Prospect of Friction Stir Welding in Automobile TWB Production as Alternative of Laser Welding

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Abstracts:
In some situation, commonly used welding processes (Laser and Seam welding) in car industry do not produce mechanically acceptable Tailor Welded Blanks (TWB). The present work explores whether the Friction Stir welding (FSW) can overcome three major drawbacks of Laser welding process to produce TWB for car industry. It is identified that some types of Aluminum to Aluminum joints, some combinations of High Strength Steels (HSS) to HSS joints and Steel to Aluminum joints are troublesome to produce by laser welding. Review of literature was used to get experimental and simulation results to a comparison of the results produced by Laser and FSW. Findings indicate that in many cases better mechanical qualities such as formability, hardness, tensile and yield strength of the welded joints and TWB can be achieved by using FSW, implying interesting alternative in car manufacture.

Keywords:
Tailor Welding Blanks, Friction Stir Welding, Laser Welding, Automobile
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1 Notations

Abbreviations

AHSS- Automotive High Strength Steel
CCD tests- Cylindrical Cup Drawing tests
DP steel –Dual Phase Steel
FSW – Friction Stir Welding
HAZ- Heat Affected Zone
HDS tests -Hemisphere Dome Stretching tests
HSLA steels –High Strength Low Alloy Steels
PCBN- Cubic Born Nitride
TMAZ- Thermo-Mechanically Affected Zone
TRIP steel– Triple Phase Steel
TWB - Tailor Welded Blank
UM- Unaffected Material of weld
UTS- Ultimate Tensile Strength
WN- Welding Nugget of weld
2 Introduction

The present work explores, whether the Friction Stir Welding (FSW) can overcome three major drawbacks of Laser welding process to produce Tailor Welded Blanks (TWB) for car industry.

2.1 Background

Tailor-welded blanks (TWB) allow auto industries to improve design, construction and performance in ever competitive field of car industry. But, TWBs are limited to some degree when the laser welding process is used for producing TWB because of its difficulty in joining some alloys and low tensile elongation of laser welds.

Additionally, Seam weld can show a larger formability with respect to the laser one but it is much more visible and may affect the cathodic protection in galvanized tailored blanks. The both laser and seam welding process develop martensitic structures, which strongly reduce the local elongation to fracture of the base material.

This is why other options like stir welding should be explored for further improvement. This kind of welding process develops no martensitic structures. And produces higher quality welds with fewer defects and material properties closer to the parent materials. And it is much more forgiving with regards to the edge quality when creating a functional weld [1].

If it is found in research that FSW is technically feasible to produce TWB and which also can solve the drawbacks of laser welding within economical strains then with further research, engineer will have more design options and material options for producing TWB [2].
2.2 Research question

Most used laser Welding in auto industry has some limitation in creating TWB, both in capacity to make an acceptable weld and having good formability in the weld materials.

Specifically below mentioned areas or joining is difficult with laser weld, as it reduces ductility and quality after welding.

1. Quiet steels and the high end of DP and TRIP steels are very hard to laser weld.
2. Some types of aluminums (2xxx and 7xxx series) cannot be weld
3. Also some combinations such as steel to aluminum cannot be done with a laser [3].

But, I intend to find out whether those claims are accurate or not and if not, are those problems are solvable by Friction Stir Welding process to produce TWB.

2.3 Aim and Scope

This dissertation is based on previous literatures review, so It relies on the quality and properties of those literatures presented data, mainly about welds data, like tensile, formability and micro hardness testing results.

In addition, no economic analysis was performed to determine economic feasibility. Only faster travel speeds of tool to make joints by stir welding more economical [2] was considered. As, faster travel speed of welding tool will increase mass production.

2.4 Method and Structure

Literature Review of the past papers was used as method of study for this thesis. This method was considered, as there was enough literature to organize, structuring the thesis, and draw necessary information from those literature.
This method was used to find weldibility and Formability of Tailor Welded Blanks produce by Laser welding process and Friction Stir Welding process in car industry.

The thesis is structured according to below areas.

- Tailor Welded Blanks: This area of thesis gives hint of what Tailor Welded Blanks (TWB) is. And why they are of interest to have in car production, how they are produced, potential for improvements in terms of performance and manufacturing.

- Material Considerations: these area covers motivation to why strong lightweight materials are of interest in design, what materials are of interest to study, why it is a benefit to combine different types of materials and challenges in manufacturing structures maintaining intended material properties

- Welding process: This area of thesis gives overview of the laser welding and the friction stir welding processes, typical characteristics, benefits, limitations and expected productivity.

- Joining and formability performance: this portion covers, survey of found published results on joining and formability performance of laser welded vs. friction stir welded combinations of blanks. And it intends to give structured presentation organized by material combinations and thickness combinations (and other parameters of interest). Results are included for both experimental and simulation studies. A summarizing comparison of performance is made with respect to stated criteria found to be relevant.
3 Tailor Welded Blanks (TWB)

Generally TWBs are produced from two or more sheets that have been welded in single plane to form it into different shapes. Different materials and thickness can be combined by TWB. Tailor-welded blanks are used to reduce the weight of the automobile and that in turn increases fuel efficiency of the auto. Tailor-welded blanks are becoming more popular day by day in auto industry when oil prices are increasing and environmental wellbeing is consider important.

