	UTS (mPa) as % of base	% Elongation	Elongation as % of base	Failures
	10	800		1.4	1.4	522	103.8%	605	76.3%	5.7	32.8%	3/3
	15	800		1.4	1.4	521	103.6%	617	77.8%	6.0	34.5%	3/3
	20	800		1.4	1.4	525	104.4%	676	85.2%	5.9	33.9%	3/3
	10	600		1.4	1.4	533	106.0%	607	76.5%	6.3	36.2%	3/3
	15	600		1.4	1.4	526	104.6%	694	87.5%	7.6	43.7%	3/3
	20	600		1.4	1.4	532	105.8%	714	90.0%	8.5	48.9%	3/3
DP 780	30	800	4500	1.4	1.4	522	103.8%	728	91.8%	7.5	43.1%	3/3
	35	800	4500	1.4	1.4	532	105.8%	565	71.2%	3.8	21.8%	3/3
	40	1000	5000	1.4	1.4	521	103.6%	658	83.0%	7.2	41.4%	3/3
	40	800	5000	1.4	1.4	534	106.2%	751	94.7%	9.4	54.0%	3/3
	40	600	5000	1.4	1.4	344	68.4%	372	46.9%	4.1	23.6%	3/3
	40	800	4500	1.4	1.2	592	117.7%	694	87.5%	6.1	35.1%	3/3
	40	600	4500	1.4	1.2	588	116.9%	658	83.0%	5.7	32.8%	3/3
DP 780	40	1000	4500	1.4	1.2	584	116.1%	601	75.8%	6.6	37.9%	3/3
	30	800	4500	1.4	1.2	514	102.2%	629	79.3%	7.2	41.4%	3/3
	35	800	4500	1.4	1.2	515	102.4%	568	71.6%	5.4	31.0%	3/3
	40	800	4500	1.4	1.2	565	112.3%	589	74.3%	7.2	41.4%	3/3
	10	324	4000	1.4	1.4			526	66.3%	5.7	32.8%	3/3
	15	324	4000	1.4	1.4			343	43.3%	3.9	22.4%	3/3
	15	436	4000	1.4	1.4			309	39.0%	3.1	17.8%	3/3
	15	436	4000	1.4	1.4			128	16.1%	1.6	9.2%	3/3
DP 780	20	436	4000	1.4	1.4			650	82.0%	6.5	37.4%	3/3
	10	324	4000	1.4	1.4			509	64.2%	5.3	30.5%	3/3
	15	324	4000	1.4	1.4			549	69.2%	5.5	31.6%	3/3
	20	324	4000	1.4	1.4			687	86.6%	7.6	43.7%	3/3
	20	436	4500	1.4	1.4			185	23.3%	2.4	13.8%	3/3
	15	436	4500	1.4	1.4			315	39.7%	4.5	25.9%	3/3
	10	436	4500	1.4	1.4			207	26.1%	2.4	13.8%	3/3
	10	600	3000	1.4	1.4			273	34.4%	2.6	14.9%	3/3
DP 780	15	600	3000	1.4	1.4			604	76.2%	5.9	33.9%	3/3
	20	600	3500	1.4	1.4			688	86.8%	8.9	51.1%	3/3
	10	800	3500	1.4	1.4			596	75.2%	6.6	37.9%	3/3
	15	800	3500	1.4	1.4			554	69.9%	5.6	32.2%	3/3
	20	800	3500	1.4	1.4			608	76.7%	6.7	38.5%	3/3
	N/A	N/A	N/A	1.4	N/A	503	N/A	793	N/A	17.4	N/A	0/3
	N/A	N/A	N/A	1.4	1.4	552	109.7%	830	104.7%	14.3	82.2%	2/3

