Minimization of Weld Line Movement and Improvement of Accuracy in Heat Assisted Forming of Tailor Welded Blanks

THESIS

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CERTIFICATE

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ABSTRACT

In recent times, the use of Tailor Welded Blanks (TWB) has gained popularity in manufacturing lighter automotive vehicles due to their higher strength to weight ratio. Reducing the weight of Body-in-White (BIW) components in the vehicle leads to improvement in fuel efficiency, thus to reduction in harmful emissions into the atmosphere and thereby reducing the environmental pollution to some extent.

Most of the TWB components are either stamped or deep drawn. In the stamping of TWBs, the current challenges being faced are related to the heterogeneous nature of the TWB, where the two parent sheet metals may undergo unequal plastic deformation resulting in the movement of weld line. When the weld line movement (WLM) exceeds the allowable range, it may lead to forming problems such as wrinkles, fractures, and springback, which affects the accuracy of the stamped components.

To overcome the problem of WLM, earlier studies suggested tooling changes and process parameter control. However, whenever any little design changes take place in the component, they result in high manufacturing costs.

The WLM occurs due to the difference in flow stress in the parent materials because the stronger material deforms much less compared to the weaker material. In order to reduce the flow stress in the stronger material, a new heat assisted forming of tailor welded blank (HAFTWB) process has been suggested in this work. In HAFTWB, the stronger material is selectively heated so that its flow stress is decreased, thereby allowing more material to flow into the die cavity. Due to equal proportions of material flow into the die from either side of TWB, the WLM could be minimized.

In this work, a new combination of TWB materials are selected and tested for mechanical properties at elevated temperatures. Simulations are carried out in LS-Dyna software to predict the WLM in the stamping of TWBs with HAFTWB process. Circular shaped blanks are formed into cylindrical cups in a newly developed HAFTWB experimental setup. Simulation studies are validated with the experimental results.

In order to understand the WLM properly, a parametric study has been conducted on the individual and combined effects of thickness ratio (TR) and weld line location (WLL) on the WLM at different temperatures. Design of experiments (DoE) is carried out in MINITAB software, to generate a relation between the TR, WLL and WLM in the form of a regression equation. This equation has been used as an objective function in the optimization studies to find out the critical values of parameters to achieve minimum WLM. This research work also emphasized on the geometric and dimensional accuracy of the TWB cups manufactured using HAFTWB process. The results show a significant improvement in the geometric accuracy, particularly in perpendicularity and cylindricity measurements.

By adopting the HAFTWB method of heating, the undesirable WLM has been reduced by 87% at the cup bottom. The reduction in WLM in the cup wall, which is in terms of the angle of the weld line, has been reduced by 75%. Thus, it is found that there is a significant improvement in the formability and accuracy of the TWB cup formed by HAFTWB process.

Keywords: Tailor welded blanks, TIG welding, warm forming, finite element simulations, weld line movement, optimization and geometric accuracy.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AISI	American Iron and Steel Institute
ASS	Austenitic Stainless Steel
ASTM	American Society for Testing And Materials
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BC	Boundary Conditions
BIW	Body in White
BM	Base Material
CMM	Co-ordinate Measuring Machine
DF	Degree of Freedom
DP	Dual Phase
DoE	Design of Experiments
FE	Finite Element
FRP	Fiber Reinforced Products
FSW	Friction Stir Welding
FZ	Fusion Zone
GPS	Geometrical Product Specification
HAZ	Heat Affected Zone
HAFTWB	Heat Assisted Forming of Tailor Welded Blank
IF	Interstitial Free
IFHS	Interstitial Free High Strength
IS	Indian Standard
ISO	International Organization for Standardization
LDR	Limiting Draw Ratio
MAT	Material
MS	Mild Steel / Mean Square
PR	Poisson’s Ratio
SS	Stainless Steel / Sum of Squares
THTB	Tailor Heat Treated Blank
TIG	Tungsten Inert Gas
TR	Thickness Ratio
TWB	Tailor Welded Blank
UTM	Universal Testing Machine
VHN	Vickers Hardness Number
WLL	Weld Line Location
WLM	Weld Line Movement

List of Symbols

E	young’s modulus,
K	strength coefficient
n	strain hardening exponent
ρ	roundness measurement
R	radius of cup
φ	diameter
σ	true stress
ε	true strain
ε_{width}	strain along the width
$\varepsilon_{thickness}$	strain along the thickness direction
r	anisotropic coefficient (parameter) / Die opening radius
r_n	normal anisotropy
Δr	planer anisotropy
Σy	uniaxial yield stress
ε_p	plastic strain
ε_w	width strain
ε_l	longitudinal strain
D_p	punch diameter
R_p	punch corner radius
R_d	die corner radius
D_d	die opening diameter
D_b	blank diameter
t	final sheet thickness
t_0	initial sheet thickness
T	temperature
T_P	temperature of punch
T_D	temperature of die
T_B	temperature of blank holder
T_{BL}	temperature of blank
ρ	density
c	specific heat capacity
α	thermal coefficient of linear expansion
υ	poisson's ratio
$\%el$	percentage elongation
O	origin (pole)

O_o	center of circle
e_i	deviation of *i*th point from assessment limacon
e_k	deviation of *k*th point from assessment limacon-cylinder
i, k	index for data points
r_i, θ_i	polar coordinates of *i*th point
r_{ij}, θ_{ij}	polar coordinates of *i*th point in *j*th section
r_o,	radius of circle for assessment limacon
x_o, y_o	centre coordiantes of circle for assessment limacon
z_i	height of the *j*th section
l_o, m_o	slope values
r_0	anisotropy along 0 degrees
r_{45}	anisotropy along 45 degrees
r_{90}	anisotropy along 90 degrees
$\bar{\varepsilon}^T$	virtual strain
σ	internal stress
dV	virtual volume
$\bar{u}$	virtual displacement
F	external body force
t	external surface force
Γ	boundary of the element
w	final width of specimen
w_0	initial width of specimen
l	final length of specimen
l_0	initial length of specimen
$\dot{q}$	heat generation rate per unit volume
R	radius of cylinder
k	thermal conductivity
σ_{ij}	cauchy stress tensor
μ	coefficient of friction
σ_n	normal stress
ζ	shear stress
σ_{ij}	cauchy stress tensor
n_j	surface with normal
F_i	component of force
t_i	traction vector
Ω	domain

Chapter 1

Introduction

Stamping and deep drawing are one of the most important sheet metal forming operations for automobile, aerospace and defense industries. Deep drawing involves sheet metal being stretched while metal stamping involves sheet metal being bent (Kalpakjian and Schmid, 2008). For several reasons, including the need to save material by using scrap sheet metal and to obtain specific functional strength and geometry requirements, the practice of using Tailor Welded Blanks (TWBs) as raw material for stamping and deep drawing is fast becoming a preference for over a decade. It is considered to be a promising technological development in the application of lightweight material, because one of the two parent sheet metals in TWB can be thinner than the other based on the strength requirements and thus make the structure lighter. The automobile industries are facing two major challenges today, namely, improvement of safety standards and emissions reduction. Day by day, there is a growing concern about the environmental degradation worldwide, which is leading to design and manufacture of lighter vehicles.

1.1 Tailor welded blanks

Tailor welded blank is a type of raw material used in sheet metal forming operations viz. stamping, bending and deep drawing. It consists of two or more sheet materials with different shapes, material properties, thickness, sense of coating and size. These sheets shall be joined using welding process before being subjected to metal forming operations. For joining the sheets, laser welding, tungsten inert gas welding (TIG welding), resistance spot welding or friction stir welding (FSW), may be adopted

(Montazerolghaem et al. 2014). TIG welding, which is a low cost welding process has been preferred in place of laser welding, though the formability of TIG welded TWB is less compared to laser welded TWB. In this work, TIG welding is carried out to join the materials without using filler material.

In addition to the reduction in cost and weight, the other advantages of employing TWBs are better utilization of scrap material, weight reduction without any loss of rigidity and cost reduction by cutting down the number of dies and punches. They minimize wastage of material and ensure that the components are stronger, lighter and provide greater functionality at lower costs compared to the components produced from monolithic sheets. They allow greater flexibility in materials selection, as well as improved structural integrity, safety and corrosion resistance in specific areas (Sanders and Wagoner, 1996). The *part integration* as shown in Figure 1.1 is possible with TWBs as they reduce the assembly time required per vehicle and also the number of components.

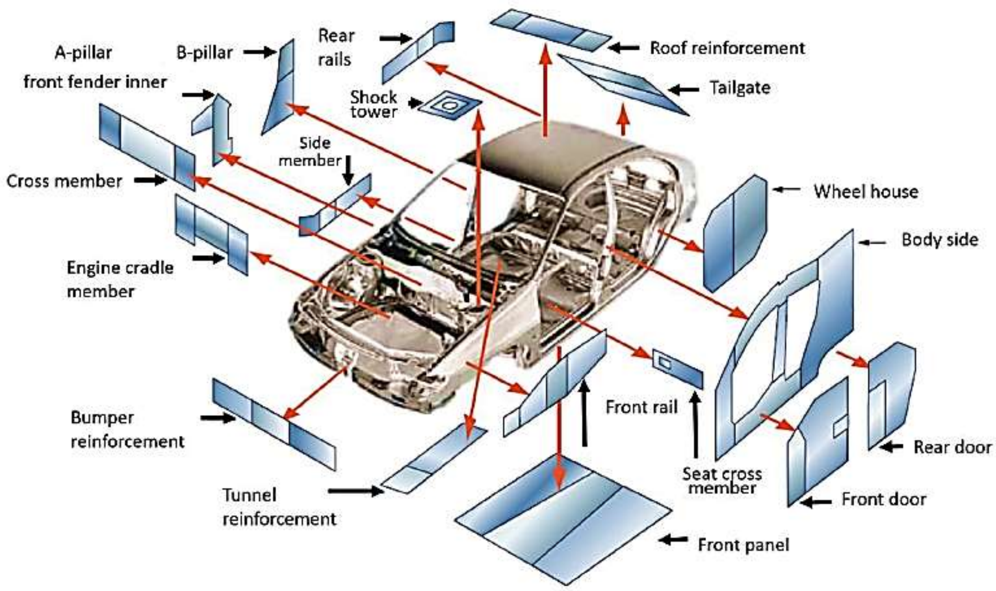


Figure 1.1: TWBs *parts integration* for various components in an automobile
(Source: https:// www.automotive.arcelormittal.com, *Retreived on 26/09/2017*)

Several important TWB components in the above mentioned industries are becoming a growing trend, though the science and technology of TWB forming is still not well understood. Previously automobile manufacturers used reinforcements to strengthen the components wherever high strength is required. Today, the TWBs have replaced these additional reinforcements, thus enabling it to save material without compromising on the crash-worthiness.

Potential applications outside automotive include solutions for industries such as: trucking, shipbuilding, alternative energy, appliance, rail car, trailer, elevator/escalator, furniture and construction. Wherever aluminium and steel materials are used, TWB products can be applied to improve results.

In the product manufacturing companies, these TWBs are subjected to forming operations viz. deep drawing, stamping and bending to obtain the component of desired shape. There is a growing trend of the steel manufacturers themselves supplying these TWBs. Usage of TWB in automobile industries has gained popularity in the past two decades for making the body-in-white components viz. A-Pillar, B-Pillar, C-Pillar, shot gun, three piece door, front tunnel, longitudinal member, door inner, outer body panel, large inner panels and brackets (Shah and Ishak, 2014).

1.2 TWB forming process

During the forming operation, the TWB sheet is placed between a binder and die. In the first step of the forming operation, a binder force is applied on the periphery of TWB sheet to provide a restraining force to avoid wrinkles as shown in Figure 1.2. The blank may be subjected to bending resistance if drawbeads are used. In the second step of the forming operation, a punch is displaced to draw the blank under the binder into the forming zone and to plastically deform the blank into a desired shape.

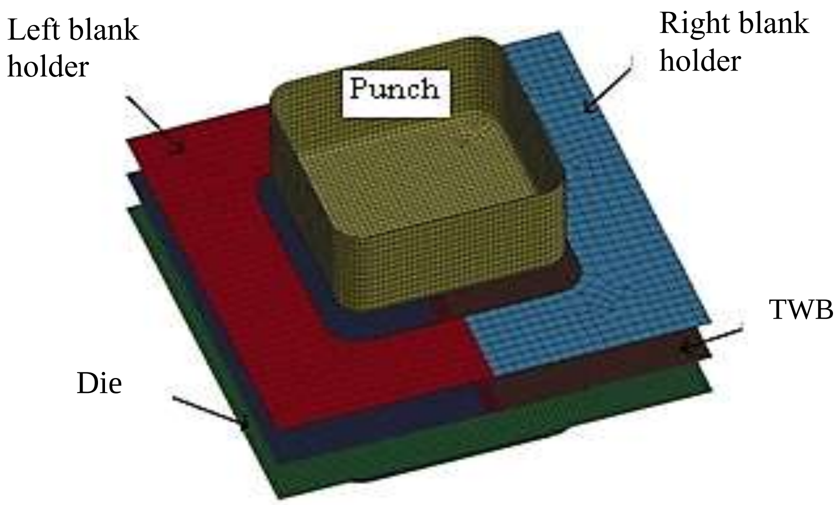


Figure 1.2: TWB forming setup

Unfortunately, the forming difficulty, in particular weld line movement, introduced by the TWB forming process has resulted in usage of extra thicker/stronger material. This has led to increase in weight and reduced material savings. To overcome this disadvantage, shop floor workers have attempted to apply a lower restraining force to the side of the stronger material section of the blank than that applied to the weaker material section of the blank in a conventional one-die forming operation. However, they are successful to a limited extent due to the complexity involved in tooling.

The limiting drawing ratio (LDR) i.e., the ratio of the maximum blank diameter to the punch diameter for successful drawing of cup is less in a TWB sheet compared to the cup drawn using a monolithic parent sheets. It has been found that the height of the cup drawn is more in the latter case.

The stamping process is considered deep drawn stamping, or deep draw, when a part is pulled (drawn) into a die cavity and the depth of the recess equals or exceeds the minimum part width (Ramezani and Ripin, 2012). Specifically, if the depth of the item created is equal to or greater than its diameter, then the metal forming process can be called deep drawing otherwise it is known as stamping.

Though deep drawing is similar to metal stamping, the terms are not interchangeable. In general, deep drawing is used to fabricate parts and products that are deeper than metal stamping can accommodate. Stamping is extensively used for the forming of only slightly curved parts with low depth of draw (e.g. roofs, fender, top cover, doors etc.). Deep drawing is used to make cup shaped sheet metal objects whose depth is at least greater than the diameter. Cross-sectional shapes are often limited to circular or rectangular. Examples are vessels for process industries etc.

Stamping or deep drawing of TWBs results in the movement of weld line due to dissimilar materials being used which lead to deform preferentially or tear prematurely. The higher plastic strain on the softer sheet side results in the movement of weld line as shown in Figure 1.3. Since the TWB sheet is diverse, consisting of weld and dissimilar materials, there are chances that the thinner/weaker material may fail during stamping which may lead to cracks and also results in the weld line movement (WLM).

Deep drawing parts are relatively simple shapes produced at high production rates. They require high tooling which escalates equipment costs. Stamping generally includes a variety of operations, such as punching, blanking, embossing, bending, flanging, and coining. They produce simple or complex shapes at high production rates. The tooling and equipment costs are high, but labor costs are low.

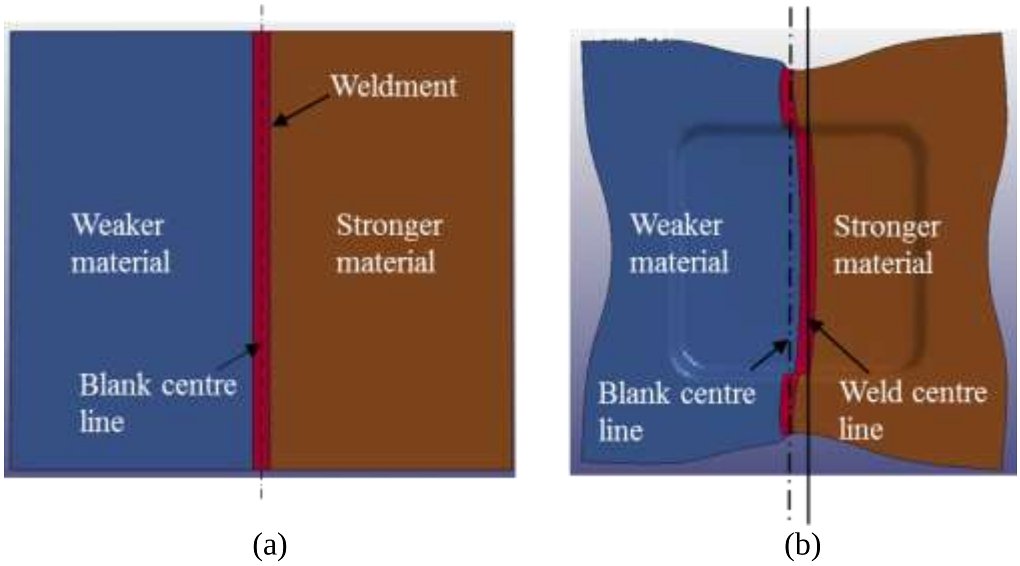


Figure 1.3: Weld line in TWB (a) Before stamping (b) After stamping

1.3 Weld line movement

Weld line movement (WLM) is one of the primary concerns in the stamping of tailor welded blanks. It is considered to be significant on two aspects: Firstly, weld line location (WLL) in the final part is critical because TWB part will be assembled with other parts and WLM can influence on assembling. Secondly, WLM which is normally towards the stronger / thicker material causes fracture and necking in the weaker / thinner material. Such WLM contributes to wrinkling, tearing, distortion, die wear and parts dimensional variations when compared to conventional monolithic single blank forming.

To control the movement of weld line, several investigators attempted to identify the most important parameters influencing the WLM during forming. They identified few of them such as thickness ratio, strength ratio, location of weld line and lubrication aspects. They suggested remedies to solve the problem by applying variable blank holder force, use of drawbeads of various sizes and incorporating tool changes. However, sufficiently exhaustive research studies to effectively control this problem has not yet been carried out, needing closer attention. Moreover, the above mentioned solutions increase manufacturing costs.

One approach to reduce the WLM involved the use of different drawbead heights/shapes or binder radii on two opposite sides of the weld line so that the stronger material section of the blank can flow into the deformation zone more easily than the weaker material section of the blank. Another approach is to apply variable blank holder force on the TWB material. All the above mentioned techniques are disadvantageous, in that, control is difficult and it involve lot of changes in tooling. Moreover, major design changes are needed whenever little alterations in thickness of sheets or geometries are brought up. So, these methods are expensive to be adopted in practical situations wherever thickness is one of the variable factors.

WLM is not an issue with soft steel combinations (<400 MPa strength), however it becomes critical when high strength steels are joined with soft forming steels. Due to substantial difference in flow stress, based on thickness and strength ratio, the stronger material deforms much less compared to the softer material.

In this work, industrially relevant material combinations are identified. A new combination (ASS-IS) of TWBs consisting of austenitic stainless steel with grade of 304 (popularly known as ASS-304) and mild steel with grade of 513 (popularly known as IS-513 or AISI-1018), which are the most important automotive materials, are selected (Kalpakjian and Schmid, 2008). Interstitial free steels and Dual phase steels (IF-DP) which are the currently used combination in automobile industry has been also tried, since these materials have similar properties compared to ASS-IS combination. Only simulation studies are carried out for IF-DP combination.

The mechanical properties of the new combination of materials have been tested at elevated temperatures to carry out the simulation studies for stamping of TWBs under warm forming conditions. In the warm forming of TWB, in order to obtain a satisfactory cup height with reduced amount of WLM, the blank has to be subjected to heat at selected zones before subjecting to the forming operation.

The WLM occurs due to the difference in strengths of the respective materials because the stronger material deforms much less compared to the weaker material. In order to reduce the strength of the stronger material, a new heat assisted forming of tailor welded blank (HAFTWB) process has been suggested as part of the research work. In this process, the stronger material is selectively heated so that its flow stress is decreased, thereby allowing more material to flow during stamping operation.

1.4 Warm forming method

Warm forming method has been extensively used in the forming of monolithic blanks. Lai et al. (2007) developed the warm forming setup shown in Figure 1.4 to improve the formability of stamped components by heating the blank. Initially, the blank holder and the die are subjected to heat, whereas the punch and blank are maintained at room temperature.

Warm forming differs with hot forming. In the former case, heat is supplied to blank during forming, while in the latter case, the blank is heated externally to the temperature above recrystallization conditions and shall be brought and placed over the die. Warm forming is carried out below recrystallization temperature, hence no metallurgical changes takes place in the material during heating.

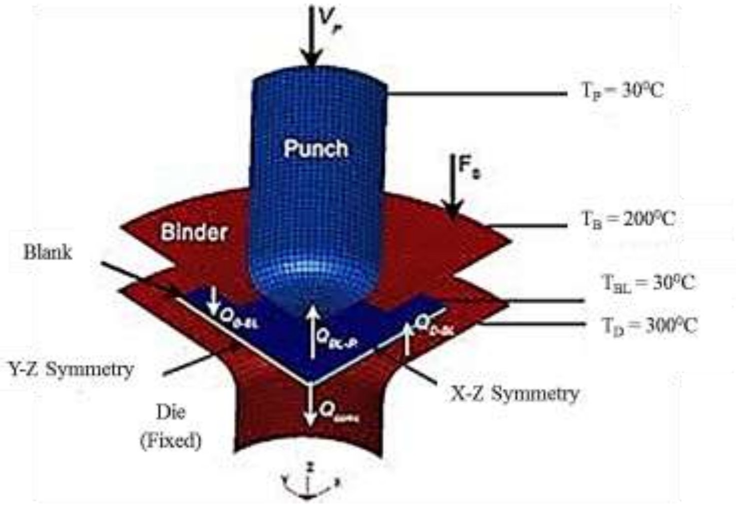


Figure 1.4: Warm forming die setup (Lai et al. 2007)

The utility of warm and hot formed parts in automobile industries is progressing at a rapid pace as shown in Figure 1.5 (Fukuchi and Nomura, 2016). Nearly, 30% of the body-in-white (BIW) components are manufactured using TWBs. The utility of heating in the forming process has led to develop a novel experimental setup discussed in the next section based on the works carried out by Abdulhay et al. (2009).

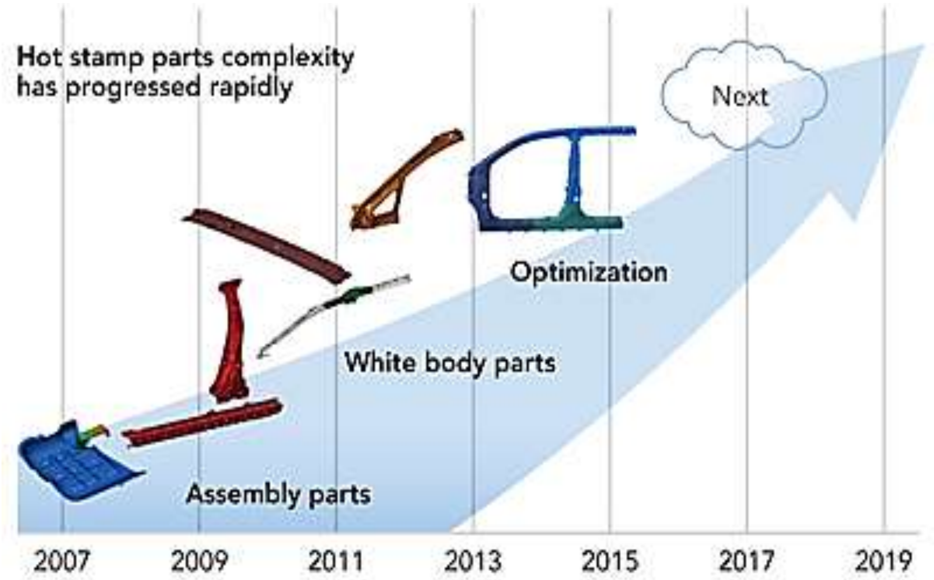


Figure 1.5: Trend showing usage of warm and hot stamped components (Karbasian and Tekkaya , 2010)

1.5 Heat assisted TWB forming

TWBs consists of different thickness/strength need selective heating and cooling of sheets in order to control the WLM. The thicker/stronger material would be subjected to selective heating, thereby, enabling it to decrease its flow stress. This will allow more metal to flow into the die cavity. Precautionary measures should be taken by providing insulation in-between the punch; so that the heat does not flow to weaker blank material, otherwise it will further weaken the material. Also, a cooling mechanism must be arranged by circulating ice water to the thinner/weaker side.

The novel experimental setup used in this work to reduce the WLM is shown in Figure 1.6. In this setup, the punch has been split into two halves vertically. One part is allowed to heat from inside, the other part maintained cool by circulating cold water internally. Between them, insulation has been provided. The heated part comes into contact with the stronger material and the cooled part with the softer material.