Besides reducing weight, TWB can improve crash performance of the auto body. It has become possible by using high strength materials or thick materials in areas where stress is too high and using soft deep drawing materials in other areas of the automobile [4]. TWB brings big improvement in not only in single parts but also in whole automobile. It also helps to reduce car noise or vibration, material waste, stamping cost.

Noise reduces as fewer dies, stamps and forming operations are required when welding is used for joining together in the auto [5]. In TWB, waste becomes lesser because thinner material is used and there is no need to use any extra material in large opening. And fewer stamps, dies and forming operations can reduce the Stamping cost for the same parts [6]. Improved dimensional tolerances, increased part stiffness, reduced manufacturing costs, improved corrosion resistance are other benefits of tailor welded blanks make it more preferable option.

Limitations of Laser welding or Seam welding limit the quality of the tailor welded blanks (TWB). TWB, produce by laser welding, generally has problem like reduction of ductility or formability. Study shows that increased ductility is possible in stir welds. But to produce TWB by stir welding as an alternative of laser welding, it must show better or equal mechanical properties like strength and ductility than that of laser welding does [2].
4 Material Considerations

Car manufacturers are developing cars which need less fuel consumption, have higher safety level and are more cost effective. It is possible by better design and introducing light and stronger materials in automobile production. Strength and formability of the material should be maintained in TWB production.

In short, Strong lightweight materials are of interest in design as
- It reduce the weight of the automobile
- It reduces the fuel consumption or better mileage
- Better design and higher safety level in automobile can be found by using those materials.

4.1 Automotive High Strength Steel (AHSS)

Besides steel, high strength steels are used these days. The Automotive High Strength Steel (AHSS) can give higher strength levels with improved formability and crash-energy absorption compared to the current High Strength Low Alloy (HSLA) grades. This requirement is fulfilled by the DP and TRIP grades of steel. Which have increased values of the work hardening exponent [7]. Mechanical properties like weld ability and Formability are most important characteristic of High strength steels to produce better Tailor Welded Blanks.

4.1.1 Dual-Phase (DP) Steels

DP steels have a microstructure of mainly soft ferrite, with islands of hard martensite dispersed throughout. The strength level of these grades is related to the amount of martensite in the microstructure [8].

Figure 4.1. Formed Panel Strength [8].
As the product arrives from the steel mill, its yield strength typically is much lower than its tensile strength, with a YS-to-TS ratio of about 0.6. (For comparison, the YS-to-TS ratio for HSLA steels is closer to 0.75.) The lower yield strength at a given tensile strength translates to higher elongation values and better formability [8].

In addition, the work-hardening response to deformation is different between DP and HSLA steels. HSLA steels begin to lose formability as soon as deformation starts. As a result of the soft ferrite matrix of DP steels, they can maintain their formability further into the press stroke and can better distribute the strains across the part.

It can be seen from Figure 4.1, DP steels usually are bake-hardenable (strengthening occurs after the steel goes through a paint-bake cycle), whereas HSLA steels do not exhibit this characteristic. Between this bake hardenability and the higher level of work hardenability, it is not unusual to see an increase in yield strength of about 140 MPa (20 KSI) after forming and baking. In comparison, HSLA steels may have an increase of about 20 MPa (3 KSI).

Enhanced energy absorption is another DP steel characteristic. For a given yield strength, the DP steel tensile strength is higher than that of HSLA steels, which enhances crash performance. If crash performance equivalent to that of an HSLA steel is desired, using a DP steel may allow for down gauging of about 10 percent.

DP steel weldability usually is similar to that of HSLA steels, although different parameters may be required. The welding current range is almost the same (about 3 kiloamps), but the actual currents may be somewhat shifted [8].

4.1.2 Transformation Induced Plasticity (TRIP) Steels

Like DP steels, the microstructure of TRIP steels is comprised of mainly soft ferrite. While DP steels have martensite as the only other phase, TRIP steels have a combination of martensite, bainite, and retained austenite. The various levels of these phases give TRIP steels their unique balance of properties [8].
Figure 4.2 shows the stress-strain curves for a HSLA steel, a DP steel, and a TRIP steel, each with a yield strength of about 350 MPa (50 KSI). As forming continues, the retained austenite in TRIP progressively transforms to martensite with increasing strain. This leads to a volume and shape change within the microstructure, which accommodates the strain and increases the ductility. In TRIP steels, the high work-hardening rate persists at higher strains, while that of DP begins to diminish. This work-hardening difference is one of the primary reasons for the enhanced formability of DP steels over HSLA steels, and this is what that gives TRIP steels a further advantage over DP steels.