Tensile test results of DP 980 to DP 980

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	YS (mPa)	as % of base	UTS (mPa)	UTS (mPa) as % of base	% Elongation	Elongation as % of base	Failures
	N/A	N/A	N/A	1.4	N/A	703	N/A	1009	N/A	15.5	N/A	0/3
	N/A	N/A	N/A	1.4	1.4	731	104.0%	1057	104.8%	11.5	74.2%	1/3
	10	800	4250	1.4	1.4			763	75.6%	4.6	29.7%	3/3
	15	800	4250	1.4	1.4			425	42.1%	2.7	17.4%	3/3
	20	800	4250	1.4	1.4			568	56.3%	2.4	15.5%	3/3
	10	600	?	1.4	1.4			582	57.7%	2.8	18.1%	3/3
DP 140	15	600	?	1.4	1.4			736	72.9%	4.5	29.0%	3/3
	20	600	?	1.4	1.4			771	76.4%	5.3	34.2%	3/3
	30	800	4500	1.4	1.4	658	93.6%	721	71.5%	4.4	28.4%	3/3
	35	800	4500	1.4	1.4	672	95.6%	816	80.9%	7.5	48.4%	3/3
	40	800	4500	1.4	1.4	641	91.2%	789	78.2%	6.3	40.6%	3/3
	40	800	5500	1.4	1.4	610	86.8%	765	75.8%	5.6	36.1%	3/3
DP 140	45	800	5500	1.4	1.4	632	89.9%	786	77.9%	6.1	39.4%	3/3
	50	800	5500	1.4	1.4	629	89.5%	645	63.9%	4.1	26.5%	3/3
	40	1000	5000	1.4	1.4			540	53.5%	4.5	29.0%	3/3
	40	800	5000	1.4	1.4			771	76.4%	5.9	38.1%	3/3
	40	600	5000	1.4	1.4			354	35.1%	4.2	27.1%	3/3
	40	1000	4500	1.4	1.2	721	102.6%	844	83.6%	5.5	35.5%	3/3
DP 140	40	800	4500	1.4	1.2	694	98.7%	820	81.3%	6.2	40.0%	3/3
	40	600	4500	1.4	1.2	579	82.4%	513	50.8%	3.4	21.9%	3/3
	30	800	4500	1.4	1.2	693	98.6%	809	80.2%	5.4	34.8%	3/3
	35	800	4500	1.4	1.2	693	98.6%	833	82.6%	6.3	40.6%	3/3
	40	800	4500	1.4	1.2	669	95.2%	813	80.6%	7.3	47.1%	3/3
	10	800	2000	1.4	1.4	648	92.2%	765	75.8%	6.3	40.6%	3/3
DP 140	15	800	2000	1.4	1.4	599	85.2%	737	73.0%	6.4	41.3%	3/3
	20	800	3000	1.4	1.4	622	88.5%	730	72.3%	5.9	38.1%	3/3
	10	600	3500	1.4	1.4	600	85.3%	751	74.4%	5.7	36.8%	3/3
	15	600	3000	1.4	1.4	580	82.5%	718	71.2%	5.5	35.5%	3/3
	20	600	3500	1.4	1.4	583	82.9%	778	77.1%	6.9	44.5%	3/3
	10	600	3000	1.4	1.4	531	75.5%	692	68.6%	5.2	33.5%	3/3
	10	800	3000	1.4	1.4	582	82.8%	694	68.8%	4.6	29.7%	3/3