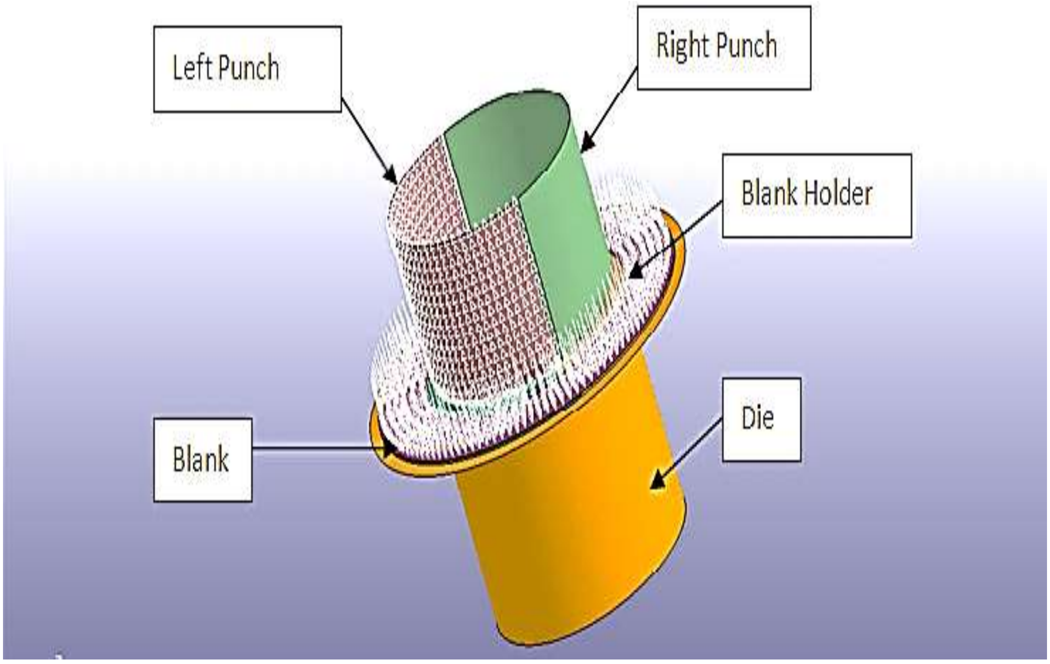


Figure- 1.6: Heat assisted TWB forming setup

The stamping process has been simulated by finite element analysis using LS-Dyna software and the results obtained are experimentally validated, indicating that the simulation model could be used further to predict the formability and accuracy of TWBs involving other parameters such as thickness variations and WLL.

Simulation experiments have been conducted on the TWBs involving thickness ratio aspects at room temperature as well as elevated temperature. Whereas, both simulation as well as laboratory experiments were conducted on TWBs with the weld line located at an offset distance of ± 1 mm from the centre of the blank at the respective temperatures.

1.6 Objectives of the proposed research

Based on the detailed literature review and the research gaps as presented in Chapter 2, the following objectives have been identified for this research work:

- Identification of a new combinations of automotive sheet materials for TWB manufacturing along with alternative welding method for joining of sheets
- Development of a simulation model for stamping of TWB under warm forming conditions and its experimental validation
- Experimentation on heat-assisted forming of TWB for studying weld line movement behavior
- Optimization of weld line movement in TWB under the influence of thickness ratio and WLL
- Analysis of geometric accuracy in heat-assisted forming of TWB

1.7 Organisation of the thesis

This thesis is divided into seven chapters as follows:

Chapter 1: It focusses on the motivation and need to address the problems involved with weld line movement in TWB. It highlights the importance of warm forming method in general and the newly developed HAFTWB process. This chapter also discusses about the objectives of the research work and the organization of the thesis.

Chapter 2: Detailed literature survey is presented on the existing methods of controlling weld line movement during the forming of TWB. The literature survey also includes the studies related to the accuracy of TWB components under warm forming conditions, the experimental and numerical simulations of TWB warm forming and the optimization techniques used in the process. At the end of the chapter, the research gaps are presented.

Chapter 3: It discusses the material characterization related to new combination of materials along with the alternative TIG welding process. Numerical simulation model is developed for HAFTWB and the simulation results are compiled with regard to weld line movement at cup bottom as well as at the cup wall. Simulation results are analyzed to check the thickness variation and stress distribution within the component, which otherwise would be difficult to measure experimentally.

Chapter 4: The novel experimental setup of HAFTWB to reduce the weld line movement is explained in this chapter along with a detailed discussion on the preparation of TWB specimens. These experiments have also been used to validate the developed finite element model.

Chapter 5: The influence of weld line location (WLL) and thickness ratio (TR) on the weld line movement in the HAFTWB process has been investigated. A combined effect of all these parameters is carried out with a detailed parametric study. Based on this, the optimization model for minimization of weld line movement has been developed and solved using the regression analysis.

Chapter 6: The effect of HAFTWB on the geometric accuracy of TWB components is analyzed in this chapter. The performance of the TWB components has been evaluated by the geometrical measurements, viz. roundness, cylindricity and perpendicularity using high precision measuring instruments

Chapter 7: The summary of the findings and specific contributions made from this research work are outlined along with the scope of future work in this chapter.

Next chapter deals with extensive literature review and identification of research gaps based on which the research objectives are formulated

Chapter 2

Literature Review

Forming operation using tailor welded blanks got significant attention from automotive industry as well as academic institutions worldwide during the last two decades. Several publications addressed the advantages and problems faced in the implementation of TWBs in practical situations. This chapter covers a detailed literature survey involving the state-of-the-art in TWB forming. The literature review covers an exhaustive search in the field of TWBs and is broadly categorized into sections based on forming method of TWBs, existing methods to address the problems of WLM, experimental works carried out, finite element studies on TWBs, warm forming aspects, geometric accuracy of warm formed components and optimization studies. The chapter is concluded by identifying the research gaps associated with the WLM and proposed methodologies in fulfilling these gaps.

2.1 Forming of Tailor Welded Blanks

Tailor welded blanks consist of two or more sheet materials with different thickness, coating, strengths and are welded together before subjecting to forming operation to obtain a desired shape. The disadvantages of TWB are related to the heterogeneous nature of the blank during forming which results in weld line movement (WLM). The WLM occurs due to the difference in strengths of the respective materials because the stronger material deforms much less compared to the weaker material (Saunders and Wagoner, 1996) hence, the weld line is pulled towards its side. However, the advantages of using TWBs are reduced component weight, proper utilization of scrap, improved structural integrity and part integration (Rooks, 2001).

Merklein et al. (2014) reviewed an article on TWBs with applications connected to automotive industry. They discussed about the new technologies and future processing techniques of TWBs, viz. warm forming method, heat treatment of TWBs before forming operations etc. Tekkaya et al. (2015) reviewed an article on metal forming beyond shaping by predicting and setting product properties. They stressed the need to tailor mechanical properties at specific locations within the blank to obtain desired component shape. Allwood et al. (2016) could predict and control product properties in metal forming operations. They have surveyed current and emerging applications across a broad spectrum of metal forming processes which includes stamping and deep drawing operations.

In stamping operations, both manufacturing and control engineers have faced two main quality aspects viz. formability aspects (the ability to avoid wrinkling and tearing caused due to compression and tension stress respectively) and geometric accuracy. In addition, consistency in terms of minimization of dimensional variations as shown in Table 2.1 (caused by variation in material properties, lubrication, or thickness) is a key requirement in manufacturing.

Table 2.1: Design variables affecting WLM in TWB

Material	Process	Tooling changes
Sheet thickness	Mode of Stretching	Draw bead
Material properties	a) In-plane	Die corner radius
a) Strain hardening coefficient(n)	b) Out-of-plane	Punch corner radius
b) Anisotropy (r) / Plastic strain ratio	Strain path	Punch-die clearance
c) Strain rate	a) Bi axial	Preform design
d) Strain rate sensitivity coefficient (m)	b) Plain strain	Segmented die
Grain size	c) Uni axial	
Inclusions	Deformation speed	
Welding	Blank holder force	
	Lubrication	
	Temperature	

During manufacturing of TWB components, it has been observed that critical issues such as WLM, reduction of sheet thickness and maintaining geometric accuracy are also needed to be addressed. WLM will increase the chances of wrinkling, tearing and distortion of parts. Under cold forming conditions, WLM is severe in TWBs.

2.2 Existing methods of controlling weld line movement

Use of draw beads

The draw bead adds additional restraining forces to the blank as shown in Figure 2.1, so that the movement of the weld line is reduced and the thickness strain distribution is changed. Heo et al. (2001a, 2001b) investigated quantitatively the effects of the draw bead dimensions on the weld line movements in the deep drawing of the TWBs. Various profiles of draw beads viz. triangular, square, semi-circular shapes are considered in their work to effectively control the WLM. Hariharan et al. (2014) designed various shapes of drawbeads and carried out multi-objective optimization problem with minimum weld line movement and maximum dome height as design objectives using genetic algorithms.

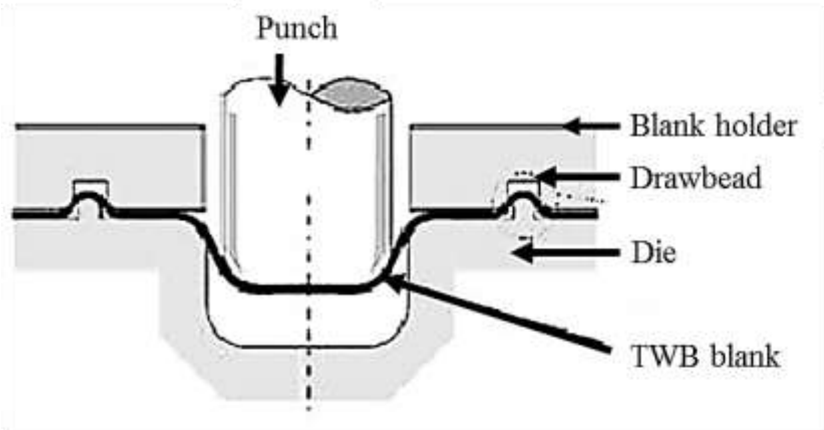


Figure 2.1: Use of drawbeads in controlling WLM (Heo et al. 2001a)

Variable blank holder force

Variable blank holder forces increase the formability of TWB as well as control the draw-in. Hu et al. (2012) carried out simulations using curved weld line under different blank holder forces. They found a change in the movement of the weld line when the blank holder forces on the two blanks are varied. In order to obtain variable blank holder forces, nitrogen springs are commonly used as shown in Figure 2.2.

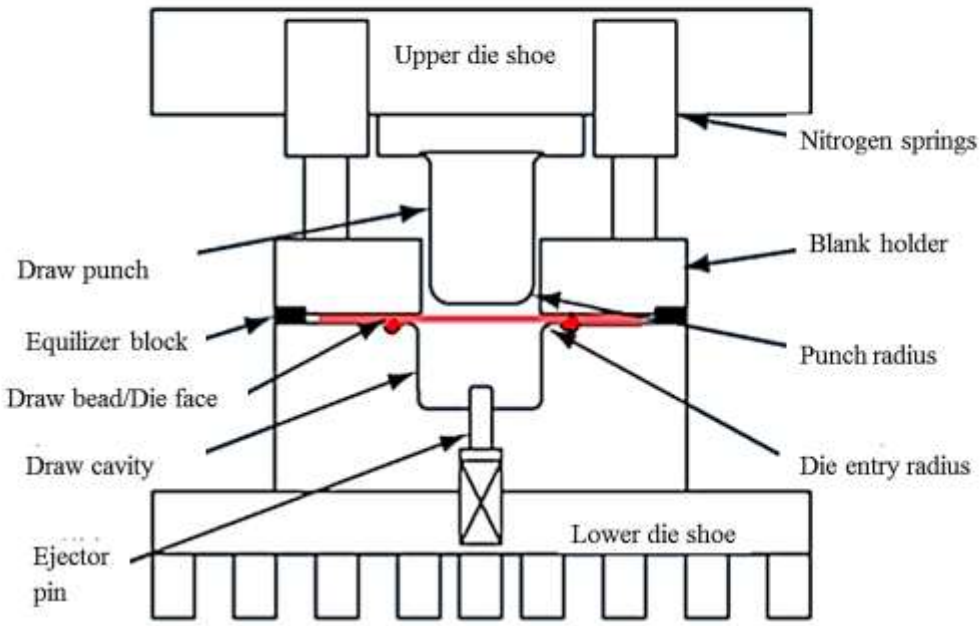


Figure 2.2: Variable blank holder force with the help of nitrogen springs (Dawood et al. 2015)

Dawood et al. (2015) proposed a scheme wherein uneven blank holder forces are applied on either side of the blank by considering the reaction forces which are obtained from the finite element simulation model. Jiang et al. (2015) concluded that by effectively controlling the sizes of TWBs, loading conditions and blank holder forces, improvement in thinning ratio could be achieved in TWBs.

Location of weld line

The formability of TWBs may change according to weld line position in critical areas. By placing the weld line at an offset distance with reference to the centre of the TWB, WLM could also be reduced considerably. Narayanan and Narasimhan (2008) found that WLL does significantly reduce the forming limit strains in welded blanks as compared to the unwelded blanks. Panda et al. (2009) found that the WLM is maximum at the pole i.e. at the center of the TWB and occurred towards stronger/thicker side. Based on this result, Panda et al. (2010) concluded that the formability, limiting dome height and location of failure during forming depended on WLL. Riahi et al. (2012) also investigated on the effect of WLL on the TWB component and found an improvement in cup height by shifting the weld line towards stronger/thicker material. Li et al. (2013) studied the effect of the weld line positions on the TWB consisting of similar and dissimilar materials. They predicted the initial weld line placement by trial and error method and conducted experiments and compared the results with the numerical simulations. They concluded that weld position affected the formability of TWBs with similar material properties. Mennecart et al. (2014) chose to position the weld line away from the centre line and concluded that during forming, the weld bead resisted failure.

Effect of Strength ratio

The mechanical properties of weld play a significant role in the movement of weld line in a TWB during forming operation (Scriven et al. 1996, Raymond et al. 2004, Bayraktar et al. 2008). It is a known fact that when two dissimilar materials are joined by welding, the weld joint would shift in the direction of high strength material during forming, because the stronger material begins to act as a rigid body. Tusek et al. (2001)

welded tailored blanks consisting of different materials. Fusion welding was carried out in their work without using filler material. Investigators namely Cheng et al. (2007b) and Rojek et al. (2012) have shown that tailored blanks of high-alloy stainless steel can be laser or TIG welded to those of low-alloyed ferrite steel without the addition of filler material.

Shi et al. (1993), Bhagwan et.al (2004) and Gaied et al. (2009) found an increase in the formability of TWBs by conducting experimental and numerical simulations. Chatterjee et al. (2009) made an attempt to combine Interstitial-free (IF, 300 MPa) and Dual Phase (DP, 590 MPa) steels. They studied the forming limit diagrams and obtained defect-free TWB components. Vasudevan et al. (2012, 2013) used different steel combinations and studied the influence of anisotropy in the forming of TWBs through experimental and numerical studies.

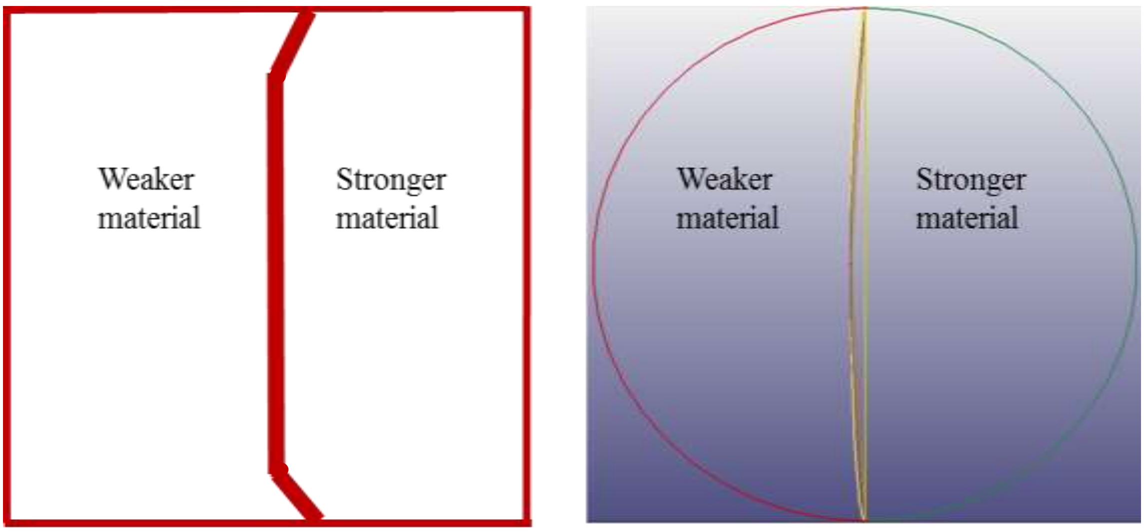
Effect of Thickness ratio

Studies related to the effect of thickness ratio were carried out by many researchers. Studies carried out by Chan et al. (2003) and Chan et al. (2005) used same materials but with different thickness combinations. They found a decrease in the formability of TWBs at higher thickness ratio. Cheng et al. (2007a) studied various thickness combinations of TWBs and their effects on WLM through the forming limit diagrams. They noticed that the majority of deformation in the TWB is contributed by the weaker/thinner side of TWB. Riahi and Amini (2013) studied the effect of weld zone location and thickness ratio on the formability of TWB sheet. Korouyeh et al. (2013) concluded that the WLM is directly proportional to the thickness ratio and as the thickness ratio increases the WLM also increases. Abbasi et al. (2014) studied TWBs consisting of Interstitial Free (IF) steels with different thicknesses (0.8 and 1.2 mm) to assess the formability aspects. Safdarian et al. (2015) concluded that the

WLM is directly proportional to the thickness ratio. Recently, Elshalakany et al. (2017) investigated the formability aspects of TWB involving low Carbon steel for different thickness ratios. By shifting the weld line towards thicker material along with reduced thickness ratio, they found an increase in cup height. Formability studies on Austenitic stainless steel material of grade 304 were carried out by Kaya (2016) at different thickness ratios in which a new technology based on mechanical servo control has been used to obtain precise movement of punch. Kumar et al. (2017) relocated the weld line towards the thinner/weaker side of the TWBs and achieved improvement in dome height by conducting hydraulic bulge test. They also worked on the effect of thickness ratio on WLM and maximum dome height using numerical simulations. It has been found that the maximum bulge height decreased with increase in thickness ratio, and WLM increased towards thicker/stronger side. Gautam and Ravi Kumar (2017) observed that the forming behavior of TWBs affected when there is a difference in thickness, high anisotropic behavior of materials and the presence of weld zone. They concluded that the accuracy of TWB components depended more on the weld zone properties than the anisotropy of the sheets.

Preform design

Ku et al. (2005) predicted the WLM using the backward tracing scheme in finite element simulations. They could be able to generate a neat net shape of the TWB component without wrinkles. Tang et al. (2007) also did similar work by predicting the WLM using one-step FE simulation and accordingly developed the initial blank design before stamping. Li (2010) and Li et al. (2013) suggested preform design as shown in Figure 2.3(a). They have proposed a non-linear welded joint in a TWB to overcome the problem of WLM. Hu et al. (2012) studied about the formability of tailor welded blanks with curved weld line under different blank holder forces. Li et al. (2013) have studied the dependence of formability on the weld shape by conducting experiments on laser welded TWBs. They have considered different curvilinear weld profile shapes and studied its effect on the formability of TWB. They also placed the weld at a distance away from the centre of the blank and studied its effect on WLM. Using the above method, they could optimize the TWB component, which led to manufacture a better stamped product. Hossein et al. (2015) studied about the formability of TWBs with curved line under blank holder force strategy to achieve force equilibrium. Non-linear weld were prepared instead of a straight linear weld to overcome the movement of weld line. Similarly, weld profiles based on parametric representation of curves viz. circular, elliptical, spline curve etc. as shown in Figure 2.3(b) can also be attempted in future work to solve the problem of WLM.



(a) (b)

Figure 2.3: Preform design to minimize WLM (a) Non-linear weld (b) Parametric curves

A few researchers felt that not only the shape of the weld but its properties also contributes to WLM. Panda and Ravi Kumar (2009) studied the formability of tailor welded blanks under plane strain conditions. They concluded that the weld properties play an important role especially in longitudinal specimens. Narayanan and Naik (2010) considered a longitudinal weld bead and predicted the forming limit. They assessed the validity of TWBs by modifying failure criteria. Leitao et al. (2011) analysed the weld bead geometry and observed that the weld bead shape has a strong influence on the formability of TWBs.

Tooling changes

In order to create a uniform distribution of strain near the weld zone in the TWB material, Cao and Kinsey (1999) developed a segmented die as shown in Figure 2.4, by using local adaptive controllers to minimize the WLM. They used hydraulic controlled cylinders to clamp on the weld line during the forming of TWBs. Jeffrey and Aitharaju (2010) patented a device forcing the mass of the blank by adopting a non-linear weld at the structural inners formed from tailor welded blanks.

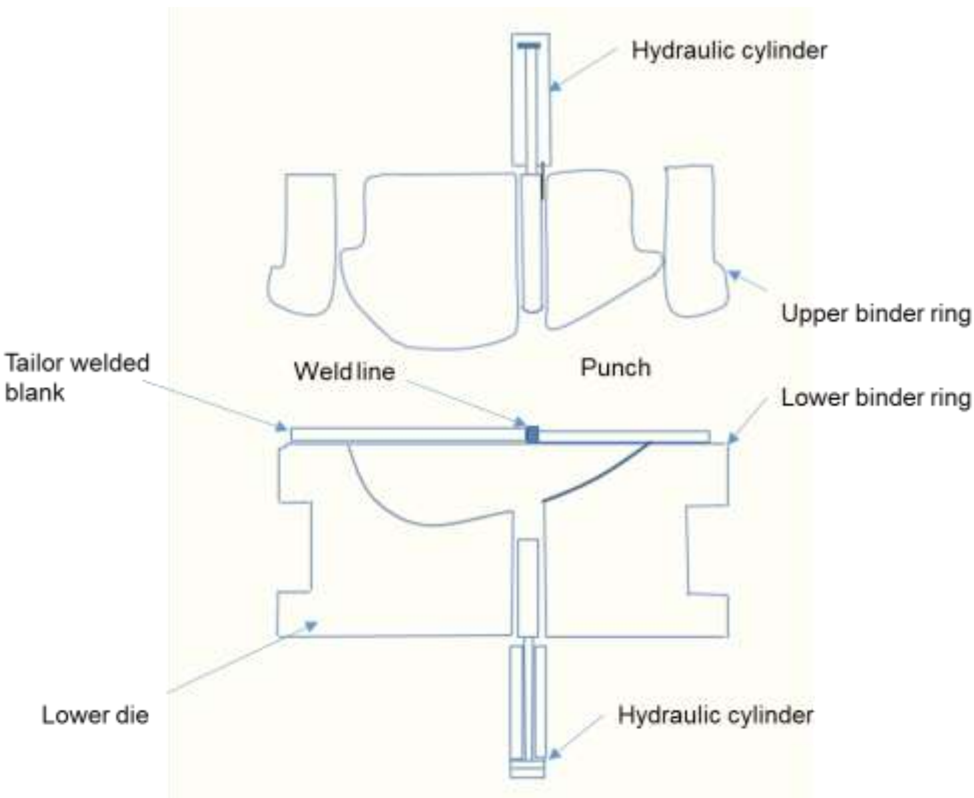


Figure 2.4: Segmented die using local adaptive controllers (Kinsey and Cao, 2003)

2.3 Forming at elevated temperatures

Formability improvement in stamping operations using thermal energy has been studied by researchers for a long time (Davies et al. 2002, Hoffman et al.2007, Bong et al. 2013, Hippchena et al.2016 and Kim et al. 2017). Warm deep drawability of steel sheets has been examined by Kim et al. (2017). They used an experimental setup with heated die and cooled punch as shown in Figure 2.5. They conclude that the relaxation of strain concentration by using a heated die favors the deep drawability of the sheets. Karbasian and Tekkayya (2010) reviewed a paper on warm forming which involved hot stamping. They separated the TWB as heat treatable and non-heat treatable before subjecting to warm forming. They identified gaps in the fields of warm forming in terms of metallurgical aspects such as phase transformations, flow of material during forming and established relations between geometric and mechanical properties. Merklein et al. (2014) highlighted the application of localized heat treatment in a TWB in a review article. They also discussed about the new technologies and future processing techniques of TWBs.