The strain level of retained austenite-to-martensite transformation can be engineered through carbon content adjustment. If lower carbon levels are used, transformation starts at the beginning of forming, leading to excellent formability and strain distribution at the strength levels produced. At higher carbon levels, retained austenite is more stable and persists into the final part. The transformation occurs at strain levels beyond those produced during stamping and forming. Transformation to martensite occurs during subsequent deformation, such as a crash event, and provides greater crash energy absorption.
4.2 Aluminum and Combining Dissimilar Materials

Low density of Aluminum helps to reduce auto part weight. That improves the oil efficiency of the automobile. It was found 100 pound reduction in car weight can reduces up to 2% fuel consumption of an automobile [9]. Another study shows, 1% reduction in vehicle weight may results in a .6 to 1% reduction in fuel consumption [9].

Material model for aluminum alloy
Aluminum can be modeled more precisely by empirical material model, as shown figure 6.6, and that was developed based on experimental results [10].

\[ k_f(\dot{\phi}, T) = a_a + b_a \cdot T + c_a \cdot T^2 - a_b \cdot (T - b_b) \cdot \ln(\dot{\phi} + a_c + b_c \cdot T + c_c \cdot T^2) \]

Figure 6.6. Stress vs. strain for aluminum alloy EN-AW 6060. Comparison between the proposed empirical material model with experiments and the best fit Johnson-Cook model [11].
Both Aluminum and High Strength Steels used by auto industry for making light weight automobile these days. Joining of different materials has been given much attention in recent years due to their superior functional capabilities. One such combination of dissimilar materials is of aluminum with steel due to its potential application in aerospace and automotive industries [12, 13, 14].

Aluminum has good strength to density ratio, good formability characteristics and is light in weight. Steel has good formability characteristics and strength. Hence, the use of aluminum–steel tailor-welded blanks (Al–steel Tailor Welded Blanks) can be exploited in producing components such as car door inner panel [14], where rigidity at the hinge portion and lightweight at other portions is a necessity.
5 Welding Process

In general, car manufacturers use resistance Mash seam welding or Laser welding process to produce TWBs are the mash seam welding and the laser welding [15, 16].

5.1 Laser Welding

In laser beam welding, laser beam is used to joint metals or sheets. Here laser beam is the source of concentrated heat which is the reason we get deep and narrow welding with high welding rates. This type of process is mainly used for high volume auto industry production.

Typical characteristics of laser welding are

- Laser used in this type of welding can be transmitted through air. And Laser welding is fast, precise, can join a wide variety of materials. Low Heat Input, deep penetration, fast cooling and high hardness are possible in this type of welding.
- Usually, depending on various parameters, laser welding is able to weld from 3.4 – 4.6 meters (12 – 15 feet) per minute. In laser welding 100 percent uptime is possible and most of the work can be done by robots [5].
- Speed and reliability is the main advantage to choose it as a current method of welding or creating TWB.

But Laser welding is not totally perfect as it does not produce good quality Tailor Welded Blanks (TWB) every single time. Laser welding process requires high edge tolerance to create a functional weld. High level of precision is needed for Laser welds as laser welding are narrow and run at a very high speeds. For laser welding .08 mm of edge tolerance is needed [17]. For these tight tolerances, special tooling is needed and weld lines generally are kept linear.

Second problem is high hardness of weld zone, which is prone to brittle failure in the forming operations that TWB undergoes. This is why; design engineer need to consider weld location of the weld before forming
operation is done in TWB. Engineers are forced to design around each weld location which is not optimal use of materials.

Some materials cannot be weld properly by laser welding. For instance, some high strength steel like DP steels, TRIP steels, quiet steels (a sandwich of steel and plastic), and aluminums are not suited to laser welding.

5.2 Friction Stir Welding

It is quite a new technology but with huge potential or applications. It was invented and experimentally proven by Wayne Thomas and a team of his colleagues at The Welding Institute (TWI) UK in December 1991. TWI holds a number of patents on the process, the first being the most descriptive [1].

Welds produced by FSW have a higher strength and formability due to the low welding temperatures compared to fusion welding processes [18].

Friction-stir welding (FSW) is a solid-state joining process (meaning the metal is not melted during the process) and is used for applications where the original metal characteristics must remain unchanged as much as possible [19].

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, FSW is much more forgiving with regards to the edge quality when creating a functional weld [1].

At the beginning, Materials with Lower melting temperature like Aluminum was used to join together by FSW. After that many research and development was carried out, and now it is possible to join harder materials like steels, stainless steels, and titanium. For harder materials, hard tool like Polycrystalline Cubic Born Nitride (PCBN) is used which is harder and has higher melting temperature [20].
5.2.1 Friction Stir welding process

In this welding process, a cylindrical-shouldered tool, with a profiled threaded/unthreaded probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together [21].