Hardness test results of DP 590 to DP 590

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	Peak Hardness	Minimum Hardness	Hardness of base	Failures
	8	800	?	1.8	1.8			220	5/5
	8	700	?	1.8	1.8			220	3/3
	6	800	?	1.8	1.8			220	3/3
	6	700	?	1.8	1.8			220	3/3
DP 590	8	800	1700	1.6	1.6	223	179	220	3/3
	8	600	1700	1.6	1.6	216	179	220	3/3
	6	800	1700	1.6	1.6	224	166	220	3/3
	6	600	1700	1.6	1.6	216	172	220	3/3
	8	800	?	1.6	1.6	362	200	220	3/3
	8	700	?	1.6	1.6	355	199	220	3/3
	6	800	?	1.6	1.6	360	199	220	5/5
	6	700	?	1.6	1.6	311	191	220	3/3
	40	1200	5300	1.4	1.2	311	198	220	0/4
	8	900	2000	1.4	1.4			220	3/3
	8	900	2000	1.4	1.4			220	3/3
DP 590	8	800	2000	1.4	1.4			220	3/3
	8	700	2000	1.4	1.4			220	3/3
	8	800	2000	1.4	1.4			220	3/3
	8	700	2000	1.4	1.4			220	3/3
	6	700	2000	1.4	1.4			220	3/3
	6	800	2000	1.4	1.4			220	3/3
	30	800	5000	1.4	1.4			220	3/3
	35	800	5000	1.4	1.4			220	3/3
	40	800	5000	1.4	1.4			220	3/3
	40	1000	4500	1.4	1.4			220	3/3
	40	800	4500	1.4	1.4			220	3/3
DP 590	40	600	4500	1.4	1.4			220	3/3
	40	1000	5000	1.4	1.4			220	3/3
	40	800	5000	1.4	1.4			220	3/3
	40	600	5000	1.4	1.4			220	3/3
	50	800	5000	1.4	1.4			220	3/3
	60	800	5000	1.4	1.4			220	3/3
	30	800	4500	1.8	1.4	231	172	220	3/3
	35	800	4500	1.8	1.4	224	182	220	1/3
	40	800	4500	1.8	1.4	220	182	220	0/3
	N/A	N/A	N/A	1.8	N/A	N/A	N/A	220	0/5
DP 590	N/A	N/A	N/A	1.6	N/A	N/A	N/A	220	0/3
	N/A	N/A	N/A	1.4	N/A	N/A	N/A	220	0/3
	N/A	N/A	N/A	1.4	1.4	411	201	220	0/3

Hardness test results of DP 590 to TRIP 590 and TRIP 590 to TRIP 590

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	Peak Hardness	Minimum Hardness	Hardness of base	Failures
DP 590 - TRIP 590	8	800	1700	1.8	1.6	312	180	210	5/5
	8	700	1700	1.8	1.6	255	177	210	4/5
	6	800	1700	1.8	1.6	406	172	210	0/5
	6	700	1700	1.8	1.6	380	169	210	0/5
	8	800	1700	1.8	1.6			210	3/3
	8	700	1700	1.8	1.6			210	3/3
	6	800	1700	1.8	1.6			210	3/3
	6	700	1700	1.8	1.6			210	3/3
	8	800	1700	1.6	1.6	392	198	210	3/3
	8	700	1700	1.6	1.6	417	202	210	3/3
	6	800	1700	1.6	1.6	404	198	210	0/5
	6	700	1700	1.6	1.6	420	197	210	0/4
	8	800		1.4	1.6			210	3/3
	8	700		1.4	1.6			210	3/3
	6	800		1.4	1.6			210	3/3
	N/A	N/A	N/A	1.4	1.6	480	219	210	0/3
TRIP 590	8	800	1700	1.6	1.6	294	195	210	0/5
	8	700	1700	1.6	1.6	304	192	210	0/5
	6	800	1700	1.6	1.6	376	190	210	0/5
	6	700	1700	1.6	1.6	356	191	210	0/5
	8	800		1.6	1.6	452	215	210	0/3
	8	700		1.6	1.6	351	210	210	0/3
	6	800		1.6	1.6	444	211	210	3/3
	6	700		1.6	1.6	335	195	210	0/3
	N/A	N/A	N/A	1.6	N/A	N/A	N/A	210	0/5
	N/A	N/A	N/A	1.6	1.6	476	221	210	0/4