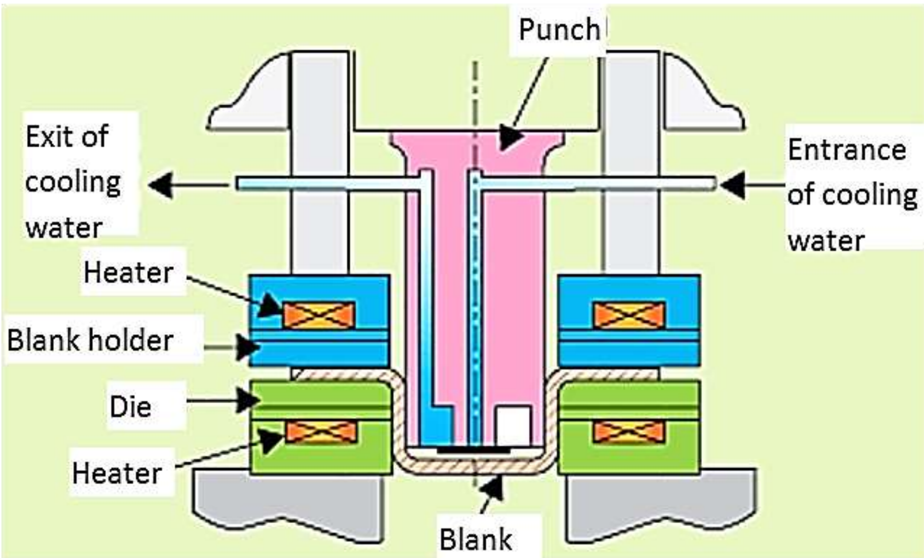


Figure 2.5: Warm forming setup with provision of heaters (Kim et al. 2017)

Park et al. (2015) proposed a coupled thermo mechanical analysis and had proven that without a significant increase in cycle time, the drawing punch can be efficiently heated. Kahrimanidis et al. (2015) proved that forming properties can be adjusted by carrying out local heat treatment. They used a thermo-mechanical simulation model and validated with laboratory experiments. They have adopted a new concept of tailor-heat treated blanks (THTB) and observed the metallurgical changes occurring at hot forming conditions, i.e., at re-crystallization temperature (Rm). These changes do not occur under warm forming conditions as the experiments are usually conducted below Rm i.e., between 0.3 Rm and 0.5 Rm.

Lai et al. (2007) developed a tooling system with a heating control function which can be used to heat the specimens up to 600 ^{o}C. Their results revealed that the formability of TWB components could be optimized within a well-controlled tooling temperature system, thus resulting in a more efficient and effective forming of TWBs. Staud and Merkelin (2008) adopted heat treatment method whereby they heat treated aluminium TWBs locally to induce tailored properties for improving formability. Venkateswarlu et al. (2010) worked on forming behavior of sheets at elevated temperatures. They concluded that different temperatures are required for different materials when TWBs are prepared.

Bagheriasl et al. (2010) adopted a coupled thermo-mechanical analysis in numerical simulation using LS-Dyna software under warm forming conditions. Babu et al. (2014) studied the effect of formability of TWBs by subjecting the blanks to differential heat treatment process. Their results were verified with experimental samples. Bandyopadhyay et al. (2015) conducted numerical simulations and experimentally validated the LDR of TWBs. Kaya (2016) carried out simulation work and validated experimentally on a new technology with a provision for precision motion by using an elastic-visco-plastic-thermal material model on ASS 304 material.

Merklein and Svec (2013) investigated in the area of hot stamping by manufacturing components under the influence of tool temperature and applied contact pressure. They cited the use of local heat treatment technique of TWBs in their work. They promised a bright future for TWB processes leading to new discoveries. They included hot and warm forming aspects in their study. Harrison et al. (2015) designed a die based on the heater wattages, locations of thermocouple, insulation strategies and die architecture. They have validated the simulation results with laboratory experiments. Their results showed that there is an improvement in the formability of TWB in a well-controlled tooling temperature system.

Kim et al. (1996) have investigated the warm deep drawability of ASS 304 material. Square cups were drawn by heating the die and blank holder to a temperature of 210 ^{o}C keeping the punch cooled by circulating water from inside. Their results show that the maximum drawing depth occurred at 150 ^{o}C and reached 1.6 times the drawing depth at room temperature. They concluded that by increasing the temperature above 150 ^{o}C in a hydraulic press, no effect on the drawing depth is observed. Warm deep drawing has been carried out on a monolithic sheet by Takuda et al. (2003). They investigated the warm deep drawability of Austenitic Stainless Steel ASS 304 material at room temperature and upto 150 ^{o}C using a cylindrical punch. They had heated the die, keeping the punch cooled by circulating water into it. They also compared the material properties between ASS 304 material and mild steel material and found that mild steel material properties did not get affected at elevated temperatures. An improvement in LDR is observed for ASS material in their studies as shown in Figure 2.6.

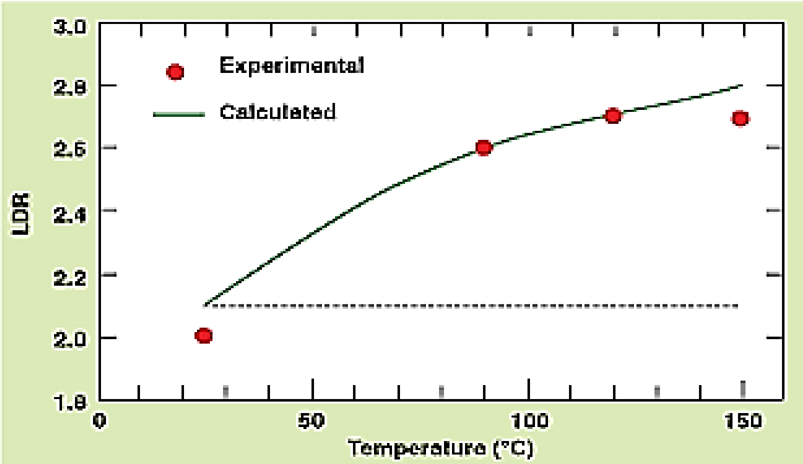


Figure 2.6: Improvement in LDR using warm forming method (Takuda et al. 2003)

Warm forming is also examined on monolithic sheets by Lee et al. (2016) on the lines of the work by Takuda et al. (2003). They used the same set up with a square punch. The drawing tests were carried out at six different temperatures ranging from 25 ^{o}C to 250 ^{o}C. Their results showed that LDR has been increased from 2.4 at room temperature to 2.8 at 150 ^{o}C. They also reported that the distribution of thickness strain is more uniform at elevated temperatures than at room temperature.

2.4 Accuracy of stamped components

In the manufacture of TWB components, dimensional and geometric accuracy of the products are very vital especially while assembling the parts. Spring back reduction in sheet metal forming is a typical goal to be pursued which is conflicting with WLM and accuracy of parts. Spring back results in a deviation from the desired shape, which needs to be adjusted. Presently, workers in the workshop compensate it by an iterative experimental way. It is a known fact that the amount of spring back depends on the variations in thickness/strength of the TWB material and it changes upon heating at warm forming temperatures.

Most of the simulation studies on spring back were carried out on a monolithic sheet and not on TWB sheets. Zajkani and Hajbarati (2017) studied the effect of the various parameters on the sheet spring back. Their study is based on the influence of material properties on spring back and not on the process parameters. Zheng et al. (2016) conducted experiments at room temperature and found that by decreasing sheet thickness, the spring back angle increased. However, they noticed that the spring back angle decreased with decreasing sheet thickness at elevated temperatures. Kusumi et al. (2014) investigated the drawability of cylindrical components in hot stamping and found that sheet thickness affects the residual stresses after forming. Hence, maintaining different thickness ratios of parent materials can solve the problem of residual stresses. Shan et al. (2013) concluded that the accuracy and performance of hot stamped workpiece depends on the cooling system provided in the hot stamping die setup. They applied localised heat input for a range of materials and found an improved dimensional accuracy and increased formability. They also indicated that the residual stresses could be reduced significantly by applying warm forming method. Lorenzo et al. (2009) proposed an integrated heat treatment and hot forming process to improve the accuracy and formability of TWBs. They could achieve excellent formability, minimum spring back, and uniform mechanical properties. Gosling et al. (2011) showed better results by varying the blank holder force and tool modification in order to control the spring back. Similar work has been done by He et al. (2003) in which they proposed to apply lower blank holder force on the stronger/thicker side of TWB to allow more material to flow into the die cavity.

Kahrimanidis et al. (2015) concentrated on the dimensional accuracy of THTB and demonstrated that distortion can be minimized and controlled in the processing of THTB. Weihua and Zhenqiang (2012) confirmed that the cylindricity error in cylindrical components has more effect on the position accuracy as compared to the roundness error. Shunmugam and Venkaiah (2010) suggested that the effect of misalignment is more significant in precision manufacturing and metrology when the tolerances are tighter. Cristofolini et al. (2013) found that dimensional shrinkage increases at elevated temperatures, however, the geometrical and dimensional accuracy is very good. Nguyen et al. (2014) studied various process parameters viz. counter-punch force, blank holding force, counter-punch-to-blank and friction conditions of punch-to-blank and they have optimized them using the Taguchi method to improve the accuracy and drawability of the TWB cups. Kim et al. (2017) also proposed a heat treatment process to improve the formability and dimensional accuracy of tailored rolled blanks. Stepien et al. (2014) described about the advantages and disadvantages of multi-probe measurement, V-block measurement, and measurements carried on the Coordinate Measuring Machines (CMMs). Cruz and Raman (2013) studied about the origin offsets, estimation of the parameters and axis misalignments for spherical, circular, toroidal and cylindrical features using CMMs.

In the literature, no attempt has been made to check the geometric accuracy of tailor welded blanks. Hence an investigation in this area is strongly needed. Under warm forming conditions, several authors have shown improvement in the cup height of TWB cups, however there is no mention of geometric accuracy especially in terms of cylindricity, roundness and taper measurement. Geometric and dimensional aspects play a significant role in the forming of TWBs; however, no investigations were carried out in this area other than those induced by sheet thickness. Duflou et al. (2007) applied localised heat input for a range of materials and found an improved dimensional accuracy and increased formability. They also indicated that the residual stresses could be reduced significantly by applying warm forming method.

2.5 Studies related to optimization

TWBs are primarily used for weight reduction. Li and Kim (2014) conducted optimization studies on cross car beam structure. They could reduce the weight by nearly 40% using aluminium TWB structure as compared to a steel TWB structure without compromising on the performance criteria. Zhu et al. (2008) used tailor welded structure to optimize the inner door panel in a car thus achieving reduction in weight and enhanced crashworthiness

Ozek and Unal (2011) used ANOVA method to study the optimization and modeling of angular deep drawing process for square cups. They have investigated the effects of die/blank holder angles, variable blank holder force and punch/die diameter on the punch force, limit drawing ratio, and minimum wall thickness in angular squared deep drawing process. Ali and Sajjad (2014) suggested shape optimization method for minimizing the effect of wrinkling tendency by combining FE and DoE methods. They have also studied the effects of WLL on the movement of weld line.

Colgan and Monaghan (2003) conducted the DoE analysis on various parameters such as lubrication, punch and die radii, die–punch clearance, in addition to mechanical properties and thickness of the sheet metal and part geometry. Hamidinejad et al. (2013) studied the parameters of laser welding using multi-objective genetic algorithm. The optimal laser welding parameters obtained by them are incorporated in this research work. In the work presented by Fazli (2013), the optimum blank shape is obtained for a TWB with dissimilar materials and uniform thickness. He concluded that the WLL affects the optimum blank shape of TWB. Padmanabhan et al. (2008a) conducted DoE based study to find the influence of process parameters on the forming process. They have used three levels of process parameters to capture the non-linear effects in the experimental design. The DoE study was conducted to find out the optimal conditions for deep drawing process. Behrens et al. (2007) conducted regression analysis using DoE and found optimal values for the process parameters viz. die angle, the reduction of wall-thickness and the friction factors.

All the above mentioned methods such as provision of draw beads / variable blank holder force / adaptive technologies could give better results in terms of dimensional accuracy and thinning, when both the TWB sheets have uniform thickness. However with variation in thickness of sheets, the above methods needed considerable changes in tooling which in turn will escalate the cost of manufacturing. Any reduction in sheet thickness beyond its allowable range leads to fracture/tearing. Hence, an alternative approach is suggested in this work to control the weld line movement in the forming of tailor welded blanks. Based on the above mentioned facts, the following research gaps are identified to address the issue of minimizing the weld line movement.

2.6 Research gaps in the literature

Most of the current research in TWBs is focused on developing light weight components produced from Aluminium, Magnesium and Carbon FRP materials. They cannot be recycled 100%, unlike steel which can be recycled completely. Thus, steels have the potential to reduce greenhouse gases as shown in Figure 2.7 (Johnson et al. 2008). Therefore, usage of steel in automotive TWB components need to be taken up.

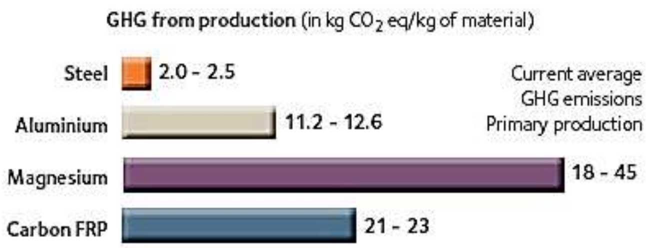


Figure 2.7: Green house gas emissions from the production of materials
(Source: https://www.worldautosteel.org, *Retrieved on 12/04/2018*)

TWBs with a large variation in material properties in steels (> 600 MPa strength) has not been undertaken. This is particularly true for certain high strength low cost sustainable materials as shown in Figure 2.8. It is observed from the figure that the currently used industrial materials viz. IF-DP steels does not have much variation in their strengths as compared to the combination of ASS-MS steel. Since the movement of weld line depends on the respective strengths of the parent materials, hence higher the variation, greater will be the movement of the weld line.

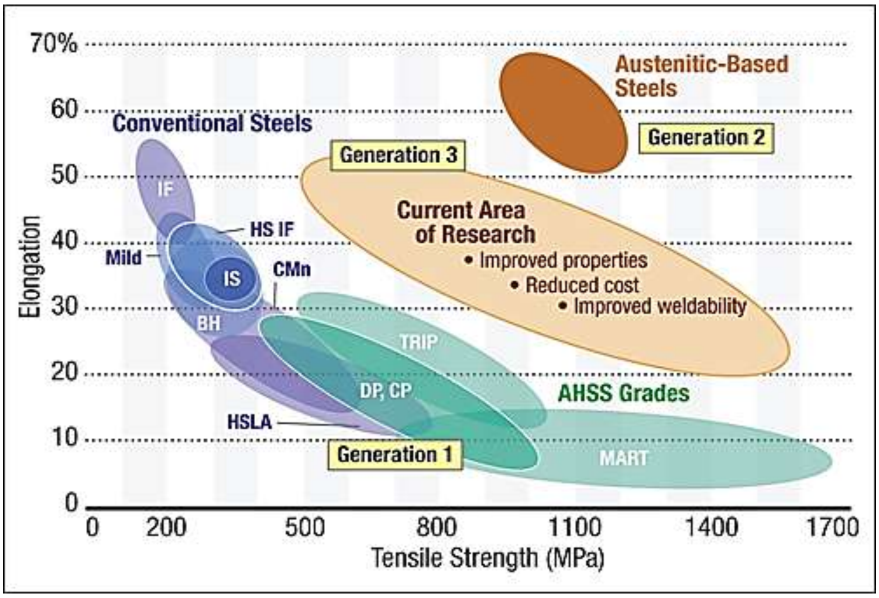


Figure 2.8: Comparison among various grades of steels
(Source: https:// www.autosteel.org, *Retrieved on 10/03/2018*)

Although the WLM has been studied by some researchers, decisive work and methodology or scheme to effectively control this problem has not yet been carried out, which needs close attention. Also, the effect of temperature on the WLM in a TWB is not carried out for which simulation studies based on thermo-mechanical forming are needed. It has been found that no work has been undertaken with heat assisted forming of TWB, though warm forming studies of monolithic sheet materials were undertaken. Further, the main implication of WLM in terms of geometric accuracy of the final part has not been studied in the literature. Therefore, there is a need for current research study.

Comprehensive understanding of the effect of various parameters on the quality variables is possible only through detailed DoE based study, which is also a gap in existing research in this field. Based on the literature review and research gaps, objectives are outlined as presented in Chapter 1. This chapter dealt with exhaustive literature review related to the current methodologies adopted in controlling the WLM in forming of TWB at elevated temperatures. The next chapter covers the first and second objectives regarding the material characterization and finite element simulations involving TWB forming.

Chapter 3

Material Characterization and Finite Element Simulation of TWB

This chapter discusses about the material selection, material characterization welding methods used and FE simulations (Zhao et al. 2001) conducted on HAFTWB process. In order to understand the formability aspects of the TWB formed cups, it is essential to know about the material properties and flow stress behavior of the respective materials viz. parent materials and weld bead at different temperatures. The weld bead properties are vital in the forming of TWB. Formability aspects are considered with respect to LDR, WLM and thickness distribution using FE analysis. These characteristics are studied for different material combinations, the details of which are outlined in the next section.

3.1 Material selection and characterization

Selection of sheet materials for the manufacture of TWB components is an important step in automotive industries. Consequently, material properties with respect to new combination of material (ASS-IS) consisting of Austenitic stainless steel (ASS-304) and mild steel (IS-513) and currently used combination of materials (IF-DP) consisting of Interstitial free high strength steel (IFHS 300) and Dual Phase steel (DP 780) materials are identified to perform the FE analysis. As per the availability of the material combination, experimental work of TWB forming could be carried out for ASS-IS steel combination only. The chosen combination of materials have good formability characteristics, easily weldable, and readily available with required thickness. They also have high variation in their respective strengths. The utility of ASS material in automobile industry is proposed by Schuberth et al. (2008) and stainless steel focus report (2009).

DP-IF steel combination

The parent materials of IF-DP combination consisting of IFHS 300 and DP 780 materials are tested for measuring the mechanical and physical properties. Uni-axial tensile testing at 30 °C (Room temperature conditions) have been conducted at a crosshead speed of 2 mm/min for all ASTM EM8 standard specimens as per Figure 3.1 for DP steel and IF steel separately (Clubotariu and Brabie, 2011, Dhumal et al. 2011).

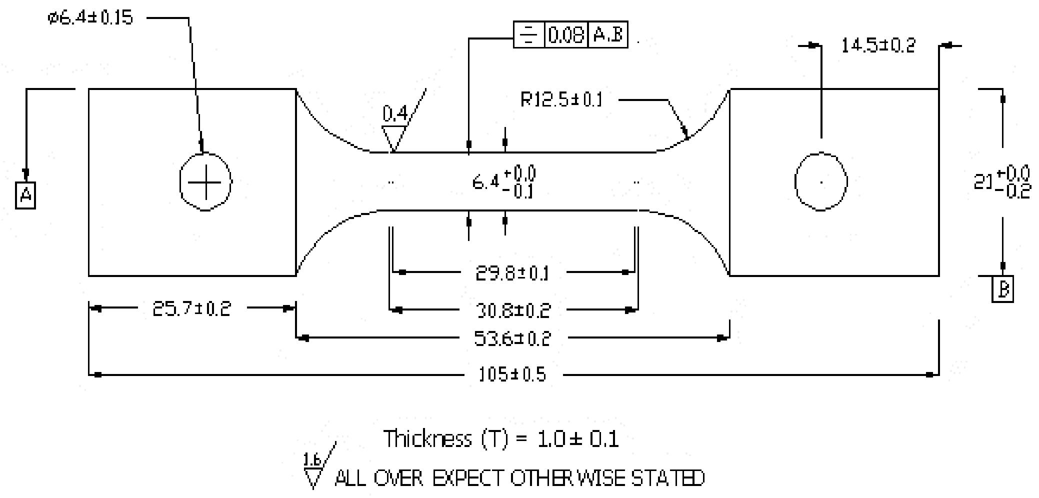


Figure 3.1: ASTM EM8 standard tensile specimen (Kotkunde et al. 2015)

The tensile properties are measured by cutting the specimens from the sheet in three directions. Mechanical properties obtained from the tensile tests are listed in Table 3.1. Tensile strength of DP steel have been found to be more than the IF steel. Tensile test performed on parent materials revealed that the percentage elongation of IF steel is 52.07% and that of DP steel is 24.67% which indicates that the IF steel is more ductile in nature. Failure criteria has been considered when fracture took place in the tensile specimens. The materials have been checked for chemical composition and are listed in Table 3.2. Presence of Niobium and Titanium in the composition of materials is vital in terms of formability aspects.

Table 3.1: Mechanical properties of the IF-DP material combination

Material	YS (MPa)	UTS (MPa)	% el	*K* (MPa)	*n*	Lankford Parameters			*E* (N/mm^2)	PR
						R_0	R_{45}	R_{90}		
DP (1mm)	517	819	24.67	1232	0.23	0.66	0.86	0.7	2.1 x 10^5	0.3
IFHS(0.7mm)	178	308	52.07	637	0.35	1.21	1.19	1.34	1.98 x 10^5	0.3

Table 3.2: Chemical composition of IF-DP materials (in percentage)

Type	C	P	Mn	S	Cr	Ti	Mo	Ni	Si	Al	Cu	Nb
DP	0.092	0.017	1.89	0.012	0.029	0.002	0.004	0.025	0.287	0.029	0.022	0.002
IFHS	0.003	0.011	0.051	0.003	0.012	0.072	0.007	0.023	0.015	0.033	0.021	0.001

3.2 Welding procedures adopted

Most of the TWB sheets are joined by laser welding due to its high production rate and defect-free welds. However, it is an expensive process. As an alternative, TIG welding which is a low cost welding process is preferred in joining the TWB sheets, though the formability of TIG welded TWB is less compared to that of laser welded TWB which is discussed in the following section.

Laser welding

Laser welding has been carried out on a 3 kW CO_2 slab laser machine for the TWB sheet consisting of IF-DP material to obtain a butt weld configuration with the weld line oriented in a perpendicular fashion to its rolling direction. IF steel of 0.7 mm thickness and DP steel of 1mm thickness together produced a weld bead of 1.22 mm width measured with the help of a vernier calliper. Argon at a rate of 20 litres/min is used as the shielding gas to protect the weldment from oxidation and contamination. Radiographic tests are performed to check the quality of weld in terms of porosity and air gaps. The laser welding parameters as shown in Table 3.3 were optimized by Jiang et al. (2016) in their FE simulation study of TWB forming. In this work, same parameter values are used in joining the TWB sheets on a 3 kW CO_2 slab laser welding machine

Table 3.3: Laser welding parameters

Parameter	Value
Power output	3 kW
Welding speed	4 m/min
Spot size	360 microns (Donut beam)
Shielding gas	Argon
Gas Flow	20 lit/mm

Vickers micro hardness tests are conducted for both parent materials and the weld bead after laser welding is done. Thin sections across the weld are mounted, polished and etched using 2% Nital solution. Hardness has been checked in the fusion zones (FZ), heat affected zones (HAZ) and the base metals (BM). It is observed from the Figure 3.2 that the hardness of weld is comparatively greater than the hardness of the parent materials. In other words, it can be concluded that the weld strength is higher than the other parent materials. These tests are conducted on the etched specimens along a straight line diagonally across the weld at an interval of 0.3 mm using an indenter load of 300 g for a duration of 15 s. The hardness value of 440 VHN equivalent to a tensile strength of 1335 N/mm^2 has been calculated as per ASTM A 370 standard conversion table for non-austenitic steels. The maximum value is obtained in the fusion zone which indicates that the weld is stronger than the parent materials. The weld bead size is found to be about 1 mm wide.

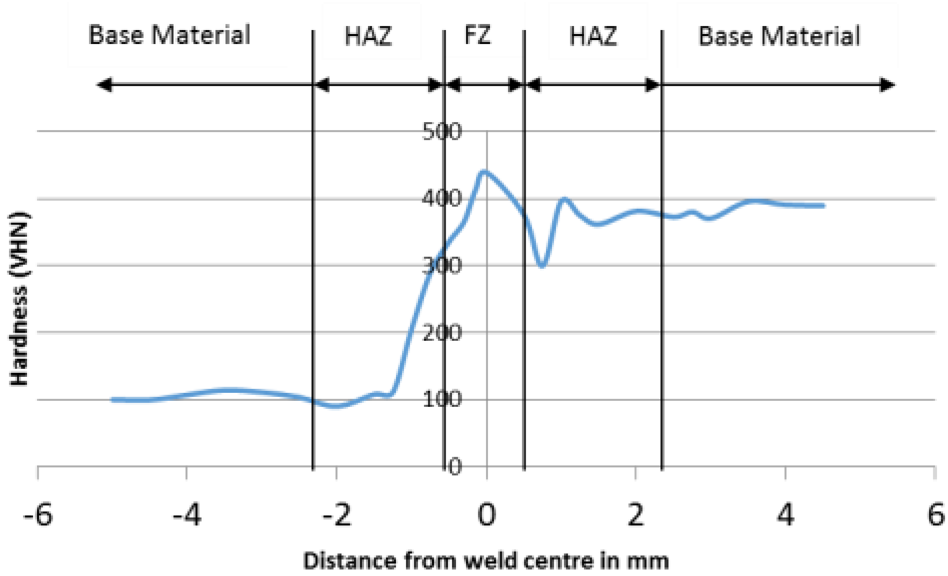


Figure 3.2: Hardness distribution in laser welded TWB sheet

TIG welding

Tungsten inert gas (TIG) welding is carried out on the same combination of materials using fusion welding with the parameters listed in Table 3.4. No filler material is added during welding. TIG welded sheet measured with the help of a vernier calliper produced a weld bead of about 3.1 mm width. Ravishanku et al. (2017) optimized the TIG welding parameters using response surface methodology which correlated the values listed in Table 3.4.