![Friction Stir Welding process](image)

*Figure 5.1. Friction Stir Welding process [10].*

The parts have to be clamped rigidly onto a backing bar in a manner that prevents the butting joint faces from being forced apart. The length of the nib is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface. The nib is then moved against the work, or vice versa [21].
Frictional heat is generated between the wear-resistant welding tool shoulder and nib, and the material of the work. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, causes the stirred materials to soften without reaching the melting point (hence cited as solid-state process), allowing the traversing of the tool along the weld line in a plasticized tubular shaft of metal. As the pin is moved in the direction of welding, the leading face of the pin, assisted by a special pin profile, forces plasticized material to the back of the pin while applying a substantial forging force to consolidate the weld metal. The welding of the material is facilitated by severe plastic deformation in the solid state, involving dynamic re-crystallization of the base material [22].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effects</th>
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<td>Rotation speed</td>
<td>Frictional heat, “stirring”, oxide layer breaking and mixing of material.</td>
</tr>
<tr>
<td>Tilting angle</td>
<td>The appearance of the weld, thinning.</td>
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<tr>
<td>Welding speed</td>
<td>Appearance, heat control.</td>
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<tr>
<td>Down force</td>
<td>Frictional heat, maintaining contact conditions.</td>
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*Table 2.1. Main process parameters in FSW [23]*.
Above table 2.1 shows, how heat is produced and be controlled by Friction Stir Welding parameters like rotation speed, tilting angle of the welding tool, welding speed and down force of the tool welding tool.

5.3 Laser versus Friction Stir Welding

To produce TWB in auto industry, Laser welding has been used efficiently. But to survive in this competitive car industry it’s necessary to adapt new technology or work on further developments of existing technology.

Even though, laser welding technology has been most used welding process so far, it’s not without limitations. For instance some of its drawbacks are

- Poor welding quality in some cases.
- Required high edge tolerance.
- In ability to join some materials.
- And laser machine or robot high cost.

So, there need to have some improvement in laser welding process to create an optimum TWB with laser welding technology.

This is the reason other welding technology should be explored. FSW is one of the methods that should be researched as it can counter above mentioned drawbacks of laser welding technology. Since it was found, welds produced by FSW have a higher strength and formability due to the low welding temperatures compared to fusion welding processes [18]. And FSW machine costs a fraction of laser machine which is about 20% to 10% [2].

As mentioned, problem areas of laser welding process, that some materials cannot be weld by laser technology properly, might be weld by FSW technology but must be studied on per-material basis.

However, FSW has some drawbacks too. Some of those are traveling speed of the tool or welding speed is bit low compared to laser welding traveling speed. Welding speed depends on thickness of the material. For the same thickness of material, weld in steel runs lower in speed than Aluminum weld speed. In addition, welding parts also require a fairly large clamping force to withstand the torque generated during the friction stir welding process [1].
6 Joining and formability performance

A survey of previously published results on joining and formability performance of laser welded vs. friction stir welded combinations of blanks will be presented. Both experimental and simulation results will be studied and welding parameters like material combination, thickness, welding direction and other relevant welding parameters will be consider to explain the influence on the weld’s joining and formability performance.

6.1 Al and steel joining

Joining and formability performance of laser welded vs. friction stir welded aluminum and steel combinations of blanks will be discussed here. Joining and formability performance of laser welds fails as

- Formation of brittle intermetallic compounds,
- Poor wetting behavior of Aluminum,
- Difference in physical and chemical properties of the Al and steel alloy [12,13]. The melting temperatures of aluminum and steel are quite different.

Conventional fusion welding processes do not yield a sound joint in case of dissimilar metals joining. In addition, fusion welding produces high concentration of intermetallic compounds that are detrimental to the joint. Intermetallic phases Fe4Al13 and Fe2Al5 are predominantly found to exist in Laser welding [24].

Some combinations such as steel to aluminum cannot be joined together in mass production before [3]. Forming difficulties are encountered at higher strength levels, since, the strain hardening value tends to fall with strength level. The appearance of an inter-metallic phase is the main drawback to join Steel and Aluminum [19], which influences the product life of the welded assemblies negatively [25].

Moreover, Friction Stir Welding out-performs other techniques in the production of such sound weld interface, especially in sheet metal
applications. It has an edge over other techniques, since; it has low energy input, short welding time, low distortion, and relatively low welding temperature, which are essential criteria for Al–steel welding [24].

Figure 6.1. Stress-strain curves of aluminum and steel alloy [26].

An example of the tensile strength properties of different steel and Aluminum is shown in figure 6.1.

6.1.1 Preheated FSW

In one study, Aluminum–steel was welded by FSW and was studied, where welding was done by pre heating steel with laser [22]. Steel DC04 and aluminum alloy AA6016 was used for this joining process and their weld ability and formability was investigated.

As shown on table 6.1, Tailor Welded Blanks made by butt joint of Al and steel is possible with good welding feed up to 2000 mm per min with FSW by pre heating joined materials. Moreover, lesser need of clamping force in in Friction stir welding (FSW) of these blanks is basically enabled by preheating the steel by a diode laser spot.
Table 6.1 Parameter setting for the stir welding [27].