Hardness test results of DP 780 to DP 780

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	Peak Hardness	Minimum Hardness	Hardness of base	Failures
	10	800		1.4	1.4	281	203	270	3/3
	15	800		1.4	1.4	249	201	270	3/3
DP 780	20	800		1.4	1.4	287	205	270	3/3
	10	600		1.4	1.4	281	202	270	3/3
	15	600		1.4	1.4	301	220	270	3/3
	20	600		1.4	1.4	296	203	270	3/3
	30	800	4500	1.4	1.4	367	224	270	3/3
	35	800	4500	1.4	1.4	355	248	270	3/3
	40	1000	5000	1.4	1.4	336	207	270	3/3
	40	800	5000	1.4	1.4	287	229	270	3/3
	40	600	5000	1.4	1.4	300	224	270	3/3
	40	800	4500	1.4	1.2	277	240	270	3/3
DP 780	40	600	4500	1.4	1.2	277	240	270	3/3
	40	1000	4500	1.4	1.2	277	216	270	3/3
	30	800	4500	1.4	1.2	289	232	270	3/3
	35	800	4500	1.4	1.2	277	219	270	3/3
	40	800	4500	1.4	1.2	308	221	270	3/3
	10	324	4000	1.4	1.4			270	3/3
	15	324	4000	1.4	1.4			270	3/3
	15	436	4000	1.4	1.4			270	3/3
	15	436	4000	1.4	1.4			270	3/3
	20	436	4000	1.4	1.4			270	3/3
DP 780	10	324	4000	1.4	1.4			270	3/3
	15	324	4000	1.4	1.4			270	3/3
	20	324	4000	1.4	1.4			270	3/3
	20	436	4500	1.4	1.4			270	3/3
	15	436	4500	1.4	1.4			270	3/3
	10	436	4500	1.4	1.4			270	3/3
	10	600	3000	1.4	1.4			270	3/3
	15	600	3000	1.4	1.4			270	3/3
	20	600	3500	1.4	1.4			270	3/3
	10	800	3500	1.4	1.4			270	3/3
DP 780	15	800	3500	1.4	1.4			270	3/3
	20	800	3500	1.4	1.4			270	3/3
	N/A	N/A	N/A	1.4	N/A	N/A	N/A	270	0/3
	N/A	N/A	N/A	1.4	1.4	427	245	270	2/3

Hardness test results of DP 980 to DP 980

Material	Feed (IPM)	Speed (RPM)	Z-Force (lb)	gauge (mm)	gauge (mm)	Peak Hardness	Minimum Hardness	Hardness of base	Failures
DP 140	N/A	N/A	N/A	1.4	N/A	N/A	N/A	330	0/3
	N/A	N/A	N/A	1.4	1.4	496	260	330	1/3
	10	800	4250	1.4	1.4			330	3/3
	15	800	4250	1.4	1.4			330	3/3
	20	800	4250	1.4	1.4			330	3/3
	10	600	?	1.4	1.4			330	3/3
	15	600	?	1.4	1.4			330	3/3
	20	600	?	1.4	1.4			330	3/3
DP 140	30	800	4500	1.4	1.4	395	242	330	3/3
	35	800	4500	1.4	1.4	374	232	330	3/3
	40	800	4500	1.4	1.4	366	236	330	3/3
	40	800	5500	1.4	1.4	348	251	330	3/3
	45	800	5500	1.4	1.4	326	223	330	3/3
	50	800	5500	1.4	1.4	380	240	330	3/3
DP 140	40	1000	5000	1.4	1.4			330	3/3
	40	800	5000	1.4	1.4			330	3/3
	40	600	5000	1.4	1.4			330	3/3
	40	1000	4500	1.4	1.2	392	236	330	3/3
	40	800	4500	1.4	1.2	374	225	330	3/3
	40	600	4500	1.4	1.2	382	217	330	3/3
	30	800	4500	1.4	1.2	364	209	330	3/3
	35	800	4500	1.4	1.2	363	219	330	3/3
	40	800	4500	1.4	1.2	338	223	330	3/3
DP 140	10	800	2000	1.4	1.4	369	210	330	3/3
	15	800	2000	1.4	1.4	328	203	330	3/3
	20	800	3000	1.4	1.4	309	208	330	3/3
	10	600	3500	1.4	1.4	350	207	330	3/3
	15	600	3000	1.4	1.4	331	208	330	3/3
	20	600	3500	1.4	1.4	324	223	330	3/3
	10	600	3000	1.4	1.4				3/3
	10	800	3000	1.4	1.4				3/3