Table 3.4: TIG welding parameters

Parameter	Value
Welding Current	100-120 amps
Welding Speed	3.0 mm/sec
Heat Input	2.38 kJ/min
Rated output voltage	30 V
Shielding Gas	Argon
Gas Flow	15 lit/min
Filler material	Nil

The hardness profile of TIG welded TWB sheet is plotted for the weld and the parent materials in Figure 3.3. The hardness of weld bead has been about 420 VHN equivalent to a tensile strength of 1200 N/mm^2.

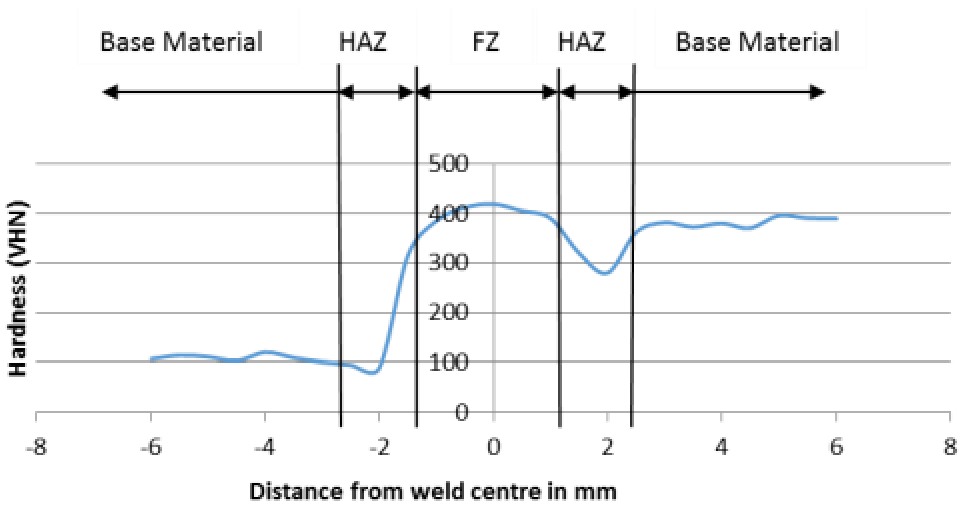


Figure 3.3: Hardness distribution in TIG welded TWB sheet

<u>Comparison between TIG and laser welded TWB forming</u>

The combination of IF-DP materials joined by laser welding as well as TIG welding process are compared among their weld properties and heat affected zone (HAZ). Material properties are evaluated for parent materials as well as weld material using hardness tests, tensile tests and micro tensile tests.

The average width of the laser weld bead measured with a vernier calliper at five locations along the length of the TWB is found to be 1.22 mm and with a uniform weld strength of 1335 N/mm^2 as shown in Table 3.5. Similarly a weld strength of 1200 N/mm^2 is obtained in the case of TIG welded TWB with the average width of weld bead found to be 3.1 mm. The contrast among other parameters are shown in Table 3.5.

Table 3.5: Contrast between laser and TIG welded TWB forming

Parameters	Laser Welding	TIG welding
Weld width	1.22 mm	3.1 mm
Weld strength	1335 MPa	1200 MPa
Surface finish	Excellent	Moderate
HAZ area	Less	More
Manufacturing cost	Expensive	Cheap
Availability	Rarely	Readily available

Since the width of laser weld is narrow compared to the TIG weld, the tendency for the movement of weld line is more due to its slenderness. It also contributes to a greater depth of stamping. Hence it can be concluded that TIG weld is a better choice for a reasonable stamping depth and minimum WLM. Also TIG welding is a low cost welding process compared to laser welding process.

To obtain the weld bead properties in laser welded IF-DP combination, the specimen is also tested by placing the weld bead in transverse and longitudinal directions. The weld bead mechanical behavior has been analyzed by arranging the weld in transverse direction as shown in Figure 3.4. Failure occurred in the IF base material in TWB in all similar welded transverse tensile specimens, which ensured that the weld material is good and strong. It is also observed that no failure took place in heat affected zone (HAZ) of the parent material. The actual material properties of the weld could not be obtained when it is placed in the transverse direction. Because, the weld being stronger than the parent materials and hence failure does not take place in the weld.

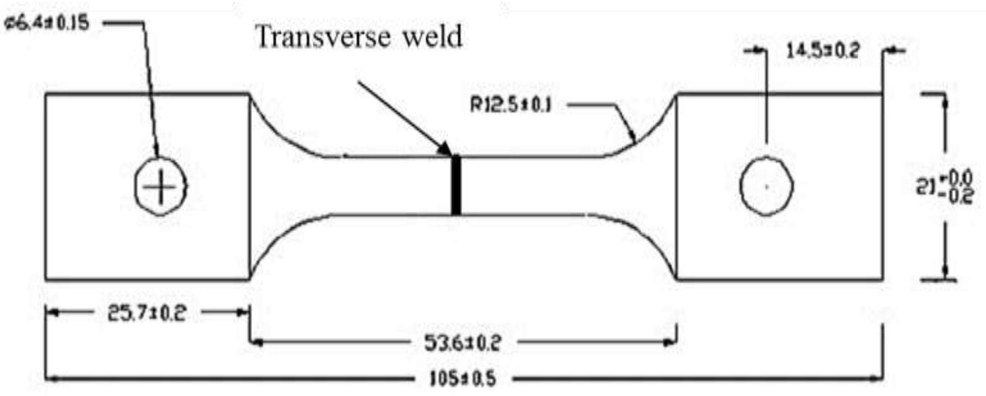


Figure 3.4 ASTM standard specimen to test weld strength

Later, the same combination of materials are tested on miniature size specimens as per ASTM standards as shown in Figure 3.5 by placing the weld in longitudinal direction. Though the weld bead measured only 1 mm width, the width of the specimen as per ASTM standards is 2 mm, which may affect the material properties of weld.

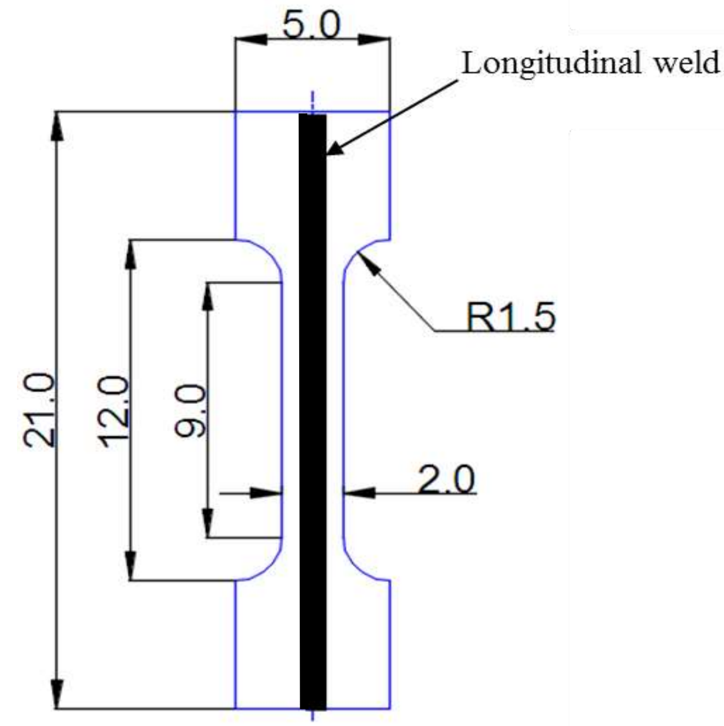


Figure 3.5 Miniature tensile specimen

The rule of mixture method (Padmanabhan et al. 2008b) is used to determine the material properties of the weld bead with the following proportions of materials.

$$X_w = X_{SS}(0.4) + X_{ms}(0.6) \tag{3.1}$$

where suffixes *w*, *ss* and *ms* stand for weld material, stainless steel and mild steel respectively.

The weld properties obtained from all the respective methods are compared and shown in Table 3.6. Among the values, it is found that the weld properties tested by placing the weld in the longitudinal direction are close to the values obtained in Table 3.5, hence the values obtained from hardness tests are used in the FE analysis of TWBs.

Table 3.6: Mechanical properties of the weld material with IF-DP combination

Direction	YS (MPa)	UTS (MPa)	% el	*K* (MPa)	*n*
Longitudinal	462	735	12.31	1194	0.19
Transverse	189	319	27.6	-	-
Rule of mixture method	313.6	512.4	41.11	875	0.302

Comparison between existing and proposed materials

From the existing literatures, it has been found that very few authors have worked on the TWB forming made of IF steel and DP steel. Chatterjee et al. (2009) prepared TWBs made of IF 300 steel and DP 590 steel and constructed forming limit diagrams. In this work, the material data related to the IF-DP material combination is compared with the results obtained from this publication. Bandyopadhyay et al.(2013) used the combination of Interstitial-free high strength (IFHS) and DP 980 steel with a thickness ratio of 1. In this research work, new combination of ASS-IS material are selected to carry out experiments. Comparisons between IF-DP and ASS-IS material combinations in terms of their mechanical properties are shown in Table 3.7.

Table 3.7: Comparison of material properties between IF-DP steel and IS-ASS steel combinations

Material	YS(MPa)	UTS(MPa)	% el	E(kN/mm^2)	K(MPa)	n
Low strength						
IS	202	337	44.02	210	677	0.3
IFHS	178	308	52.07	198	637	0.35
High Strength						
ASS	431	693	69.47	208	1483	0.45
DP	517	819	24.67	210	1232	0.23

From the Table 3.7, it is evident that the difference between the mechanical properties of these materials is marginal and hence the ASS-IS combination has been found to be suitable for further investigation.

ASS-IS steel combination

The base materials IS-513 (mild steel with drawing quality) and ASS-304 (stainless steel), tested as per ASTM EM8 standard specimen as shown in Figure 3.1.

The tensile tests are conducted at room temperature conditions, 100 ^oC, 150 ^oC, 200 ^oC and 250 ^oC on a 100 kN electro-mechanical universal testing machine as shown in Figure 3.6, which has the provision for heating the specimens. In this study, the mechanical properties of ASS 304 grade are investigated at all the above mentioned temperatures. IS 513 steel material is tested at room temperature only, since it needs to be maintained at low temperature throughout the forming process. The mechanical properties are shown in Table 3.8 for the respective materials. The chemical composition of the materials are shown in Table 3.9. Both the materials are considered to be low Carbon steels as it is evident from this table.

Figure 3.6: Universal testing machine

Table 3.8: Mechanical properties of ASS-IS materials tested at room temperature

Material	YS(MPa)	UTS(MPa)	% el	*K*(MPa)	*E*(kN/mm^2)	*n*
ASS 304 (SS)	431	693	69.47	1483	208	0.45
IS 513 (MS)	202	337	44.02	677	210	0.3

where YS is the yield strength, UTS is the ultimate tensile strength, %el is the percentage elongation, *K* is the strength coefficient, *E* is the Young's modulus, and *n* is the strain-hardening exponent

Table 3.9: Chemical composition of ASS-IS material combination (in % Weight)

Material	C	Mn	Si	Mo	Cr	Ni	Cu	Fe
ASS 304 (SS)	0.046	1.03	0.22	0.22	18.91	8.3	0.33	Rest
IS 513 (MS)	0.06	0.37	0.047	0.028	0.027	0.054	0.019	Rest

Simple tensile tests are carried out at a constant strain rate of 0.001 $sec^{-1}$for both the base materials and shown in Figures 3.7 and 3.8 respectively. Tensile tests conducted on ASS 304 material at different temperatures shows that the elongation has reduced in the material at higher temperatures. Also, fracture occurred at different places (sometimes beyond the gauge length)

Figure 3.7: Fractured tensile specimen of IS 513 tested as per ASTM standards at room temperature

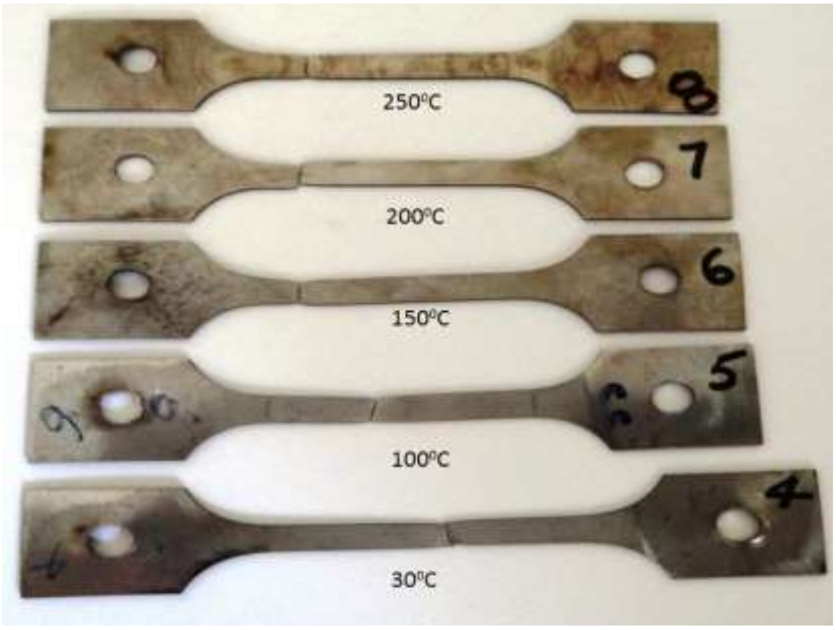


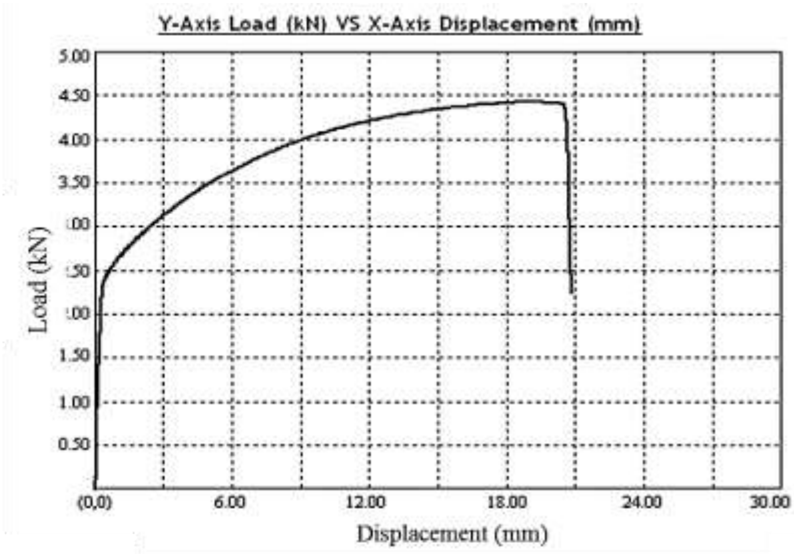
Figure 3.8: Fractured tensile specimens of ASS 304 tested as per ASTM standards at different temperatures

Load displacement graphs obtained from the universal testing machine for ASS and IS materials tested at room temperature are shown in Figure 3.9 (a and b). The percentage elongation is calculated as follows:

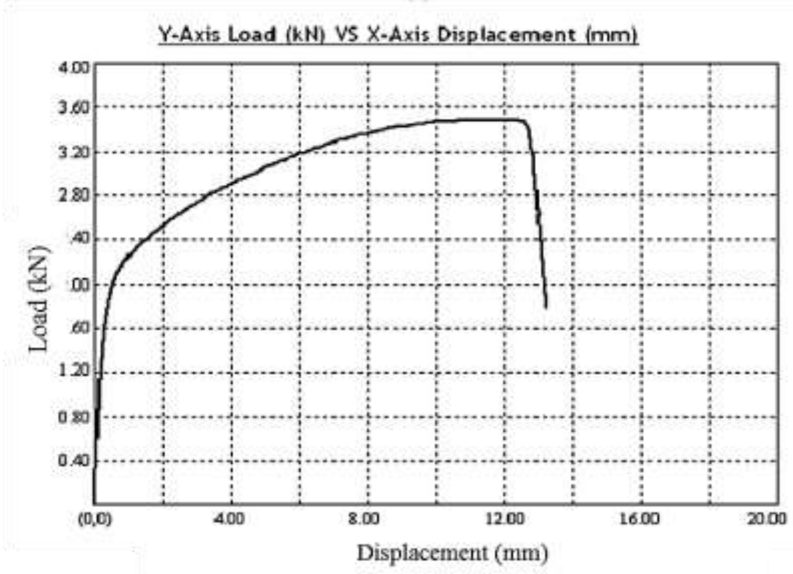
Percentage Elongation (% el) = Maximum displacement / Gauge length

For ASS-304 material, %el = 20.84/30 =69.46% (Sheet thickness = 1 mm)

For IS-513 material, %el = 13.2 / 30 = 44%. (Sheet thickness = 1.6 mm)



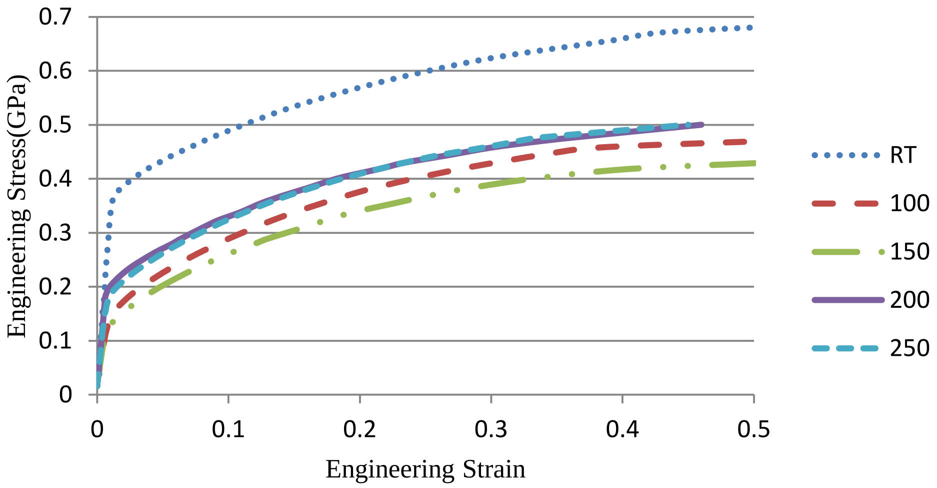
(a)



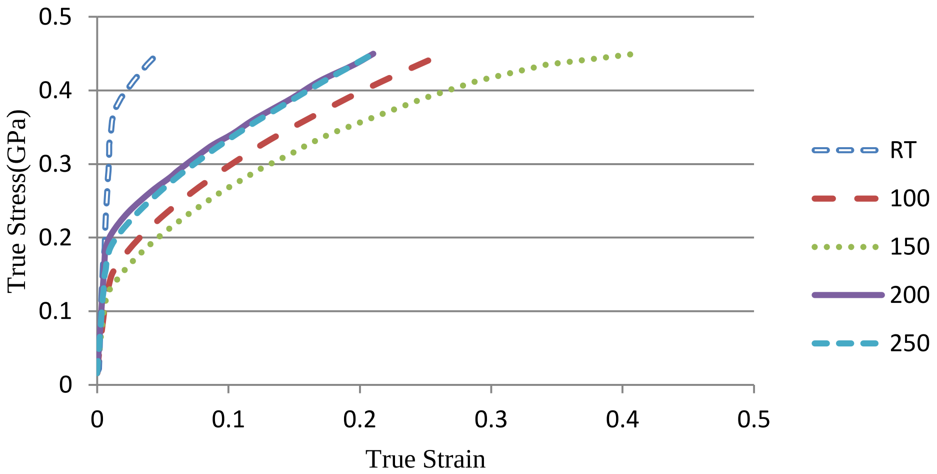
(b)

Figure 3.9 Load-displacement graph of (a) ASS and (b) IS materials tested at room temperature

Engineering stress strain graphs as shown in Figure 3.10(a) is plotted based on the load displacement graph of ASS material. It is evident from the figure that the strength value corresponding to 150 ^{o}C is lower as compared to the testing conducted at other temperatures. Hence in this study, the temperature of 150 ^{o}C has been chosen for conducting the experiments.



(a)



(b)

Figure 3.10: Stress-strain plots for ASS 304 material tested at different temperatures under (a) Engineering conditions (b) True conditions

Figure 3.10(b) shows the true stress-strain graph generated from the engineering stress-strain graph of Figure 3.10 (a) tested at different temperatures. The true stress strain graph would help in obtaining the strength coefficient (*K*) and strain hardening coefficient values.

The data related to the 0.2% yield strength as a measure of flow stress is taken from the Figure 3.10 (b). Figure 3.11 (a-e) shows the variation in the mechanical properties for the samples tested at different temperatures.

The variation in yield strength of the ASS material due to heating is shown in this Figure 3.11 (a). Similarly, the variation in ultimate tensile strength with respect to the temperature is plotted in figure 3.11(b). The values of strain hardening exponent (*n*) and strength coefficient (*K*) are plotted in Figure 3.11(c) and 3.11(d) at different temperatures ranging from 30 ^{o}C to 250 ^{o}C. Percentage elongation showed a downward trend at higher temperatures as shown in Figure 3.11(e). The experimental data matched with the works carried out by Jayahari et al. (2014) and Hussaini et al. (2015).

Desu et.al (2016) carried out tensile tests on ASS 304 material at different strain rates. They found variations in the mechanical properties even at constant strain rate under different temperatures. They have observed two phenomena, (i.e., the formation of deformation induced martensite and dynamic strain aging) during tensile straining of austenitic stainless steels. The former can result in drastic changes in the stress-strain behavior.

Strain hardening exponent (*n*) and strength coefficient (*K*) are calculated from both engineering and true stress-strain graphs. The *n* value indicates the amount of flow stress for a particular amount of strain. The flow stress increases rapidly with strain in the materials with a high *n* value. A high *n* value indicates that a large difference between yield strength and ultimate tensile strength exists, which is good in terms of formability. The characteristics of strain hardening for a particular material is usually dependent on the strain, temperature and strain rate.