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From above Table 6.1, it can be said that good feed is possible in stir welding with the help of laser pre heating for up to one mm thick Aluminum.

6.1.2 Tensile strength of the welded joints

Below Table 6.2 shows tensile strength of the welded joint is about 80% of the tensile strength of unaffected Aluminum base material. Tensile tests of these welded blanks confirm high tensile strength of up to 200 MPa [27].

Figure 6.2. Tensile Strength for Different Welding Parameter [27].
6.1.3 Formability of the weld

Below figures show the good formability of the Tailored Hybrids produced by Steel and Aluminum. Below Figure 6.3 shows the deep drawing ratio 1.6 for the combination of steel (DC04) and Aluminum (AA6016) blank. It breaks at 1.8 drawing ratio.

![Figure 6.3. Results on deep drawing of laser assisted FSW steel aluminum circular blanks [27].](image)

Above section 6.1.1, 6.1.2 and 6.1.3, indicates that laser-preheated stir-weld of Al-steel can have good tensile strength and formability and feed speed. This is promising to use in auto industry to produce TWB.

This procedure can be regarded as a very promising step as no intermetallic phases between steel and aluminum have been detected even by preheating the steel sheet with a diode laser spot.

6.1.4 Simulation

Formability or Deep drawing ability of Al–steel TWBs, depends on punch force, weld materials properties (Al, steel and weld line properties of TWB) and also on geometry of TWB. Though the evolution of the punch force is based on the combined properties of the constituent materials, yet it depends mainly on the material hardening parameters of stronger material.
After, Aluminum alloy (AA6016-T4) was welded with mild-steel (DC06) and High Strength Steels (AISI-1018, HSLA-340, and DP600) to form four different Al–steel tailor-welded models [28] and formability of those Aluminum -Steel Tailor Welded Blank (TWB) was studied numerically while deep drawing was used for formability investigation.

Here, among those welding materials, steel is the stronger and has bigger impact on the punch force which is shown in figure 6.4.

![Figure 6.4. Punch force evaluation [26].](image)

6.1.5 Summary

By introducing Lower blank holder force on higher strength material side, the tendency of tearing in weaker material parallel to the weld line can be reduced. Fairly uniform thickness distribution is observed in all combinations of Al–steel tailor-welded blanks. Different blank holder forces enhance the formability of tailor-welded blank as well as control the draw-in.

Aluminum alloys are relatively weaker compared to steel and have the tendency to flow more than steel Which is the reason for weld line shifting
toward steel in deep drawing process. Shifting of the weld line has less impact on formability; this is because it is small size and bigger gradient in weld sheet mechanical properties in them.

Preheating of steel or different punch force on the weld materials can ensure balanced material flow in Steel and Al. This can lead to good formability which is important to make Tailor Welded Blank.

6.2 Al-Al joining

Aluminum is used to produce light weight, fuel-efficient vehicles. Different papers were studied to find out weldability and formability of different Al alloys.

Formability performance is generally measured by simple tension with two weld line directions, Hemisphere Dome Stretching (HDS) or Cylindrical Cup Drawing (CCD) tests.

6.2.1 TWB of Aluminum alloys- by Laser welding:

Due to Aluminum’s high reflectivity, low molten viscosity and inherent oxide layer, conventional laser welding leads to hot cracking in the fusion zone and the poor coupling during welding process [29, 30, 31]. For instance Laser welding does not produce favorable welding between Al 2xxx and 7xxx series [32].

6.2.2 Weldability of Aluminum alloys - produce by Friction Stir welding

Many studies on FSW based on experiments and simulations [33, 34] are mainly focused to understand the process itself, especially the effect of process parameters (tool geometry, tool materials, rotation speed, moving speed, tool angle, base materials and their arrangement in the advancing or retreating sides, base material thickness) and on the quality of welding
(temperature distribution, material flow or deformation, microstructure, mechanical properties in the welded area, hardness, residual stress, defects, texture).

6.2.3 Relation between thicknesses rations and join-ability

There is strong relation between thickness ratio of the welding sheets and their mechanical properties. For instance, when different thickness and different aluminum alloys combinations like 2024-T3 and 7075-T6 sheets were joined by friction stir welding, almost 80% of mechanical tensile strength was found for up to ratio 2 [35].

Given below Table 6.2 and Figure 6.5 supports above claim. Change of thickness ratio of the joining welding material has impact on mechanical property of strength. In order to get a sound welding or to get effective joints from the mechanical resistance point of view, thermal pro-files in each blank should be as similar as possible, so that the recrystallization and aging in HAZ phenomena are similar. In turn, a wrong choice of the process parameters would determine an uneven heat flux.