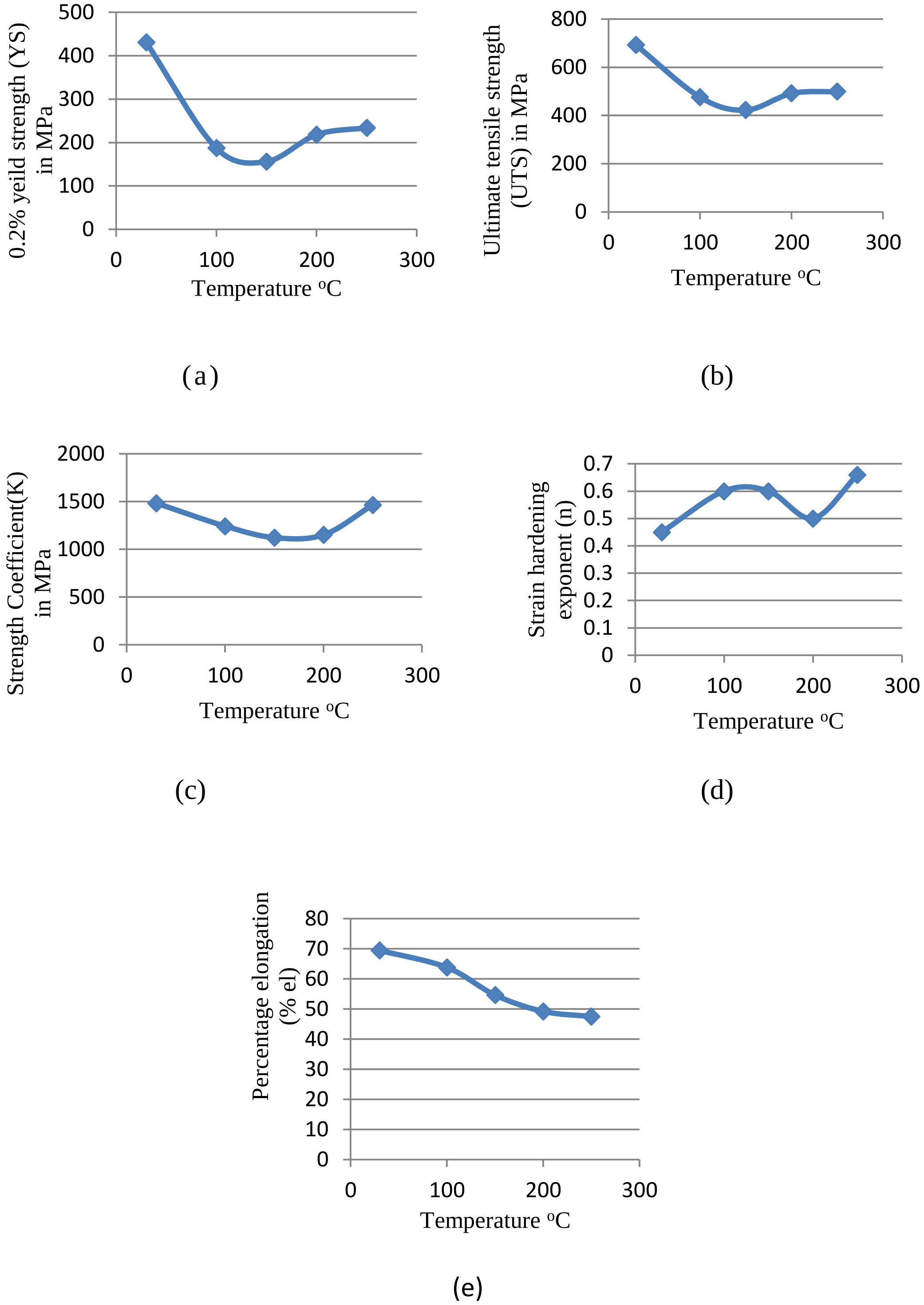


Figure 3.11: Variations in the mechanical properties of ASS-304 at different temperatures a) YS, b) UTS, c) *K*, d) *n*, e) %el

If the temperature and strain rate are assumed to be constant, the true strain can be approximated by the constitutive equation

$$\sigma = K\varepsilon^n \tag{3.2}$$

Taking natural logarithm on both sides of equation ,

$$\log \sigma = \log K + n \log \varepsilon \tag{3.3}$$

A linear equation representing a straight line is generated with the above equation (3.3). At a given point, the engineering stress is calculated as σ = load / cross-sectional area and the engineering strain is given by ε = (Change in length – Gauge length) / Gauge length. The true stress and true strain have a relationship with the engineering stress and engineering strain as: true stress = engineering stress (1+ engineering strain). The true strain is calculated by taking natural log of measured change in length plus the original measured length, divided by the original measured length. The log of true strain is taken along x- axis and the log of true stress along y-axis. The *y*-intercept of the line gives the log of strength coefficient (*K*) and the slope of the straight line gives the value of strain hardening exponent (*n*). The detailed test procedure for determining *K* and *n* values is available in ASTM E 646-07e1 standards.

The anisotropy coefficient (*r*) value is dependent on the orientation of sheet. It is also known as *Lankford parameter,* and it is determined by using three tensile test specimens cut at 0°, 45° and 90° along the rolling direction of sheet stock as shown in Figure 3.12.

The anisotropy coefficient (*r*) is defined as

$$r = \frac{\epsilon_{width}}{\epsilon_{thickness}} \tag{3.4}$$

where $\in_{thickness}$ is the true thickness strain and $\in_{width}$ is the true width strain of the tensile specimen. Rewriting in terms of the dimensions of the specimens,

$$r = \frac{\ln\frac{w}{w_0}}{\ln\frac{t}{t_0}} \tag{3.5}$$

where, w and t are the final width and final thickness and w_0 and t_0 are the initial width and initial thickness of the specimen respectively. As the thickness of the specimen is very small compared to its width, the relative errors of measurement of the two strains can be quite different. Therefore, the above relationships are replaced by considering the length of the specimen. Equation (3.5) is rearranged as

$$r = \frac{\ln\frac{w}{w_0}}{\ln\frac{l_0.w_0}{lw}} \tag{3.6}$$

Anisotropy may be measured as either normal anisotropy or planar anisotropy. Normal anisotropy (r_n) indicates the drawability of sheet and is calculated based on the average value of anisotropy in the three directions and is expressed as

$$r_n = (r_0 + r_{90} + 2r_{45})/4 \tag{3.7}$$

Planar anisotropy (Δr) is a measure of the variation of anisotropy along different directions in the plane of the sheet. It is responsible for uneven thinning and the formation of ears in the stamped parts. Mathematically, it is expressed as:

$$\Delta r = (r_0 + r_{90} - 2r_{45})/4 \tag{3.8}$$

In the present work, *Lankford parameter* of anisotropy in ASS-304 material has been found to be 0.96 based on the specimens cut along three directions as shown in Figure 3.12. Takuda et al. (2003) obtained similar values for normal anisotropy parameter (r) equivalent to 1, irrespective of heating the sheet metal. Hence isotropic conditions are assumed in the present simulation work for all temperatures.

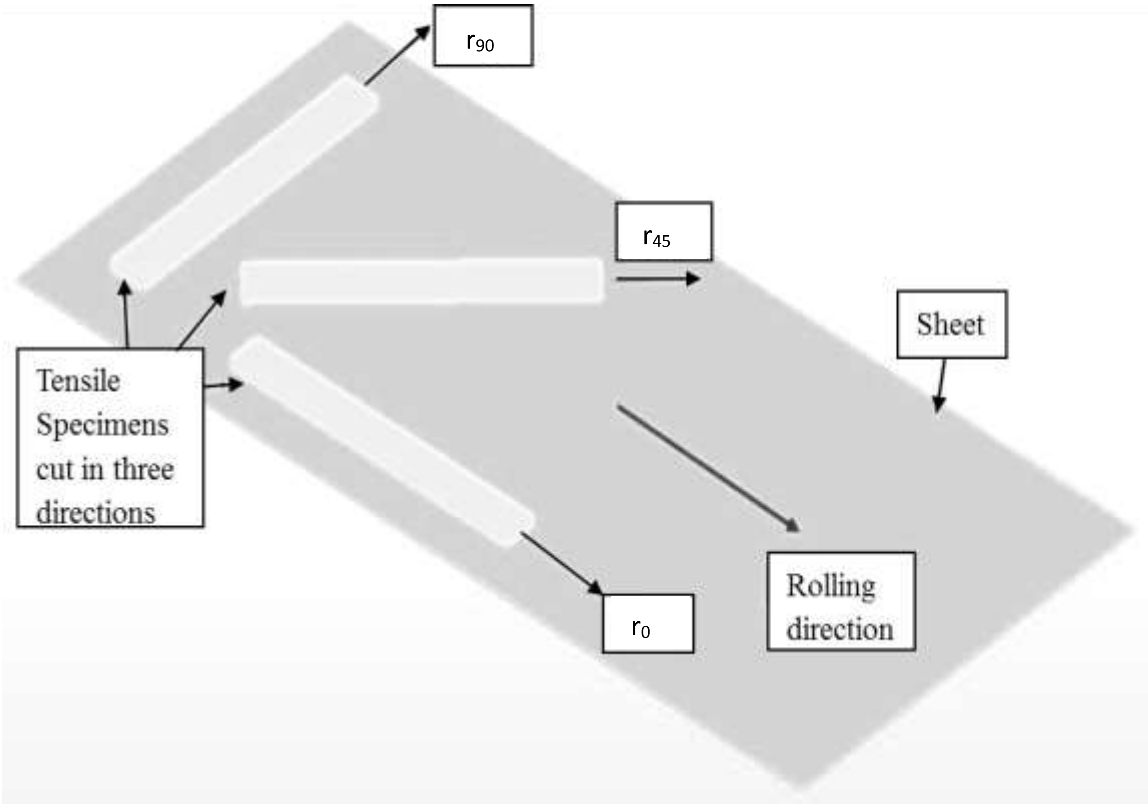


Figure 3.12: Tensile specimens cut along different directions in a rolled sheet

The ASS-IS sheet materials are joined together by TIG welding process. The rule of mixture method as per equation (3.1), is also used to determine the material properties of the weld bead and these values are used in numerical simulation.

3.3 Numerical simulations

Thermo-mechanical modeling

Transient heat conduction differential equation in cylindrical coordinates in a coupled thermo-mechanical FE simulation given by Bergman and Oldenburg (2010) is

$$k\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right\}-c\rho\ \frac{\partial T}{\partial t}+\dot{q}\ =0 \qquad (3.9)$$

where r is the radius of cylinder, k is the thermal conductivity, c is the specific heat, T *is* the temperature, ρ is the density, t is the time and $\dot{q}$ is the heat generation rate per unit volume.

In Cartesian co-ordinates, the equation of equilibrium can be expressed as

$$\frac{\partial\sigma_{ij}}{\partial x_j}+F_i=0 \qquad (3.10)$$

where F_i is the component using Einstein's summation convention, i,j = 1,2,3 and Cauchy stress tensor σ_{ij} is given by

$$\sigma_{ij}.n_j=t_i \qquad (3.11)$$

which is the i[th] component of the traction vector acting on a surface with normal, n_j .

The principle of virtual work is used to solve the governing equation (3.10). It establishes a relation between variations in internal and external work due to infinitesimal displacement variations for a deformable body.

The Galerkin weak formulation of the above stress governing equation and Cauchy stress boundary condition results in the following integral equation, which is same as the standard principle of virtual work for a solid mechanics boundary value problem.

For a general deformable body, the principle of virtual work is given by

$$\int_V \bar{\varepsilon}^T \sigma \, dV = \int_V \bar{u}^T F \, dV + \int_\Gamma \bar{u}^T t \, d\Gamma \tag{3.12}$$

where $\bar{\varepsilon}^T$ is the virtual strain corresponding to the virtual displacement, σ is the internal stress, dV is the volume, $\bar{u}$ is the virtual displacement, F is the external body force, t is the external surface traction, $d\Gamma$ is the boundary of the element to be considered. This integral equation has been solved as the domain Ω and boundary Γ considered in this problem by treating displacement vector $\bar{u}$ as the primary variable.

Initially, $\bar{u}$ = 0, on the boundary $d\Gamma$, since external forces are unknown on $d\Gamma$. This means that arbitrary virtual displacements must lead to identical variations in internal and external work.

<u>Finite element simulations</u>

Numerical simulations are carried out in LS-Dyna, a non-linear FE analysis software. Initially two semi-circular shaped geometries are joined by a 3 mm wide rectangular plate diametrically as shown in Figure 3.13 (a). A uniform thickness of 1 mm is taken for all the geometries.

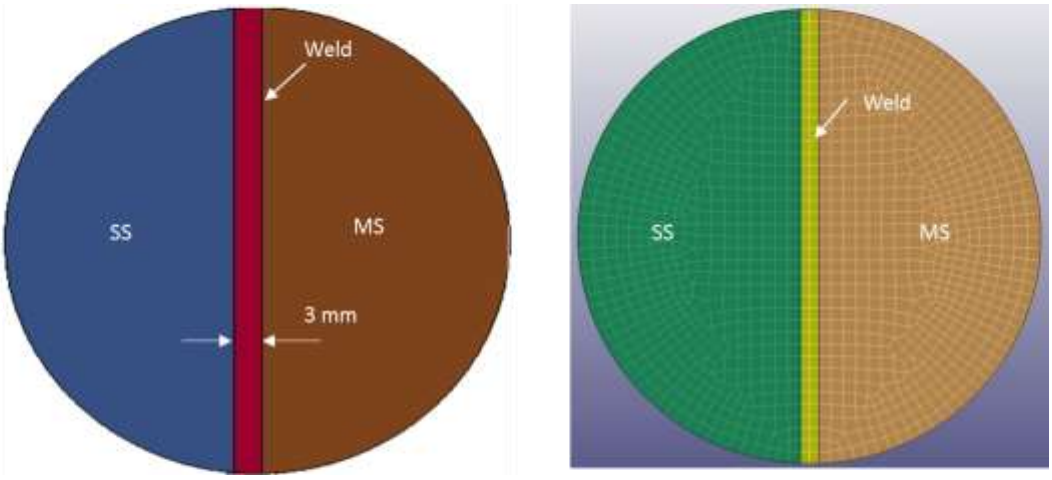


Figure 3.13: a) Geometry and b) FE mesh of TWB

Adaptive meshing has been carried out to generate elements and nodes separately. Nodes on the boundaries between weld and parent materials are merged thus producing a single TWB sheet. Material properties related to ASS-304, weldbead and IS-513 are assigned to each sheet. The TWB shown in Figure 3.13 (a) is meshed by four node quadrilateral Belytschko-Tsay shell elements using automatic meshing option. The nodes at the interface boundaries between the weld and parent materials are merged into one as shown in Figure 3.13 (b). A total of 5639 elements and 5934 nodes are generated in the FE model. All tooling surfaces, viz., die, punch and blank holder are modelled with rigid shell elements. Using fully integrated shell elements, a coupled thermo-mechanical analysis is performed. A friction coefficient of 0.1 is assumed between all the contact surfaces. The isotropic plasticity model (MAT 18) based on swift power law hardening rule with temperature effects has been chosen as the material model because as mentioned earlier in the previous section, the ASS-304 material behavior is almost isotropic.

Material model

Swift power type isotropic work-hardening equation (Altan and Tekkaya, 2012, Dixit and Narayanan, 2013) has been used in constitutive modeling of TWB forming:

$$\bar{\sigma} = K\,(\varepsilon_0 + \bar{\varepsilon}^p)^n \tag{3.13}$$

where $\bar{\varepsilon}^p$ is the equivalent plastic strain , $\bar{\sigma}$ is the equivalent tensile stress and strain to yield ε_0 is given by

$$\varepsilon_0 = \left(\frac{\sigma}{K}\right)^{\frac{1}{n}} \tag{3.14}$$

where *n* and *K* are the strain hardening coefficient and strength coefficient respectively.

The punch is split into two halves with a gap of 2 mm in between them. One part of the punch is set to a temperature of 500 °C. This part of the punch came into contact with the high strength TWB material, ASS 304 and the other part of the punch is set at 0 °C and it shall be in contact with the low strength TWB material, IS 513 blank. A uniform blank holder force of 15 kN is applied on the TWBs to avoid formation of wrinkles during forming. The complete FE model setup is shown in Figure 3.14. The data related to the punch radius, die radius and clearance between the punch and die were collected from the literature (Padmanabhan et al., 2007 and 2008 b).

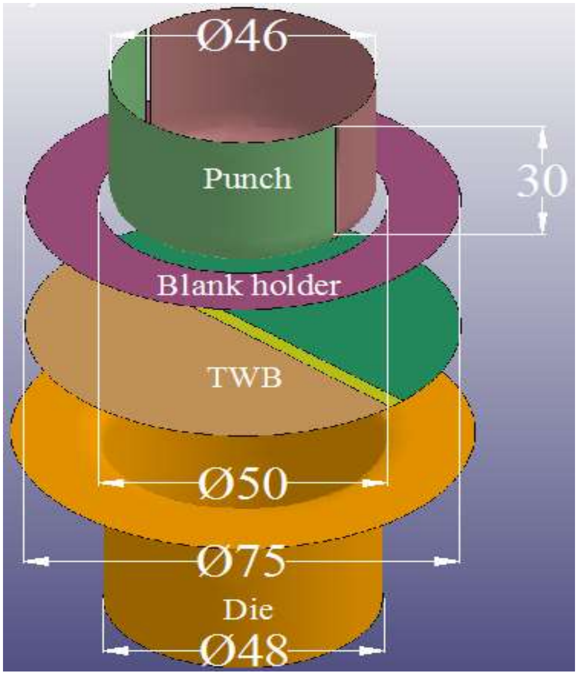


Figure 3.14: FE model setup

Model assumptions

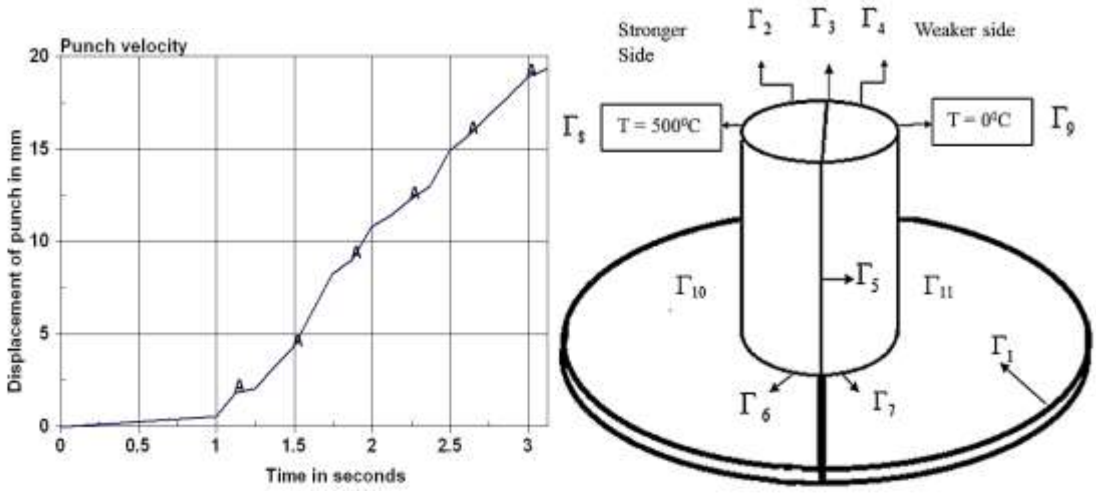
For developing the coupled thermo-mechanical model, the following assumptions are made:

- Internal heat generation and heat transfer coefficient due to friction are considered negligible due to the insulation provided around and in between the punch.

- Loading due to the transient thermal field on the body is considered.
- The blank and punch are assumed to come into contact under high contact pressure, without any thermal contact resistance so that heat transfer takes place quickly after the punch comes into contact with the blank.
- Heat transfer by convection or radiation is negligible. This is justified because all the exposed surfaces of the setup are suitably insulated against atmosphere and the radiation or convection are small because temperatures are not very high.
- The density of the material is not affected by thermal expansion.

The keyword 'BOUNDRY_PRESRIBED_MOTION_RIGID' is used in LS_Dyna to move the punch, and it has been controlled based on the time taken for punch travel. The velocity of punch is shown in the Figure 3.15 (a) and is calculated based on the load displacement graph obtained from experiments. A time interval of 0.1 seconds between 0-3 seconds is taken while defining the load curve in the LS Dyna software.

Boundary conditions



(a) (b)

Figure 3.15: a) Graph showing punch velocity b) Boundary conditions on TWB sheet

The essential and natural boundary conditions acting on the blank and the punch are shown in Figure 3.15 (b). They are listed as under:

Boundary $\Gamma = \Gamma_1 + \Gamma_2 +$ ---------- Γ_9

<u>Thermal boundary conditions </u>(Figure 3.16 (a))

Essential BCs:

On Γ_6, T= 500^0C

On Γ_7, T= 0^0C

Natural BCs:

On $\Gamma_{8,}$ Γ_9 ; insulated

<u>Displacement boundary conditions </u>(Figure 3.16 (b))

Essential BCs:

On Γ_6, Γ_7, Γ_8, Γ_9 ; $u= -u_z$

On Γ_{10} and $\Gamma_{11,}$ $u_x = u_y = u_z = 0$

Natural BCs:

On Γ_{10}, Γ_{11} ; σ_n = binder force

On Γ_2 , Γ_3, Γ_4 and Γ_5 ; $u= -u_z$

On Γ_1 ; $u= -u_i$

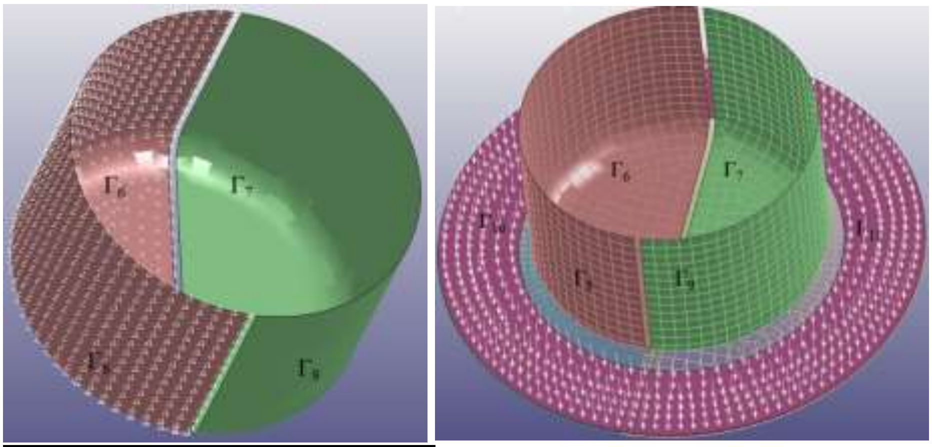


Figure 3.16: Boundary conditions on punch (a) Thermal (b) Displacement

The interface contact and friction conditions viz. Γ_6 and Γ_7 between the punch and the blank are given by the equation

$$\tau = \mu\sigma_n \tag{3.15}$$

where μ = coefficient of friction, τ = shear stress and σ_n = normal stress

Γ_8 and Γ_9 are the temperatures of the respective punches before stamping operation is carried out considering no heat transfer to the surroundings. Since the blank holder prevents the movement of material particles of the blank in contact with it in both radial and circumferential direction, all the displacement components of these particles are considered to be zero.

The temperature distribution in the ASS material during HAFTWB is shown in Figure 3.17 for a time interval of 3 sec. It shows that the temperature of the part has an upward trend in the cup section maintaining a temperature above 150 ^oC. Since a clearance of 2 mm is provided between the punch and the die, there is no contact between the punch and the cup wall. It also indicates that the temperature of the TWB blank during forming is uniform and maintained below recrystallization temperature.

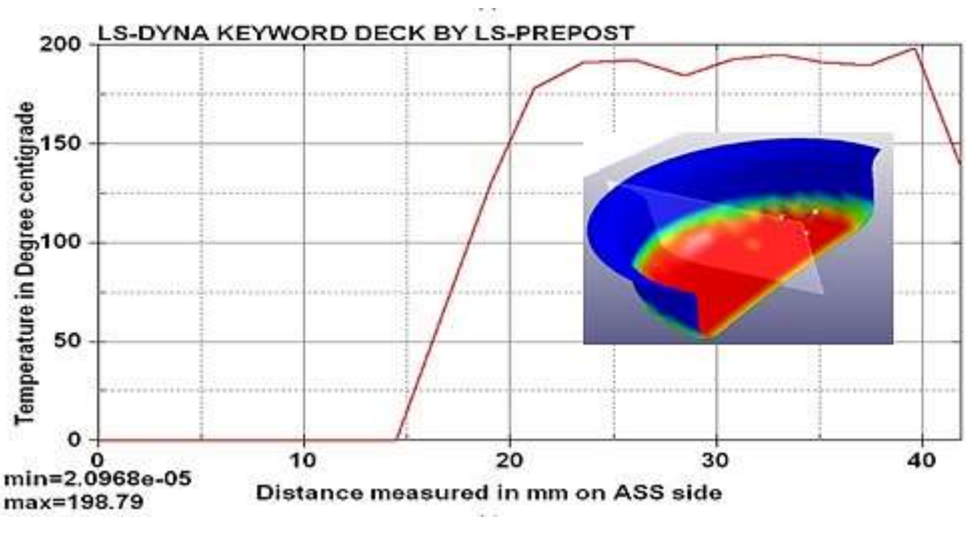


Figure 3.17: Temperature distribution in ASS material side

The boundary conditions are chosen based on the conditions of stamping process, where the punch would travel only in the vertically downward direction. Heat dissipation between the punch and atmosphere is assumed to be negligible due to the insulation being provided. Since the heat transfer is successfully constrained to the deformation zone, the temperature boundary condition on the two sides of the sheet are considered to be isothermal.

The physical and thermal properties of ASS 304 material at 150 ^{o}C were collected from literature (ASM Handbook, 1990) are shown in Table 3.10.

Table 3.10: Thermal and physical properties of ASS 304 material

Property	Value	
Density	80	kN/m^3
Thermal conductivity	16.2	W/m•K
Thermal expansion	17.2	10^{-6}/K
Heat capacity	500	J/kg K

The well-known rule-of-mixture has been used to describe the material behavior of the weld bead. Using the mechanical properties of parent metals from Table 3.1, the weld bead properties estimated by the equation (3.1) are calculated and shown in Table 3.11. The percentage elongation has been obtained from the laboratory experiments by placing the weld line in the longitudinal direction in the ASTM tensile specimen as shown in Figure 3.1.

Table 3.11: Mechanical properties of weld bead using rule of mixture method for ASS-IS materials

Parameter	Value
Yield strength (YS)	293 MPa
Ultimate Tensile Strength (UTS)	479 MPa
Percentage elongation (%el)	15.6 %
Young's modulus (E)	209 GPa
Strength coefficient (*K*)	1000 MPa
Strain hardening exponent (*n*)	0.36

3.4 Results and discussion

Some of the results obtained from simulation study are presented below. The ASS material was subjected to heating which enabled it to decrease its flow stress, thereby allowing more material to flow into the die cavity. This has led to shift the weld line towards the other side (IS side). The experimental validation of the simulation results are presented in the next chapter. WLM is checked both at the cup bottom as well as cup wall.

Weld line movement at cup bottom

The FE simulation predicted the WLM measured with reference to the centre of cup. The images of the formed cups obtained from simulation experiments are inserted in AutoCAD software to measure the deviations of WLM in the cup bottom. The images are scaled to the actual size of the cup diameter, which is 46 mm. Deviations inWLM are measured perpendicular to the weld line with reference to the centre of the cup. The cup height is restricted to 20 mm in the simulation work. TWB cup formed at room temperature resulted in a WLM of 2.2 mm measured from the centre of the cup as shown in Figure 3.18(a). It reduced to 0.4 mm when formed at elevated temperature of 150 ^{o}C as shown in Figure 3.18(b).

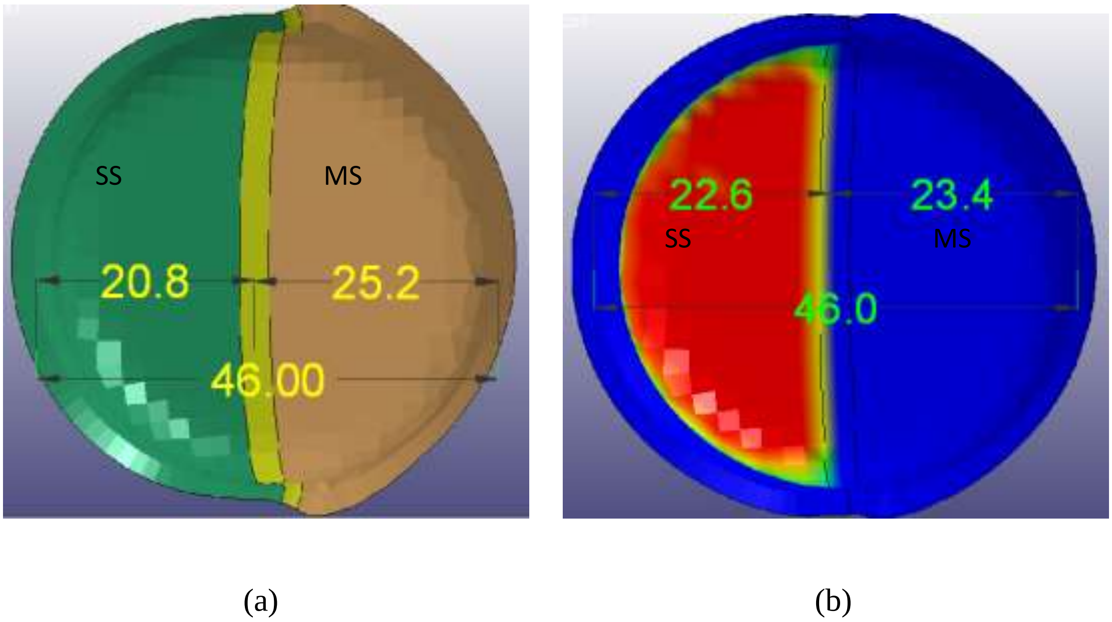


Figure 3.18: Simulation results of the WLM at the bottom of cup (a) Without heating (b) With heating

To obtain more precise movement of the weld line, a cross–section along the longitudinal weld direction is taken and measurements are carried out with reference to the centre across the weld line at the centre.The simulated results of the WLM in a TWB cup formed at room temperature and elevated temperature at the bottom of the cup are plotted in Figure 3.19. The WLM is measured in the parent materials just besides the weld line. In both cases, a symmetry of WLM is maintained. Forming at room temperature resulted in a WLM of 2.217 mm whereas forming at elevated temperature resulted in a WLM of 0.542 mm. The difference of WLM in both the cases is nearly 75% between them.

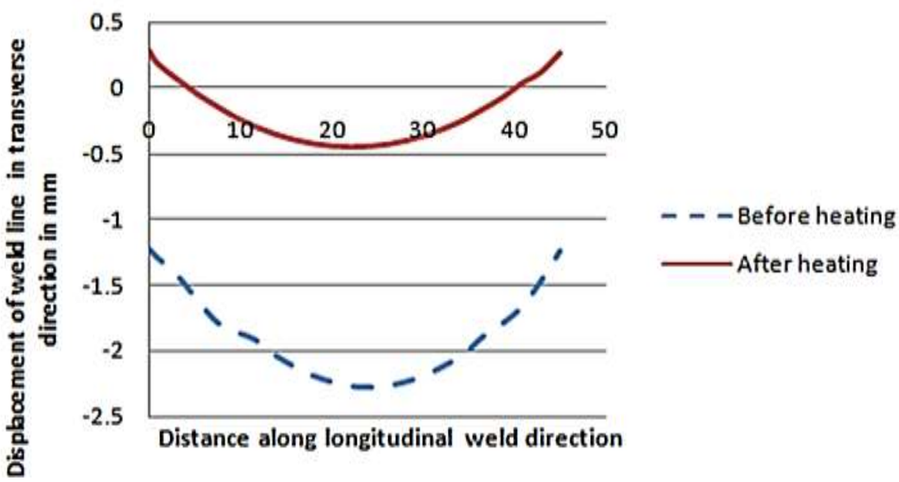
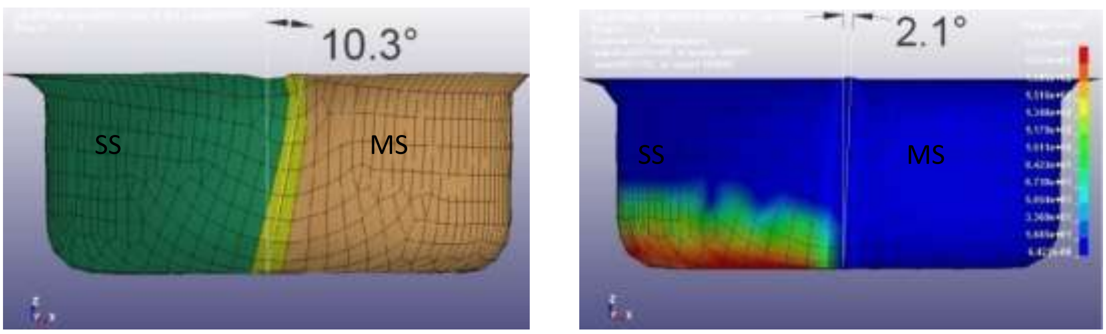


Figure 3.19: WLM in transverse direction at cup bottom

Weld line movement in cup wall

The WLM along the wall of the cup is also measured in terms of the angle of the displaced weld line to the original weld line. The TWB cup formed at room temperature resulted in a angular displacement of 10.3^{o} measured with respect to the vertical and the TWB cup formed at elevated temperature it resulted in an angle of 2.1^{o}, as shown in Figure 3.20. Thus the change in angular movement of weld line is about 79.6% in the cup wall.



(a) (b)

Figure 3.20: Angular movement of weld line in the cup wall obtained through simulations conducted at (a) Room temperature (b) 150 ^{o}C.

The simulation work has been extended to the TWB cups formed at other temperatures as well viz. at 80 °C, 100 °C and 120 °C respectively. The angular movement of the weld line is plotted in terms of angle and the corresponding temperature in Figure 3.21. It is evident from the figure that weld line varied drastically with respect to the temperature.

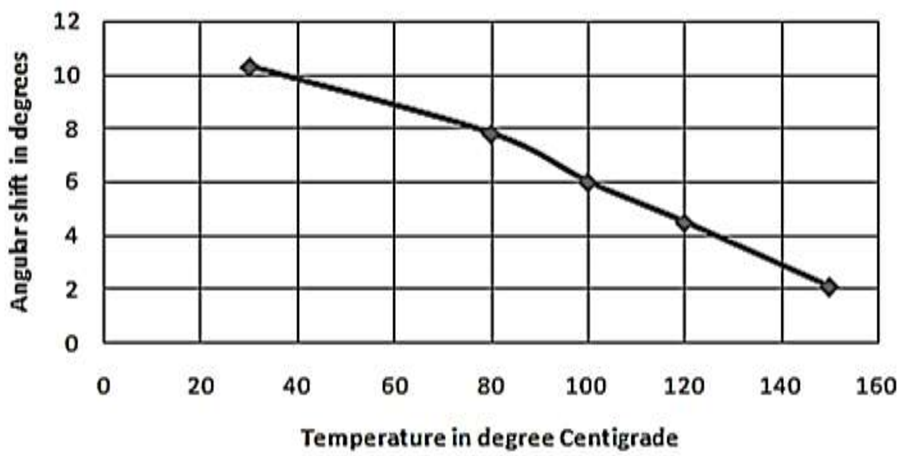


Figure 3.21: Graph showing the variation of angular shift of weld line in the cup wall with temperature.

Stress distribution

When peak stresses occur during forming of TWB, it may lead to fracture of the cup. So, it is essential to plot the stress distribution especially at the punch corner region, where severe stresses occur. Abrupt changes in the stress pattern is observed in ASS material during forming at room temperature as shown in Figure 3.22 (a). The ASS material exhibited maximum stress (sharp peak) of 0.68 N/mm^2 which is less than the allowable safe stress of 0.8 N/mm^2. It occurred in-between 20 mm and 30 mm along the section. This region corresponds to the punch corner in the experimental setup. During forming, the TWB cup may fracture due to the sudden rise in stress.

Stress pattern when forming is carried out at elevated temperature resulted in a stress of 0.47 N/mm^2 in the same region as shown in Figure 3.22(b), thus minimizing the chances of fracture in the material. It is also observed from Figure 3.22 (b) that there is no peak stress in the region and the stress is uniformly distributed.

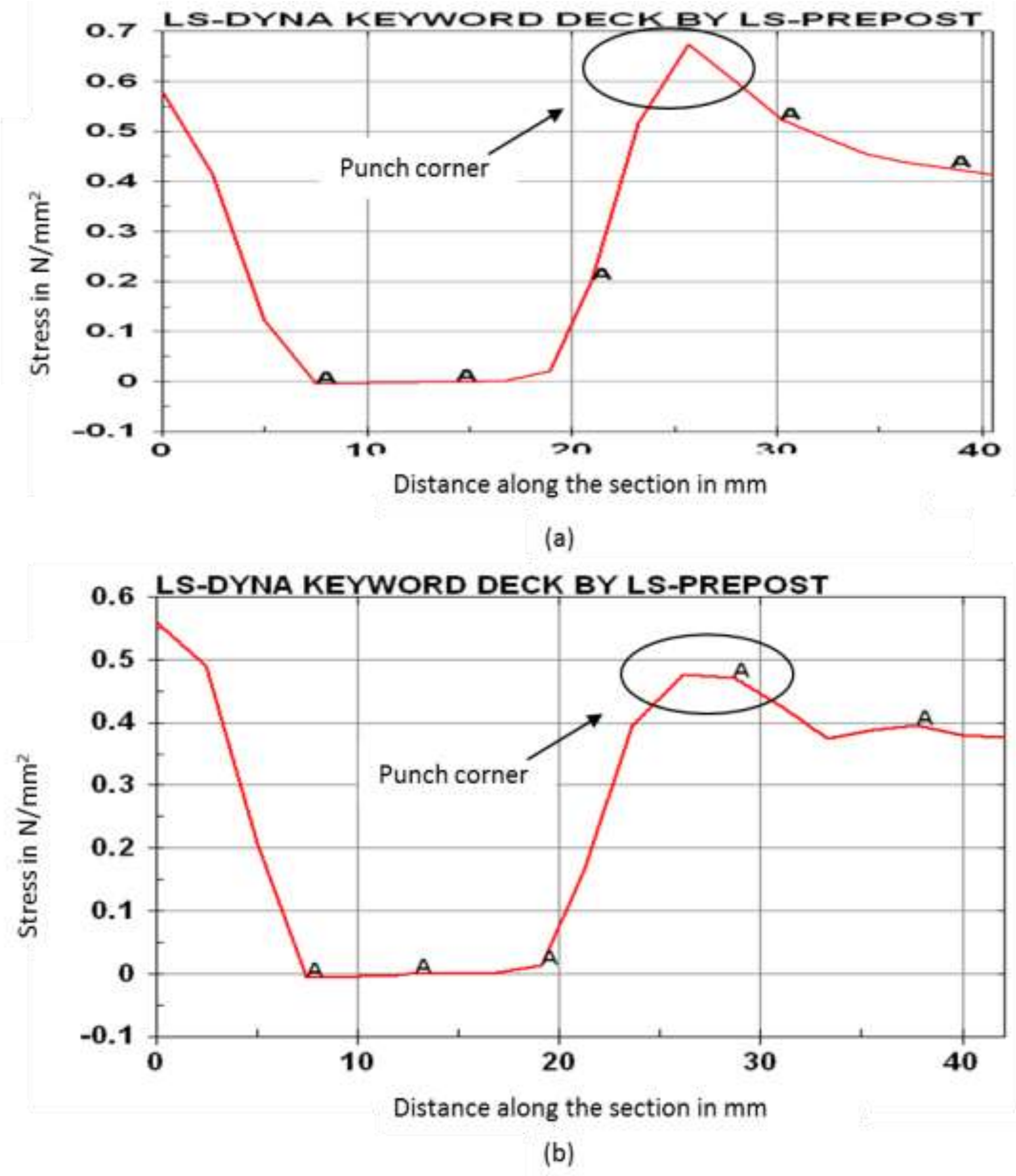


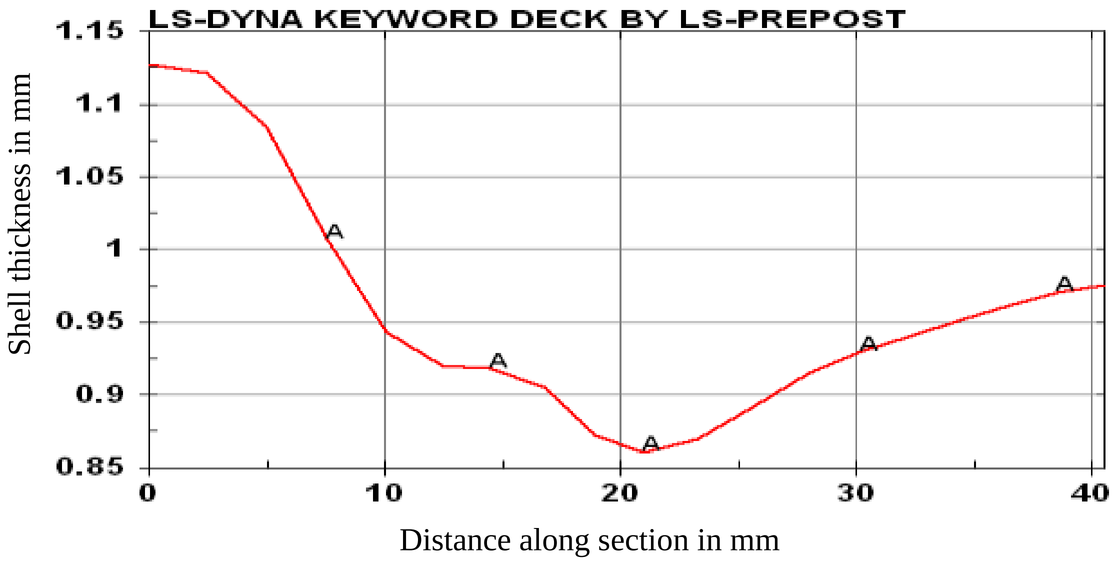
Figure 3.22: Stress distribution measured in N/mm^2 in ASS material formed at a) room temperature b) elevated temperature

Thickness measurement

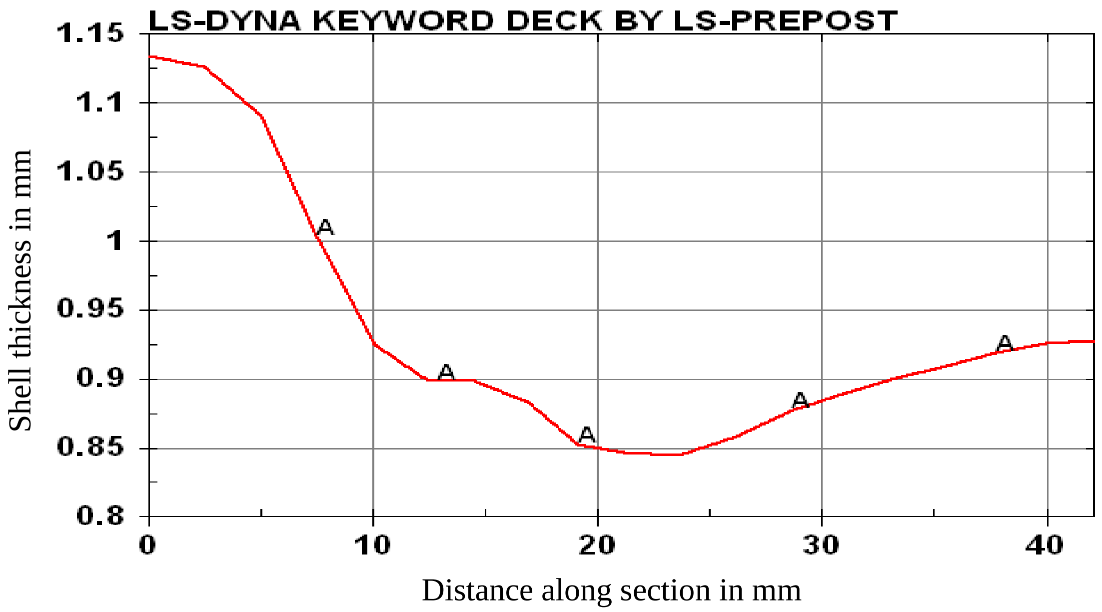
Thickness distribution is also obtained from the simulations. They gave similar results. Since it is difficult to measure the thickness of formed cups using conventional measuring devices, simulation graphs would help in predicting the values approximately by using LS-Dyna software. These graphs are used to plot the thinning behavior of each TWB material during forming. The thickness behavior of ASS material have been evaluated at elevated temperature and room temperature as shown in Figure 3.23 (a and b) respectively. The thickness of ASS material reduced to about 0.87 mm at the punch corner from the initial sheet thickness of 1 mm when the TWB is formed at room temperature as shown in Figure 3.23(a).

Forming at elevated temperature resulted in a thickness of about 0.85 mm in the same material at the same location as shown in Figure 3.23 (b). The graph showed that the thickness of ASS material has been reduced by about 0.02 mm more, when the stronger material has been subjected to heating. It predicts the chance of fracture in the ASS material when formed at elevated temperature. It also confirms that the ASS material is softening due to the application of heat, allowing more material to flow into the die, thus resulting in the movement of weld line towards the IS side.

In a similar fashion, the thickness of IS material in the TWB cup formed at different temperatures is plotted as shown in Figure 3.24 (a and b). The thickness of IS material which has been 1 mm initially, reduced to about 0.87 mm when formed at room temperature as shown in Figure 3.24 (a).



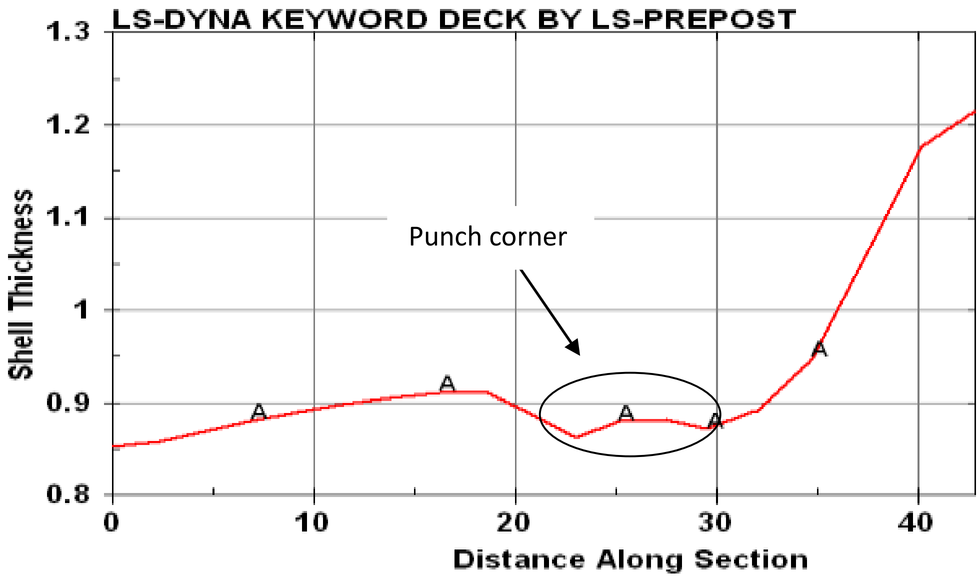
(a)



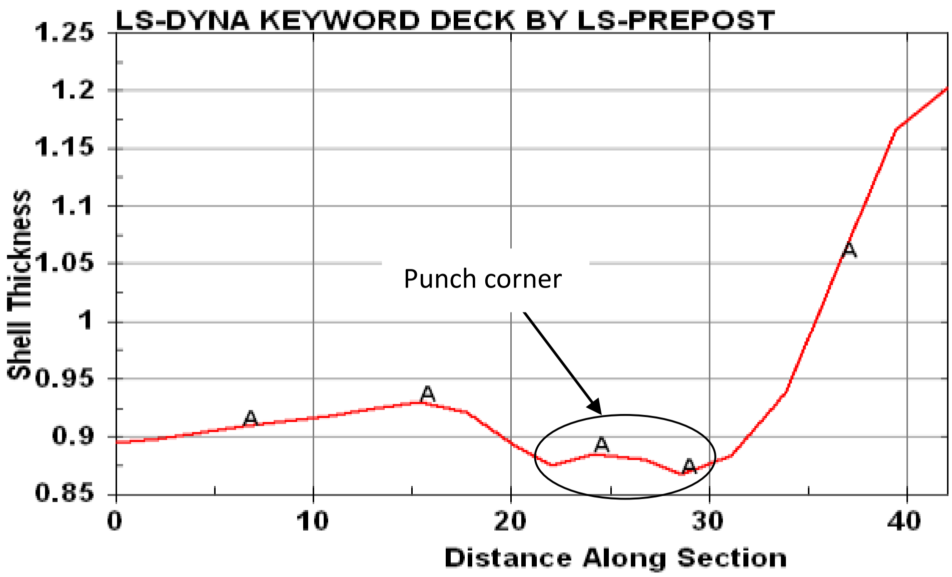
(b)

Figure 3.23: Thickness variation in mm in ASS material for TWB cups formed at a) room temperature b) elevated temperature

The thickness of it remained same at 0.87 mm even when the TWB is subjected to elevated temperature as shown in Figure 3.24 (b) making sure that no heat transfer has taken place between the parent materials.



(a)



(b)

Figure 3.24: Thickness variation measured in IS material formed at a) room temperature b) elevated temperature and measured in mm

Discussion on thinning and stress behavior in HAFTWB process

The thinning of ASS material when subjected to heating resulted in a tendency for more plastic deformation. It is also responsible for the weld line to shift to the IS side. It has been observed that large spring back in the cup wall occurred with heating.

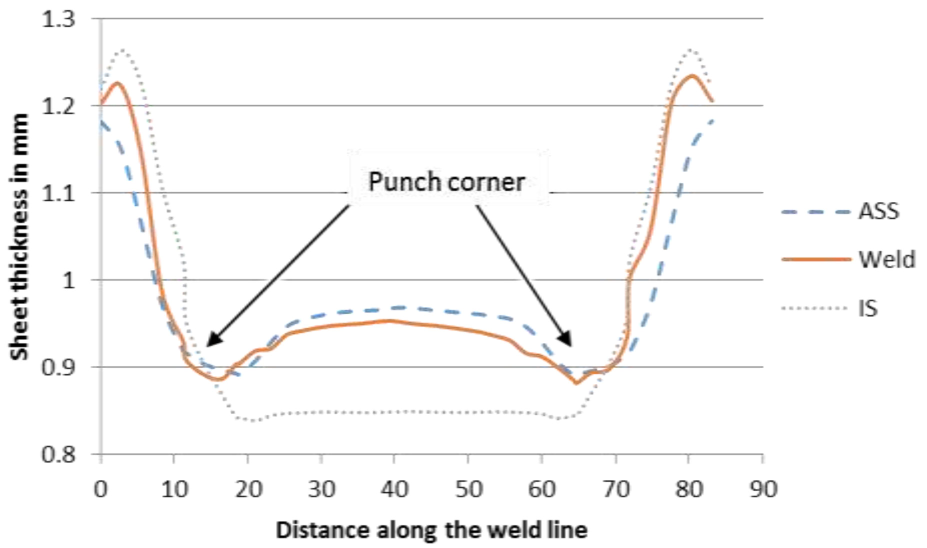
This may lead to exceed typical tolerances. The large spring back, if not sufficiently compensated in a stamping operation, may cause problems in maintaining dimensional accuracy of parts. The dimensional accuracy of the final product also depend on the sheet thickness and the clearance provided between the die and the punch.