<table>
<thead>
<tr>
<th>Series no.</th>
<th>Material I</th>
<th>$t_1$ (mm)</th>
<th>Material II</th>
<th>$t_2$ (mm)</th>
<th>$t_1/t_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2024-T3</td>
<td>2.0</td>
<td>2024-T3</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>2024-T3</td>
<td>2.0</td>
<td>2024-T3</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>2024-T3</td>
<td>2.5</td>
<td>2024-T3</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>2024-T3</td>
<td>2.0</td>
<td>7075-T6</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>7075-T6</td>
<td>2.0</td>
<td>7075-T6</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 6.2. different and thickness configuration used in the welding of 2024-T3 and 7075-T6[27].

It was found that the micro-structural features and hence mechanical properties of the welds were significantly different from those of the same-alloy - same-thickness welds.
FSW of TWBs is feasible, but particular attention must be given to the choice of the operative parameters. Like, shoulder geometry and the two nuting angles, are critical factors in obtaining sound joints with nugget integrity [26].

### 6.2.4 Simulation

Simulation can be used to get insight of different types of Al alloys joined too by stir welding. Improved material model for aluminum alloys and the level set method can be used for that. Simulation and modeling of the friction stir welding process tries to give explanations for the complex process behavior due to the complex interactions of temperature, material properties, external forces and material interactions.

A great number of publications on FSW Finite Element Method (FEM) models have been published up to now, using the Lagrangian (ALE) as well as the Eulerian (CFD) approach. As high strains observed within the welding zone and material flow is considered throughout the welding zone the CFD approach is realistic and likely to give better simulation result [36].
And Aluminum can be modeled more precisely by empirical material model and can be seen in figurexxx chapter 4 material consideration. James-Coock model will be appropriate to use it make

6.2.5 Relation between Thickness ration and Formability

For the formability evaluation of TWB, geometrical factor from thickness variation should be also considered during forming process. Based upon works by Cayssials [28], formability of TWB decreases as the strength–thickness ratio of the base material increases [37].

Also pointed out that the formability of the dissimilar gauged TWB is mainly affected by the thickness of the thinner part so that the forming limit level decreases as the thickness ratio increases. The welding speed may also affect the formability of TWB. For a given material and welding process, a specific welding speed exists to produce the improved ductility [38].

Sato et al [13] examined that particular welding parameters to create the large sub-grain size can give the high fracture limit strain for friction stir welded aluminum material. However, in general, the difference in welding conditions gives only marginal effect on formability [39]. Thickness ration has negative effect in formability.

6.2.6 Rolling Direction and Transverse Direction Effect

Both weldibility and formability of TWB are influenced by the welding directions. And Formability performance of the weld was measured by three forming operations including the simple tension with two weld line directions, hemisphere dome stretching and cylindrical cup drawing (CCD) tests [39].
In order to evaluate the formability of friction stir welded (FSW) automotive Tailor Welded Blank (TWB) Sheets, joined material Aluminum alloy 6111-T4 sheet was joined with three different combination. Above Figure 6.7 shows the hardening properties of weld zones of different welding combinations. Lower strength with reduced ductility compared to those of base material was found in those welding combination. As for the material direction, the strength and ductility slightly became better in the order of RD||RD, TD||RD and TD||TD. But all three forming tests also showed that the weld zone of RD||RD types exhibited the better formability, while TD||TD showed the least [39].

6.2.7 Metal properties and weld line arrangement Effect

There is relation between formability of the TWB and welded materials properties weld zone line arrangement. For instance, one of the formability test (Hemispherical dome stretching test) results and numerical analysis shows that, for the formability performance of the weld samples compared to that of the base sheets, the improved ductility of the weld promoted the performance for AA5083-H18 (work-hardened non-heat-treatable) and AA6111-T4 (heat-treatable).
However, the weld strength was lower for all TWB samples than welded materials, except AA5083-O (annealed non-heat-treatable) so that their TWB samples were vulnerable to the strain localization. Therefore, aligning the weld zone properly to avoid strain localization and to take advantage of the improved weld zone ductility would be important in the process design, particularly for AA6111-T4, AA5083-H18 TWB sheets [39].

6.2.8 Aluminum Alloys (AA 5182-H111 and AA 6016-T4)

Aluminum Alloys (AA 5182-H111 and AA 6016-T4) are very popular in automotive industry. The TWBs were made from 1 mm thick plates by considering similar (AA 5182-H111/AA 5182-H111 and AA 6016-T4/AA 6016-T4) and dissimilar (AA 6016-T4/AA 5182-H111) combinations of both types of base materials [40].

![Figure 6.8. The punch force-displacement curves [40].](image)

The formability behavior of the TWBs was analyzed by stamping Axissimetrical Cylindrical Cups in a Deep-Drawing laboratorial testing device specially developed to work in a classical tensile test machine. The main reported results were the punch force-displacement curves and geometrical data from the Axissimetrical Cylindrical Cups [40].
Despite the relative homogeneity in mechanical properties across the welds revealed by the hardness measurements, as shown in Figure 6.9, the similar TWBs suffer strong wrinkling under the same test conditions of the base materials. But you should know, wrinkling is one of the main reasons of failure for formable TWB. This behavior can be associated with severe changes in material microstructure, surface finishing and thickness of the weld relative to the base material, which induces non-homogeneous behavior of the blank. Optimization of the process parameters for the stamping of the Aluminum TWBs is currently in progress [40].