Based on the above mentioned results, it has been noticed that the dimensional accuracy of parts in terms of thinning, cup height and diameter (discussed in next chapter) has deteriorated when TWB is subjected to elevated temperature of forming. However, there is an improvement in reduction of stress. It appears that the dimensional accuracy need to be compromised in order to minimize the movement of weld line when the TWB is subjected to the selective method of heating. It is also found that the spring back effect played a significant role in the deterioration of dimensional accuracy.

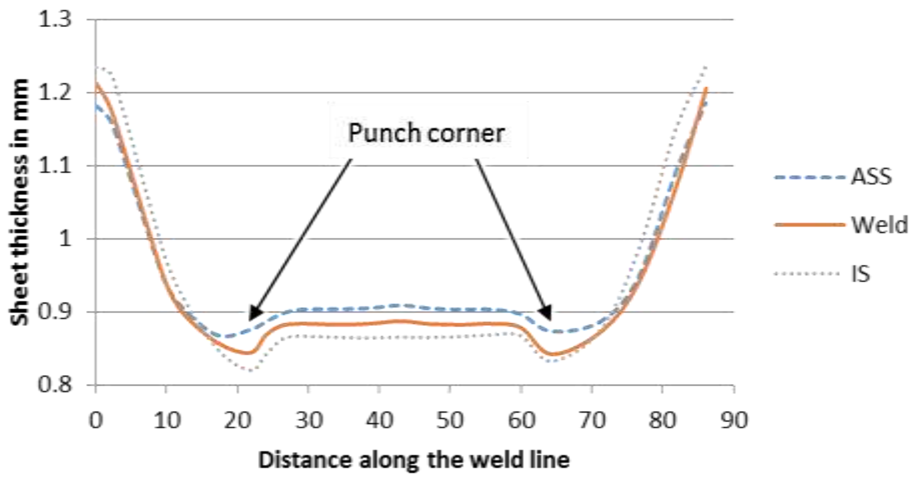
Comparison among the thickness distribution in TWB cup

Thickness distribution among the parent materials and weld bead in a TWB cup formed at different temperatures may be able to predict fracture in the cup. Fracture / failure is assumed to take place, when the allowable thinning is less than 80% of the sheet thickness. Since the initial sheet thickness considered for all the parent materials is 1 mm, therefore the thinning of sheet allowed before fracture is 0.8 mm. Below this value, the cup is considered to undergo fracture. Figure 3.25 (a and b) illustrates the thickness distribution among the parent materials and weld bead for the TWB cups formed at room temperature and elevated temperature. It has been noticed from both figures that failure/fracture of sheet is more likely to occur in IS 513 material since it showed the lowest thickness value at the punch corner.

The variation with respect to the thickness within the TWB materials is more and non-uniform for the TWB cup formed at room temperature especially in the cup region as shown in Figure 3.25 (a). Whereas, the variation is uniform and less among the materials when the TWB cup has been formed at elevated temperature as shown in Figure 3.25 (b).



(a)



(b)

Figure 3.25: Comparison of thickness distribution after forming among TWB materials carried at a) room temperature b) elevated temperature

The percentage reduction in sheet thickness among the TWB materials is listed in Table 3.12. The reduction of shell thickness for parent materials IS and ASS is more as compared to the weld bead. This may be due to higher hardness it possess. No change is observed in the sheet thickness for IS 513 material at room temperature as well as at elevated temperature. It confirms that no heat transfer took place between the parent materials because of cooling effect on the IS 513 side. The failure criteria adopted for TWB cups is a reduction of 20% or more in sheet thickness. So, in this case all the materials are lying within the limits, so it confirms that no failures took place due to thickness reduction. Due to heating, the reduction in thickness of ASS material is 7% more than the cup formed at room temperature.

Table 3.12: Percentage reduction of material thickness after stamping

Material	Room temperature	Elevated temperature
ASS-304	16.03	17.27
Weld bead	11.91	13.71
IS-513	17.52	17.23

Discussion on spring back effect in TWB components

It is also important to consider a proper spring back control. Otherwise it leads to inaccurate components (Botelho et al. 2007 and Kim et al. 2011). Spring back reduction in sheet metal forming is a typical goal to be pursued, which is conflicting with WLM and thinning reduction for instance. It has been found that at room temperature, the spring back angle is comparatively less with sufficient thickness of ASS sheet. However, the spring back angle is found to increase at elevated temperatures with decreasing sheet thickness.

Spring back needs to be adjusted since it results in deviation from the desired shape. Presently, workers in the workshop compensate it by an iterative experimental way. Based on the experience of the tool maker, the tool geometry is modified so that the shape deviations are progressively minimized. Therefore, the focus is to reduce the manual intervention prior to their production. A simulation based compensation strategy is required as a starting point to predict spring back. This can be achieved through the FE analysis. Future work can be undertaken to minimize the WLM as well as improve dimensional accuracy by applying compensation strategies through a robust, optimal process design.

The effect of spring back can be understood from Figure 3.22 (a and b) respectively which shows the profile of stress distribution in ASS material with and without heating. The stress levels in both cases are high at the interface boundary of punch and die corner. Though the stress level seems to decrease at elevated temperature, the presence of residual stresses in and around the weld region upon cooling might affect the dimensional accuracy of the components. Dimensional accuracy can be improved by holding the work piece for a longer time in a cooled environment soon after forming at elevated temperature.

The presence of residual stresses in the weld might have subsided during forming at elevated temperature. However when the material gets cooled, residual stresses might have again crept into the material, leading to more spring-back, resulting in the reduction of diameter at the cup bottom. Residual stresses may cause change in size and shape of the TWB cups due to non-uniform deformation.

A direct water quenching technique can also help in improving the dimensional accuracy of parts formed at elevated temperature. Water cooling arrangement can be provided immediately after forming to reduce the residual stresses which are causing significant changes in dimensional accuracy due to spring back.

LDR is proportional to the sheet thickness (Kusumi et.al 2014). The sheet thickness in turn affects the residual stresses in the formed part. So maintaining different thickness ratios of parent materials can also be undertaken to address the problem of residual stresses.

Improvements in tool design can also overcome the problems associated with dimensional accuracy as suggested by Nguyen et al. (2015). A study involving the optimum process parameters can be undertaken to improve the accuracy of the components, which shall enhance the drawability of the TWB cups and also arrest the WLM.

It is found that the stamping of TWB components manufactured under cold forming conditions have greater dimensional accuracy, but it also resulted in excessive WLM. Selective method of heating reduced the WLM but at the expense of dimensional accuracy of the components. The spring back effect has been found to deteriorate the accuracy of the components. Simulation results predicted the cause of these effects by plotting the stress distribution and roundness profiles. The thinning behavior in the TWB cup formed at elevated temperature has also deteriorated. Though selective heating played a significant role in reducing the WLM, it has to be compromised with the dimensional accuracy of parts. It is also observed that there is an increase in spring back at elevated temperature of forming leading to deterioration of dimensional accuracy.

Energy savings in heat assisted forming process

Based on the stress-strain graphs obtained by conducting tensile tests on ASS 304 material as shown in Figures 3.10 and 3.11, it is evident that the load required at temperature of 150 ^{o}C is less compared to other temperatures. Nearly 38% of load is saved when the samples are tested at the temperature of 150 ^{o}C as compared to the load required for forming at room temperature. The ultimate tensile strength which was 693 MPa before heating, reduced to 418 MPa when the specimens are subjected to a temperature of 150 ^{o}C, thus requiring less punch load to deform.

Hydraulic presses consume lot of power in sheet metal forming processes (Gao et al. 2016). In order to save the energy, the load on the punch should be minimal. Thus, heating the higher strength material in a TWB would facilitate an easy entry into the die cavity thereby requiring fewer loads to form a product. The proposed method showed greater potential in energy saving in sheet metal forming process. The heat assisted forming method on a 100 Tonne hydraulic press showed an improvement in energy savings compared to the traditional method of forming. It can be noted that the punch load required to form stainless steel products is greater than that of plain carbon steel for equivalent thicknesses due to its high yield strength. Further details on energy consumption has been discussed in chapter 6.

From this chapter, the following conclusions can be drawn based on the range of values of parameters considered:

1. New combinations of material viz. ASS-IS could be tested for laboratory experiments in the forming of TWBs.
2. TIG welded TWBs are equally good compared to laser welded TWBs, hence TIG welding could be undertaken for joining of TWBs.

3. In the stamping of TWB with dissimilar materials and uniform thicknesses, the weld line moved towards the stronger material.
4. It is observed that WLM in TWB cups can be reduced by modifying the strength parameters through selective heating technique.

Insights from simulation model for help in experimental work

1. The chosen materials and their thickness resulted in successful forming of TWB cups.
2. The dimensions and the shape of the TWB and the experimental setup are appropriate to obtain desired shapes.
3. The WLM has been significant both at the cup bottom and in the cup wall.
4. The chosen boundary conditions and the assumptions of the simulation model would simplify the forming aspects in laboratory experiments.
5. Fusion TIG welding of TWB sheets can be undertaken for successful forming of TWB cup.
6. Rule of mixture method considered in simulation model can be extended in experimental work without adding any filler material.
7. Experiments need to be conducted for testing weld defects using radiographic tests.
8. Simulation model has a limitation to check geometric and dimensional accuracy of TWB components especially cylindricity and roundness aspects.
9. Simulation model helps in determining the temperature and velocity of punch, punch load and the depth of cup.
10. Simulation modeling reduces the number of laboratory experiments to be conducted.

In this chapter, the FE simulation model has been developed to predict the WLM and it helped to build up the experimental setup as discussed in the next chapter.

Chapter 4

Experimental Investigations of Heat Assisted Forming

This chapter deals with the experimental investigations carried out on tailor welded blanks to validate the simulation experiments discussed in previous chapter. A new experimental setup involving the method of selectively heating the tailor welded blank is proposed to restrict the movement of weld line during stamping operation.

4.1 Experimental set up for stamping process

Stamping operation is a complicated forming process involving several process parameters (Sulaiman et al. 2015 and Kotkunde et al. 2015). The basic geometry in a stamping operation is shown in Figure 4.1. Die opening (D_d), Punch size (D_p), punch corner radius (R_p), blank size (D_b) and die corner radius (R_d) are the important physical parameters which affect the stamping process. Another important parameter to be considered is the clearance between the punch and die opening. Thinning takes place at the die cavity if small clearance is provided. To avoid thinning, clearance must be larger than the blank thickness (t). In a typical stamping process, a circular blank of radius R and thickness t is drawn by a flat-bottomed punch through a die opening of radius r with a constant blank holding force. The simulation model discussed in the previous chapter helped in the preparation of TWB samples and develop the experimental setup.

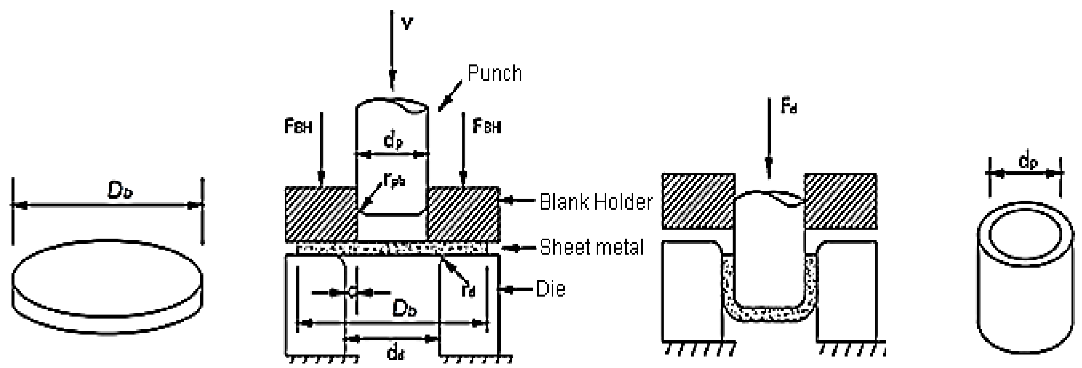


Figure 4.1: Components and parameters of the cylindrical stamping process (Kotkunde et al. 2015)

4.2 Preparation of TWB samples

The standard equation (4.1) for finding the initial circular sheet blank diameter based on volume constancy is available in the literature (Donaldson, 1976) for drawing a successful cup.

$$D = \sqrt{d^2 + 4dh} \quad (4.1)$$

where d is the outer cup diameter, h is the height of the cylindrical cup and D is the initial blank diameter, ignoring the effect of the punch corner radius.

Semi- circular shaped sheet metal pieces consisting of IS 513 steel and ASS 304 materials with a uniform thickness of 1 mm and with different sizes between 70 mm and 100 mm in diameter are fusion welded using TIG welding with the following parameters viz. Welding current=100 amps, Welding speed= 3.2 mm/sec, Heat input= 2.18 kJ/min, Rated output voltage= 25V, Shielding gas used = Argon and Gas flow= 12 lit/min.

Since the sheet material to be stamped is heterogeneous in nature, the blank size needs to be predicted accurately to avoid excessive frictional forces underneath the blank holder. Otherwise, during stamping there might be a failure in the weld region because of its brittle nature. Therefore, experiments are conducted to arrive at the initial blank size based on the above equation.

Nearly hundred experiments are conducted to arrive at the initial blank size. Later, it has been compared with the standard equation (4.1). The 75 mm diameter blank with D/d ratio of 1.63 has been found to be most suitable size beyond which fracture occurred in the weld region. The equation (4.1) gave a blank diameter of 76 mm which is close to the experimental value.

The LDR gave the information regarding the fracture appearing in the TWB cup by plotting the load-displacement graph as shown in Figure 4.2. Failure occurred in the TWB cup for a blank diameter of 90 mm with the LDR of 1.95 at a cup height of 10 mm and for a blank diameter of 80 mm with LDR of 1.73, failure occurred at a cup height of 17 mm. The TWB cup has been successfully drawn for a diameter of 75 mm and LDR of 1.63 without fracture upto a targeted cup height of 20 mm.

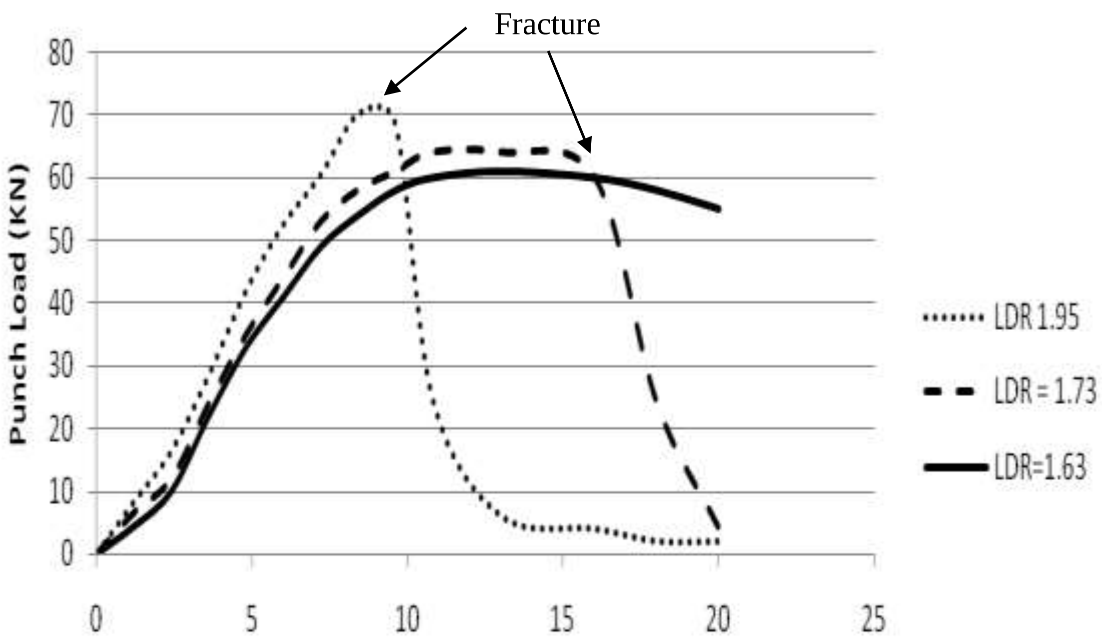
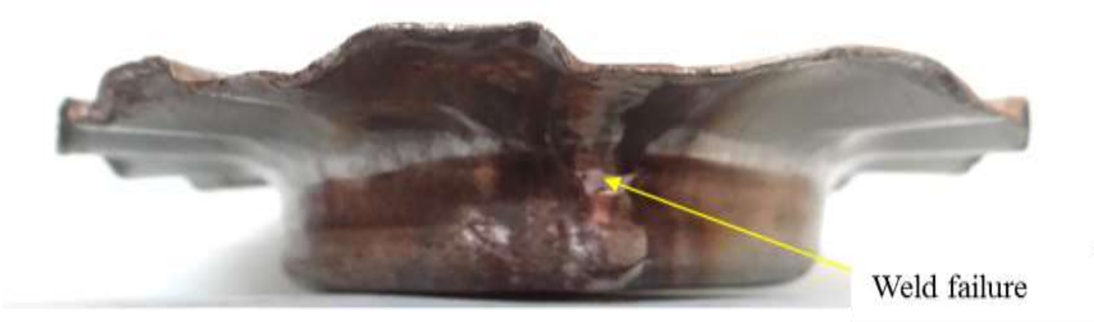


Figure 4.2: Load-Displacement graph of TWB cups formed at room temperature for LDRs

Due to greater diameter of the blank size, during forming the flow of material into the die cavity was less, thus leading the TWB cup to fracture. It can be noticed that the percentage elongation in weld bead is less as shown in Tables 3.9 and 3.11 respectively. It indicate that the weld material is more brittle in nature compared to the parent materials. Thus, the TWB cups for the blank size of 80 mm, 90 mm had fracture especially in the weld region. At elevated temperatures, failure occurred in the weld for LDR greater than 1.63, though there is an improvement in the cup height.

TWB cups formed at room temperature for LDR of 1.9 resulted in a fracture in the weld region as shown in Figure 4.3(a). Many wrinkles are observed around the periphery of the formed cup. Due to insufficient material flow into the die cavity, wrinkles are formed in the cup. The cup height measured about 9.5 mm only.



(a)

(b)

Figure 4.3: Failure of Cup and formation of wrinkles for TWB cup formed at room temperature for a) LDR of 1.9 b) LDR of 1.8

In the case of TWB cup formed at LDR = 1.8, the cup also fractured in the weld region. Wrinkles are also formed as shown in Figure 4.3 (b) with this LDR. In this case, the cup height measured about 16.5 mm. An improvement in cup height and less number of formation wrinkles prompted to lower the LDR further below 1.8. Some more TWB cups formed at different LDR are shown in the later part of this chapter.

4.3 Heat assisted forming set up

An electronically operated 40 Ton hydraulic press shown in Figure 4.4 has been used in this research work for stamping of TWB cups. A unique split punch shown in the inset has been arranged with provisions to notify temperatures by placing thermocouples at selected places. Insulation has been provided around the punch to prevent heat dissipating into the atmosphere. The temperature has been adjusted electronically by means of a programmable logic controller. A pencil heater (Specifications: Voltage: 230V, Power: 800 W, Length: 210 mm, Heater material: Stainless Steel and Max Temp: 800 ^{0}C) has been embedded in one part of the split punch and in the other, ice cooled water has been circulated through a channel by an 18W electric motor to maintain a low temperature.

Figure 4.4: Hydraulic press setup with split punch in inset

The temperature of the die has been maintained slightly above the room temperature so that steady state conditions could be maintained. The punch has been in contact with the blank for about 30 seconds, so that the desired temperature of around 150 ^{o}C could be reached. The temperature of the TWB on both sides has been measured by inserting the two thermocouples through the die opening.

Figure 4.5 shows the schematic diagram of the HAFTWB experimental setup. A uniform punch velocity of 50 mm/min has been maintained throughout the stamping operation. Cotton insulation has been provided in between and around the split punch to avoid dissipation of heat into the atmosphere. In this work, ice cold water is used as coolant.

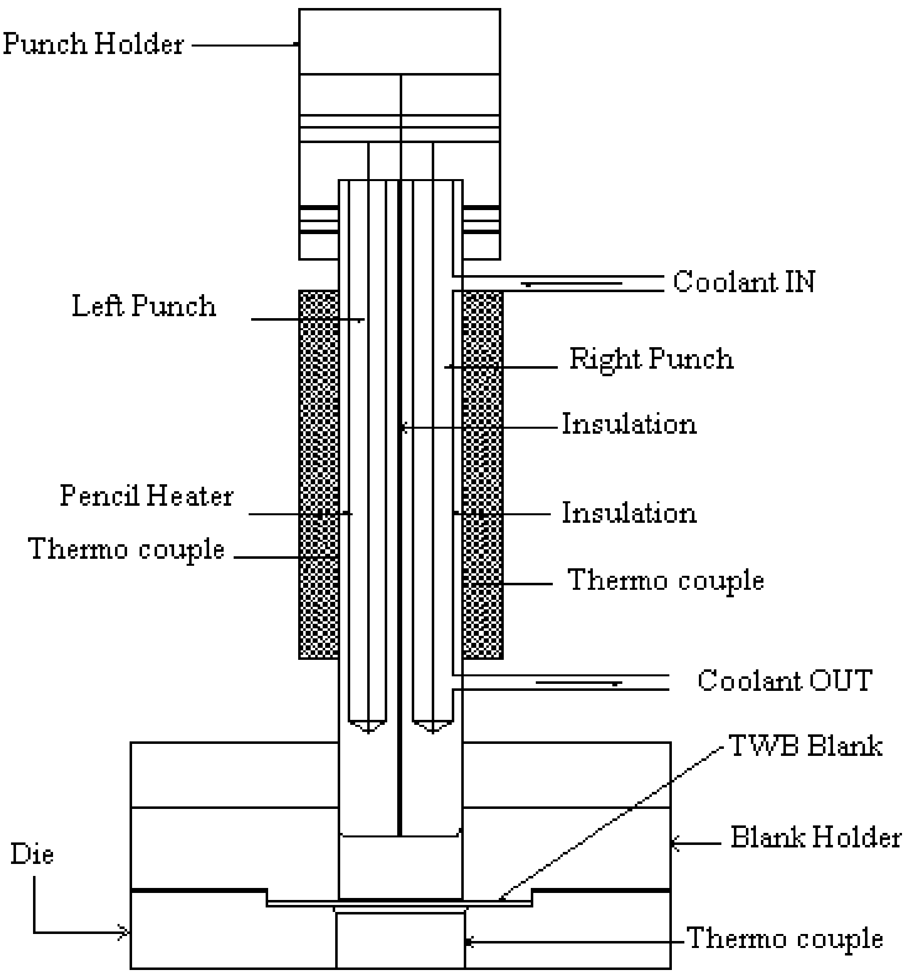


Figure 4.5: Schematic diagram of the experimental setup

A blank holder force of 15 kN has been maintained throughout the stamping process to avoid formation of wrinkles. A clearance of 1.5mm between the die and punch enhanced the TWB specimen to maintain uniformity. With the help of adjustable limit switches, the punch travel has been limited to 20 mm.

4.4 Results and Discussion

Measurement of weld line movement at cup bottom

Experimental results of TWB cups formed at room temperature showed that the weld line deformed into a curvilinear shape during the stamping operation as shown in Figure 4.6(a). By subjecting the TWB to an elevated temperature, the weld line in the TWB cup seems to become straight as shown in Figure 4.6(b). Initially, the weld line shifted towards the stronger material side (ASS 304) by a margin of 1.6 mm in the cup bottom, when formed at room temperature. By applying the HAFTWB method, the margin of movement reduced from to 0.2 mm at 150 ^{o}C.Thus, there is a reduction of nearly 87% in the WLM when the blank is subjected to elevated temperature.

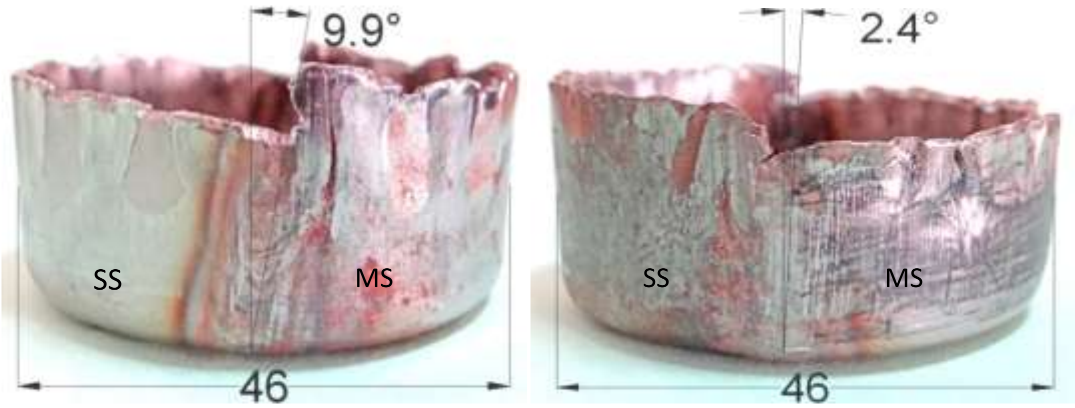
(a)

(b)

Figure 4.6: WLM at cup bottom in the TWB cup formed at (a) RT (b) 150^{0}C

Measurement of weld line movement in the cup wall

Measurements in terms of angular shift along the cup wall gave good results. The experimental results for the WLM in the cup wall are shown in Figure 4.7. It can be seen that there is a transition along the height of the cup wall from zero at the bottom to a maximum movement at the top. The angular shift of the weld line in the deformed cup from its original position has been 9.9^o when formed at room temperature which, however, reduced to 2.4^o when the TWB has been subjected to elevated temperature of 150 ^{o}C.