6.2.9 Summery

In general, formability performance of the friction stir welded TWB sheets in forming processes was dependent on the weld zone line arrangement as well as the weld zone ductility and strength. If the major principal loading direction was aligned with the weld zone line, weld zone ductility was more important, while the strength of the weld zone was more important if the major principal loading direction was vertical to the weld zone line. Therefore, when the friction stir welded TWB sheets are applied for real forming parts, designing of the weld line arrangement should be elaborately considered together with the precise material characterization of the weld zone [41].
6.3 High strength steel joining to produce TWB

DP and TRIP steel materials are most used materials in auto industry. Here, I intend to find out, whether quiet steels and the high end of DP and TRIP steels are possible to Laser weld or Friction Stir weld to produce TWB.

6.3.1 Steel Joining Problems by laser welding

Softening, caused by both excessive heat and insufficient heat can result in weld failure. Lack of 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 [2].

6.3.2 Steel Welds produced by Friction Stir Welding

Friction Stir welding of high strength auto steels was studied to find out the weldability of high strength steel. For that, tensile strength and hardness data were compared from the base material were compared to laser welded and friction stir welding samples [2].

6.3.3 Tensile strength and Hardness

Welds of material DP 590 were created using laser welding as well as the friction stir welding process. Below Table 6.3 shows the comparison between laser and friction stir welding samples.

<table>
<thead>
<tr>
<th></th>
<th>YS in % of base</th>
<th>UTS in % of base</th>
<th>Elongation in % of base</th>
<th>Speed (cm/min)</th>
<th>Acceptable welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Material</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Laser Weld</td>
<td>99%</td>
<td>94%</td>
<td>77%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>FSW 1.8 - 1.4</td>
<td>95%</td>
<td>93%</td>
<td>134%</td>
<td>up to 508</td>
<td>3/3</td>
</tr>
<tr>
<td>FSW 1.4 - 1.2</td>
<td>100%</td>
<td>93%</td>
<td>127%</td>
<td>102</td>
<td>3/3</td>
</tr>
</tbody>
</table>

Table 6.3. Welding in DP590 [2].
Acceptable welds were created in DP 590 both with laser and friction stir welding. Table 6.3 shows, relatively high speed, 102cm/min, with acceptable welds were obtained with friction stir welding indicating a possible substitution for laser welding, based on tensile test results [2]. Below Table 6.4 shows comparison among base material, laser weld and friction stir weld for TRIP 590. As with the DP 590, the TRIP 590 attained acceptable results but has low speed compared to laser welding.

Table 6.4. Welding in TRIP 590 [2].

As with the DP 590, the TRIP 590 attained acceptable results. But has low speed compared to laser welding.

Comparison among Laser welded DP 780 and Friction Stir welded DP 780 were shown below. There were no acceptable welds by Stir welding. Below you can see the Table 6.5 Laser vs. Friction Stir welding in DP 780 [2].

Table 6.5. Laser and stir welding in DP78 [2].
The speeds at which the DP 780 was welded are promising but cannot be a replacement for laser welding, based on unacceptable welds and low speed. But it is also seen that, Laser welding doesn’t give acceptable outcomes fully either. Two of the three laser welded samples were deemed unacceptable by the tensile tests. The most apparent reason for this failure is the softening in the HAZ. Figure 6.10 is shows the micro-hardness results of Laser and Friction Stir Welding samples.

![Hardness of Laser vs. FSW in DP 780](image)

*Figure 6.10. Hardness profiles of laser and friction stir welding in DP780 [2].*

From above figure, it can be said that, In case of the laser welding in DP780, It has acute hardening in the weld and that is 48% and there is also some softening of about 9% in the HAZ. Though the softening affects are seen in weld of laser welding less than that of stir welding, it is the cause of failure when failure occurred in tensile test [2].

No acceptable welds were created using friction stir welding in the DP 980. Below Table 6.6 is the comparison between laser welding and friction stir welding table for DP 980. With laser welding, one out of three welds or 33% of welds failed or do not produce acceptable weld.
Though welding speeds are acceptable, friction stir welding doesn’t give acceptable welding too. Micro Hardness test can be helpful to know the reason for this failure. Below Figure 6.11 shows the hardness profile of laser and FSW in sample DP 980.

![Table 6.6. Laser and stir welding in DP980 [2].](image)

In case of the laser welds, softening occurred in HAZ and is 21% and hardening was 50%. FSW failures in steel joining are also caused by softening in HAZ area. Although acceptable welds were not found in case of DP 980 by FSW, the study suggests that it is possible under other
processing conditions. High percentage of Ultimate Tensile Strength (UTS) that was found in FSW indicates that possibility [2].

### 6.3.4 Formability

In order to investigate formability performance of Friction Stir Welded Tailor Welded Blank (TWB) sheets produce from advanced high-strength steel DP590, the hemispherical dome stretching test was experimentally performed and then numerical analysis was performed by Wonoh Lee [41]. Experimental hemispherical dome stretching test results and numerical analysis shows that both the strain localization and reduced weld zone ductility affected the DP590 TWB performance [41].

But in case of Laser welds DC06 - DC06 and DP600 - DP600, TWB has strong mismatch in mechanical properties or hardness after welding which is shown in figure 6.12.

![Figure 6.12. Hardness profile of laser welded DC06 and DP600 [40].](image)
For laser welded DC06 and DP600, high hardness in weld zone, as shown in figure 6.12, hardly has any influence on the formability behavior of the tailored blanks as shown in figure 6.14.

However, if the two different steels (DC06 and DP600) are joined together, the plastic behavior of those dissimilar TWB is substantially different from the similar ones. In fact, as shown in figure 6.14, rupture of the dissimilar welded blanks was found under the same deep-drawing conditions of the similar blanks.
7 Results and Discussion

The present work explores, whether the Friction Stir Welding (FSW) can overcome three major drawbacks of Laser welding process to produce Tailor Welded Blanks (TWB) for car industry. And below you can see the summary of the thesis findings.

- In general, from above studies, it can be said that, produced TWBs are influenced by loading direction, mechanical properties of base materials, thickness ration of welding sheets, rolling direction, welding parameter like, welding speed, nutting angle. For better weldability and formability, thermal profiles in each blank for welding should be as similar as possible, so that the recrystallization and aging in HAZ phenomena are similar.

- When laser welding is used for Joining material combinations such as Aluminum and Steel pose a number of problems viz., formation of brittle intermetallic compounds, poor welding behavior of Aluminum cause by difference in physical and chemical properties of the base metals, etc. [42, 43]. Some combinations such as Steel to Aluminum cannot be weld using laser welding [3].

Preheating of steel or applying different punch force can be used to get better welding feed and balanced material flow in Steel and Al when friction stir welding is used which can lead to good formability. Improved speed and formability found by stir welding of steel and aluminum joints is one of the proofs of economic feasibility and better TWB production possibility by stir welding. Both experimental and Simulation results indicate that even with large dissimilarities in material properties, Al–steel tailor-welded blanks can produce superior deep drawn parts.

- Due to Aluminum’s high reflectivity, low molten viscosity and inherent oxide layer, conventional laser welding leads to hot cracking in the fusion zone and the poor coupling during welding process [30, 31, 32]. For instance Laser welding does not produce favorable welding between Al 2xxx and 7xxx series. For Aluminum Alloys, strength becomes less than the base metal. During laser, Al alloys (Heat treated) normally lose a lot of their
strength; this is why HAZ also has lower hardness. In laser welded Aluminum alloys, reduction of tensile strength and ductility may cause from reduction of the magnesium in weld content during welding.

In case of FSW, better ductility can be found compared to base material but strength reduces for most of the Al alloy welds because of strain localization. This can be overcome by careful process design. Some Aluminum like AA5083-O is not affected by strain localization. Those have higher Magnesium content in Aluminum alloys will get higher strength after welding.

For the different-thickness configurations, the hardness and other mechanical properties (like formability) of the machined specimens decrease as the thickness ratio increases. But, better weldability is possible when welding parameters like tool angle, tool speed, feed etc is optimized. And for that, more research on joints of different thickness and for different Aluminum alloys by stir welding is also needed.

- Stir welded TWB produce steel joining does not produce better formability than laser welded TWBs. Infact, friction stir has problem welding different steel alloys more than laser welding. But higher UTS in stir welded steels indicate better weldability under different processing conditions.
  In some special cases same quality as laser welding is possible by friction stirs welding with lower feed speed. Lowers welding speed is another drawback of friction stir welding for mass production.

As mentioned before stir welding gives better quality in many cases but needs further study too. TWB for automobile industry is limited to auto production but can be used in other areas like Aerospace, Boat manufacturing too.
8 Conclusions

It can be concluded that, from above studies, produced TWB is influenced by loading direction, mechanical properties of base materials, thickness ratio of welding sheets, rolling direction, welding parameter like, welding speed, nutting angle.

At present, stir welding can join Aluminium alloys which can produce acceptable TWB.

Same things can be told for Aluminum and Steel joints for TWBs. But need more research on different thickness and joint types for Aluminum and steel joint tailor welded blanks.

But, so far High Strength Steels TWB by Friction Stir Welding are not feasible option yet to use as alternative of TWB’s production by laser welding.

For future work, more experiments and simulations for TWB production by Stir welding can be done for joining different alloys, with different thickness, different shapes, different joint types (not only just by butt joints) aiming better welding speeds or at least, same speed, compare to Laser welding speed in TWB production.
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