(a) (b)

Figure 4.7: WLM in cup wall for TWB cup formed at (a) RT (b) 150 ^{o}C.

4.5 Experimental validation of simulation results

Comparing the results of experimental and simulation studies discussed in the previous chapter, it can be observed that there is an excellent correlation between them as shown in Table 4.1. The deviation in measured values between experimental and simulation results is less than 0.5^o.

Table 4.1: Angular movement in weld line along the cup wall in degrees

Nature of work	Room Temperature (30 ^{o}C)	Elevated Temperature (150 ^{o}C)
Experiment	9.9^o	2.4^o
Simulation	10.3^o	2.1^o

Measurements of TWB cups formed at room temperature

The linear and angular measurement of the formed TWB cup has been carried out by taking photographs of the cups in the bottom and side views with a high resolution camera. These images are inserted in AutoCAD software. The images are resized proportionally according to the punch diameter. A curvilinear shape of the weld line has been observed from both the laboratory experiments as well as simulation experiments as shown in Figure 4.8(a and b). It has been observed that significant WLM took place towards the stronger material ASS 304 at the cup bottom. The weld line moved by 1.6 mm (24.6 mm – 23.0 .mm = 1.6 mm) from the centre of cup as shown in Figure 4.8(a). Similarly, the WLM recorded in the simulation experiments is 2.1 mm measured from the centre of the cup as shown in Figure 4.8(b).

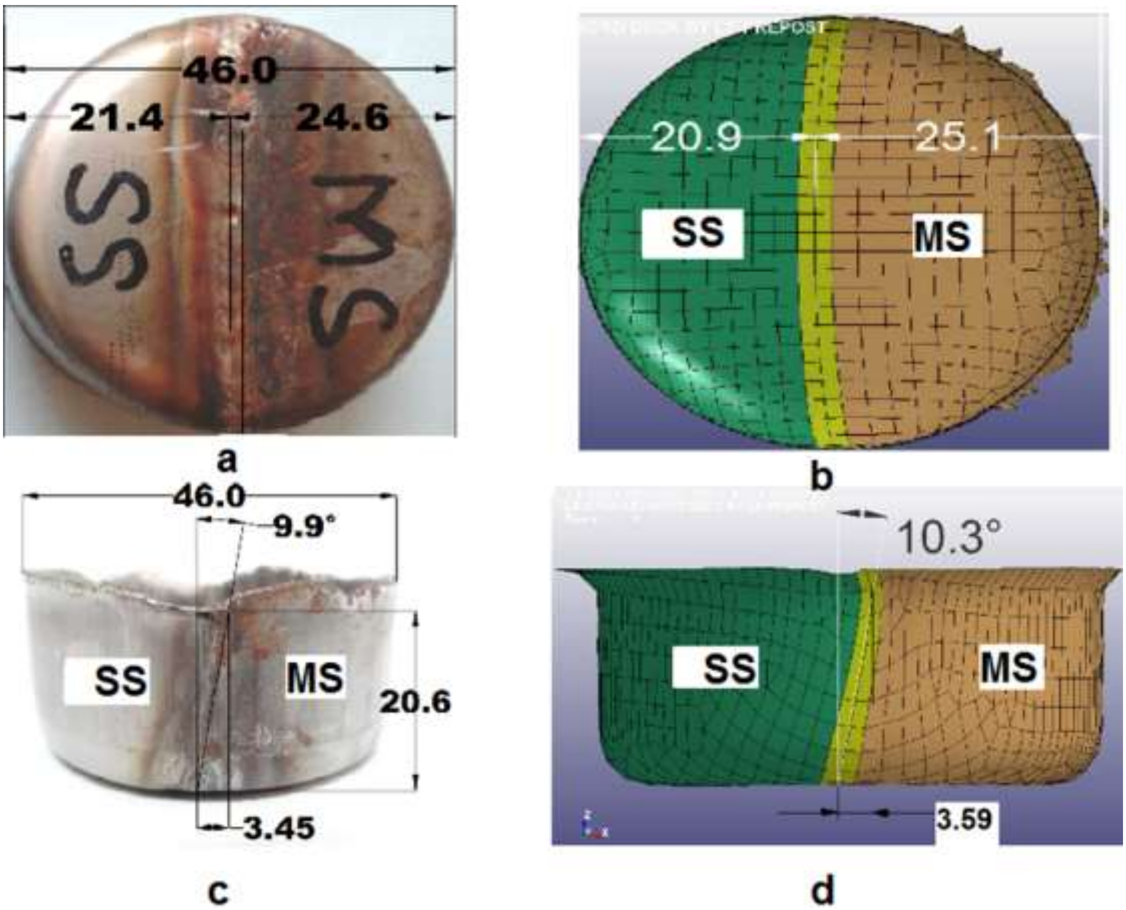


Figure 4.8: Linear and angular measurements of the weld line deviation in the TWB cups formed at room temperature

Angular and transverse measurements of these images are also checked to a reasonable accuracy as shown in Figures 4.8(c) and 4.8(d). It is observed that the slope of the weld line is more or less same in both cases. Since the variation between the measurements obtained from simulations and experimental results is less than 10%, the simulation model has been further investigated at elevated temperature conditions.

Measurements of TWB cups formed at elevated temperature

Simulation and experiment results showed greater reduction in WLM after the TWB is subjected to HAFTWB process. Stamping operation of TWB with selective heating setup restricted the movement of weld line to 0.2 mm as shown in Figure 4.9(a). Simulations resulted in 0.4 mm WLM as shown in figure 4.9(b). The difference between them in terms of angular movement measured in degrees has been only 0.3^{o} as shown in Figures 4.9(c) and 4.9(d) respectively.

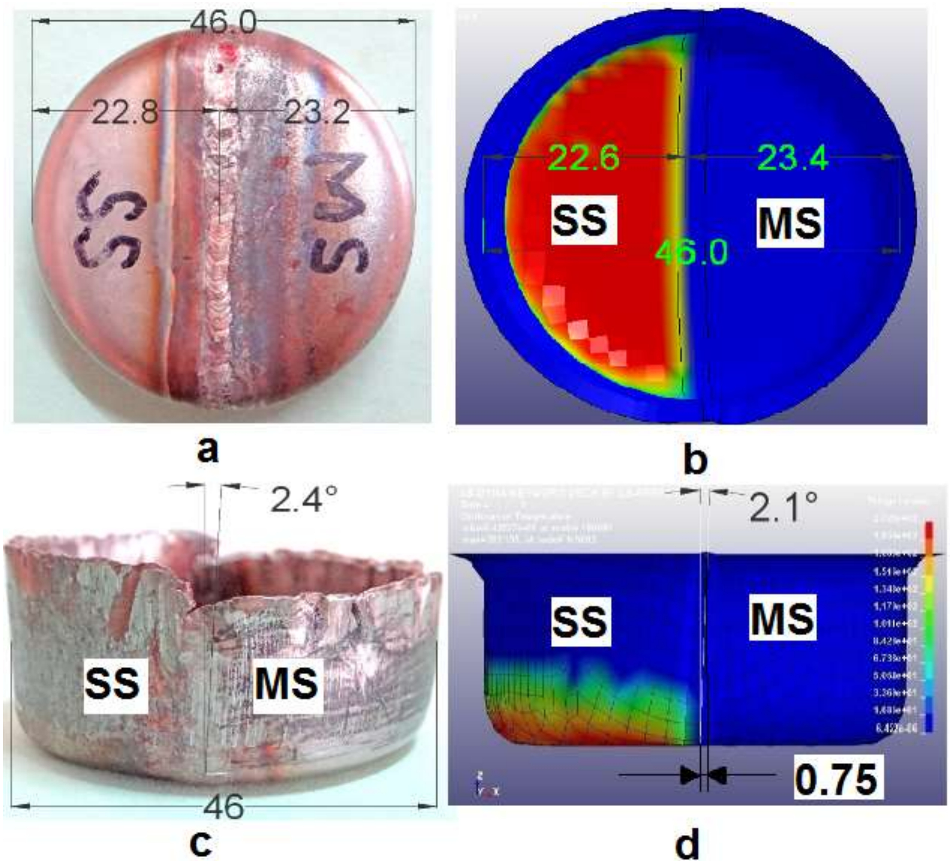
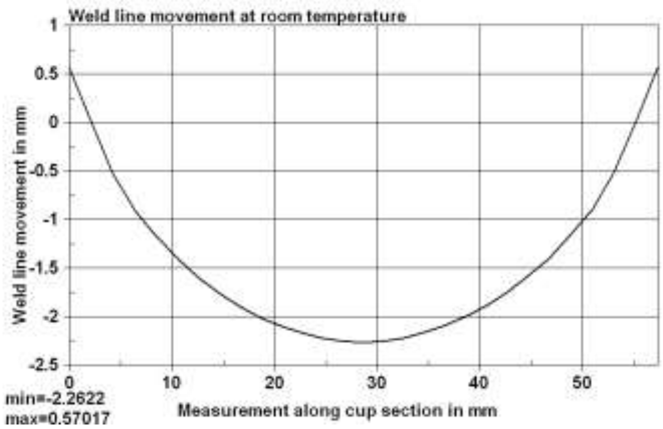


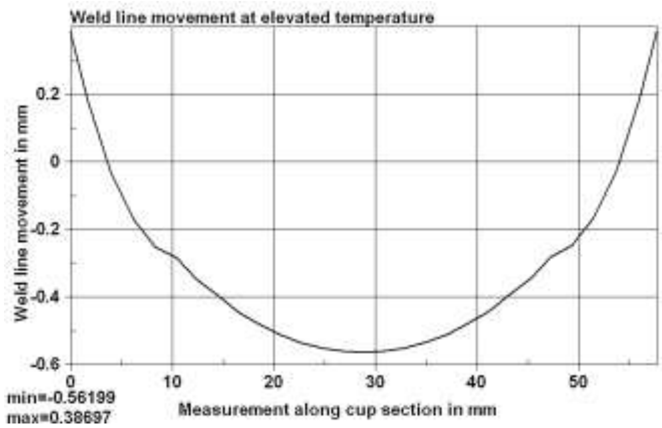
Figure 4.9: Linear and Angular measurements of WLM in the TWB cups formed at elevated temperature

Comparing the Figures 4.9(d) and 4.10(d) for measurements in transverse direction, the WLM measured laterally decreased from 3.59 mm to 0.75 mm, thus a reduction of about 1/5th from the initial WLM.

Using LS-Dyna software (2017), the movements of weld line measured with respect to the centre of the cup are plotted in a graphs shown in Figures 4.10(a) and 4.10(b), thus substantiated with the experimental results. Cup formed at room temperature resulted in a WLM of 2.26 mm as shown in Figure 4.10(a). It reduced to 0.56 mm when the TWB cup has been formed at 150 ^{o}C as shown in Figure 4.10(b).



(a)

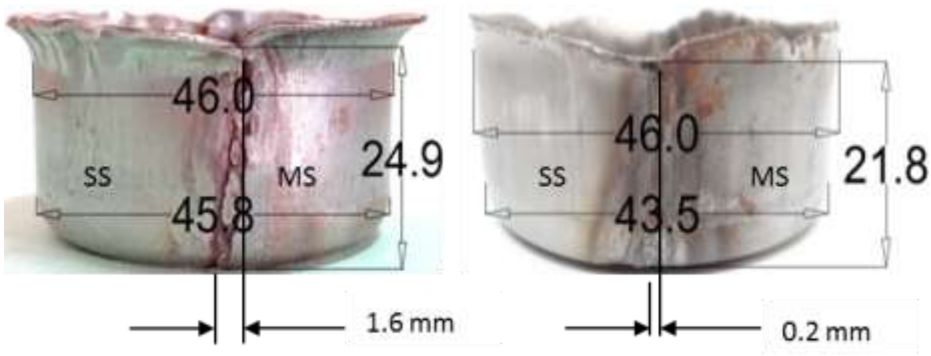


(b)

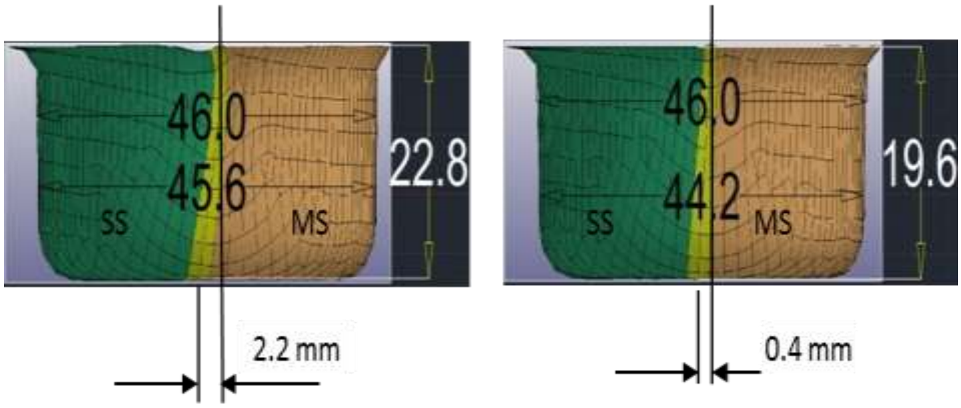
Figure 4.10: Deviation of weld line from the centre of TWB cup formed at (a) Room temperature (b) Elevated temperature

Dimensional measurements of TWB cups formed at different temperature

Dimensional measurements viz. diameter and height of TWB cup are checked with callipers as shown in figure 4.11. The internal diameter of TWB cup has been measured at the top and bottom of cup with a vernier calliper. The average height of TWB cup has been 24.9 mm, taken by measuring the height at different locations with the help of a vernier height gauge.



(a) (b)



(c) (d)

Figure 4.11: Measurements of TWB cups formed experimentally (a) Without heating (b) With heating. Measurements of TWB cups through simulations (c) Without heating (d) With heating

Stamping operation carried out experimentally at room temperature resulted in a diameter of 45.8 mm at the cup bottom and a diameter of 46 mm at the cup top as shown in Figure 4.11(a). Weld line appeared to be inclined with respect to the vertical, which suggests that there is a considerable WLM. It has been also observed that the movement of weld line at the cup bottom measured horizontally with respect to the centre of cup has been 1.6 mm. Forming at elevated temperature resulted in a diameter of 43.5 mm at the cup bottom and a diameter of 46 mm at the cup top as shown in Figure 4.11(b). The average cup height obtained has been 21.8 mm. It reduced due to the formation of earrings on the periphery of the cup. In this case, the weld line appeared to be straight and the movement of weld line has been 0.2 mm measured from the centre of blank in horizontal direction.

The snap-shot images taken from LS-Dyna FE software are imported into AutoCAD software to measure the height and diameter of the cup for the TWB cups formed at both temperatures. The images are proportionally reduced to an actual diameter of the cup as shown in Figures 4.11(c) and 4.11(d). Forming at room temperature resulted in a diameter of 45.6 mm measured at the cup bottom and a diameter of 46 mm at the cup top respectively. The cup height has been 22.8 mm measured with respect to its base as shown in Figure 4.11(c). Movement of weld line along the horizontal direction has been 2.2 mm measured from the centre of the TWB cup. Forming at elevated temperature resulted in a diameter of 44.2 mm at the cup bottom and a diameter of 46 mm at the cup top respectively. The height has been 19.6 mm and movement of weld line in the horizontal direction has been 0.4 mm from the centre of blank as shown in Figure 4.11(d). Comparing the experimental and simulation results, the differences in their measurements seems to be less. Simulations carried out on LS-Dyna FE software predicted almost the same results as obtained from the laboratory experiments as shown in Table 4.2.

Table 4.2: WLM in mm at cup bottom

Nature of work	Room Temperature (30 ºC)	Elevated Temperature (150 ºC)
Experiment	1.6	0.2
Simulation	2.2	0.4

Later, the TWB has been tested for a blank diameter of 80mm at elevated temperature at 150 ºC at an LDR of 1.8. Samples are checked and it has been found that the TWB cup fractured in the weld as shown in Figure 4.12 (a). Though no wrinkles are found in the TWB cup formed for a blank diameter of 78 mm and an LDR of 1.7, failure occurred in the weld region with incomplete drawing of cup as shown in Figure 4.12 (b)

(a)

(b)

Figure 4.12: Failure of Cup for (a) LDR of 1.8 formed at 150^0C (b) for LDR of 1.7 formed at room temperature

The angular deviations are also measured with respect to the vertical axis along the cup wall for the cups formed at elevated temperatures for LDR of 1.63. Heat is supplied to the ASS material at temperatures of 100 ^oC, 130 ^oC, 140 ^oC and 160 ^oC respectively. The maximum angle recorded along the cup wall has been 17^o and the minimum angle being 2^o for the cups formed at different temperatures as shown in Figure 4.13.

Figure 4.13: Angular WLM of TWB cups formed at different temperatures for LDR of 1.63

Similarly, the WLM at the cup bottom are measured with respect to the cup centre for the cups formed at different temperatures for LDR of 1.63. The maximum deviation recorded is 2.4 mm and the minimum deviation is 0,2 mm with respect to the cup centre. The cups successfully formed are shown in Figure 4.14.

(a)

(b)

Figure 4.14: WLM at the cup bottom for TWB cups formed at (a) at 160° C and 50° C (b) 150° C and 30° C

The reduced flow stress has been found to increase plastic strain on ASS 304 side to a level equal to that on the softer side, namely, IS 513, eventually resulting in the movement of weld line. It is also observed that during the forming process there is a drastic reduction in the load requirement due to decrease in the flow stress. Through the HAFTWB method, the undesirable WLM is reduced by 87% in the cup bottom when formed at elevated temperature for a LDR of 1.63. The reduction in WLM in the cup wall in terms of the angular measurement is about 75%. Thus, it has been found that there is a significant improvement in the quality of the TWB formed product through the use of selective heating stamping process which resulted in the reduction of WLM as well.

In this chapter, experiments were conducted on the newly developed HAFTWB setup with the ASS-IS steel combination. The simulation work has been validated with experiments. It has been found that the WLM in TWB forming could be reduced to a large extent by applying the HAFTWB process. In order to reduce the WLM completely, it is required to maintain correct thickness ratio and placement of the weld line in the TWB before conducting stamping operations. The effect of both the above mentioned parameters on the WLM in the TWB formed at different temperatures is discussed in the next chapter.

Chapter 5

Parametric Study and Optimization of Weld Line Movement

The HAFTWB method discussed in the previous chapters could minimize the WLM to a certain extent when the thickness ratio is 1 and the weld line is placed at the centre of the blank. In order to reduce the WLM further, it is important to vary the thickness ratio of the TWB and also place the weld line at an offset distance from the centre of the blank. In this chapter, the effect of thickness ratio and WLL on the WLM is addressed. Laboratory experiments has been conducted by placing the weld line at ± 1 mm on either side of the TWB centre. FE analysis is also undertaken to study the effect of thickness ratio on WLM. Combined effect of thickness ratio and WLL on the WLM at different temperatures is also analyzed. Parametric study is undertaken to find the most influencing parameter on the WLM and later optimization is carried out.

5.1 Effect of thickness ratio on WLM

Referring to the previous works carried out by researchers, maintaining a correct thickness ratio could solve the problem of WLM. However, steel manufacturers produce sheets in standard thicknesses, hence to obtain correct thickness ratio is always a difficult task. In this work, laboratory experiments are conducted for thickness ratio of 1 and simulation experiments are conducted for thickness ratios of 1, 1.25 and 1.5 also. In the simulation model, the thickness of the IS 513 material is maintained constant at 1 mm and ASS 304 material thickness is varied by picking 1 mm, 0.8 mm and 0.66 mm sheets respectively, so that thickness ratios of 1, 1.25 and 1.5 could be obtained. Experiments are conducted at room temperature as well as elevated temperature and the results are shown in Table 5.1 and 5.2 respectively.

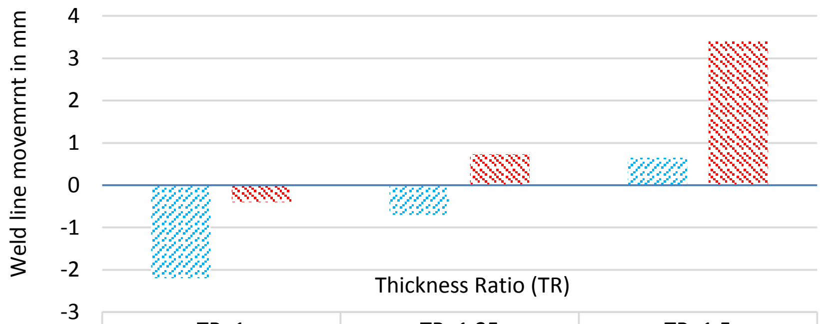
Table 5.1: WLM in mm for the TWB cups formed at room temperature for different thickness ratios

Thickness ratio	Nature of work	Cup Bottom	Cup wall
1	Simulation	-2.2	3.59
	Experimental	-1.6	3.45
1.25	Simulation	-0.7	1.66
	Experimental	-	-
1.5	Simulation	0.65	-1.52
	Experimental	-	-

Table 5.2: WLM in mm for the TWB cups formed at elevated temperature for different thickness ratios

Thickness ratio	Nature of work	Cup Bottom	Cup wall
1	Simulation	-0.4	0.75
	Experimental	-0.2	0.83
1.25	Simulation	0.73	-1.31
	Experimental	-	-
1.5	Simulation	3.4	-2.89
	Experimental	-	-

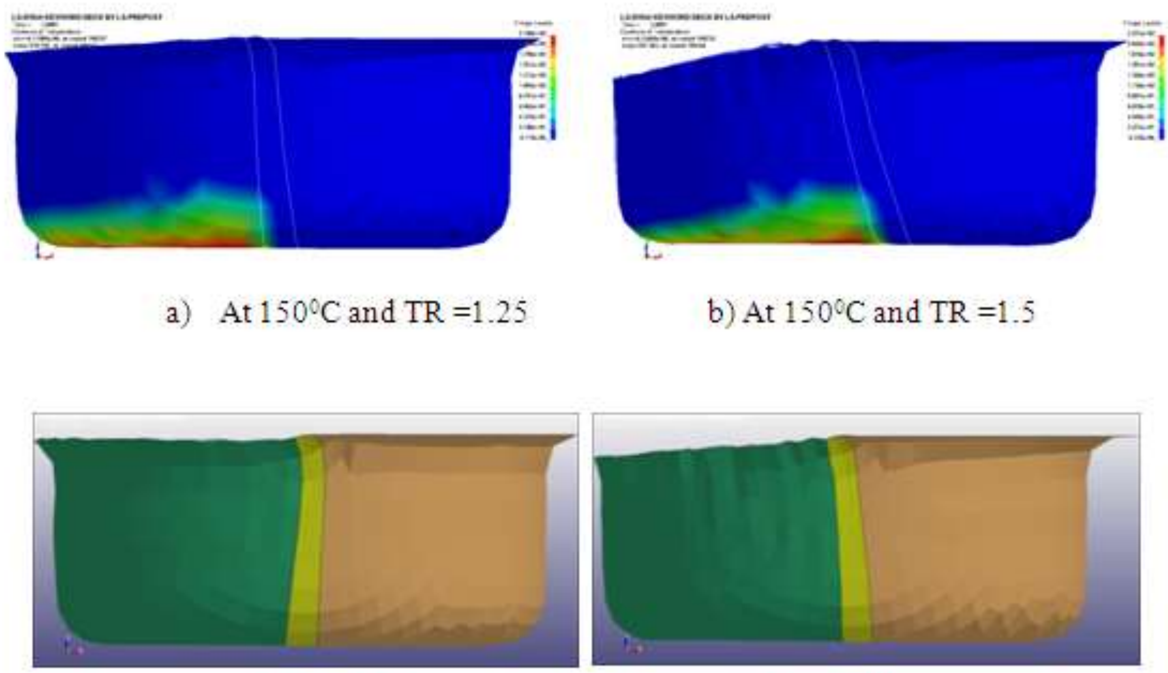
It is observed that as the thickness ratio increased, a considerable reduction in the WLM has been noticed when the TWB is formed at room temperature and also at elevated temperature. The movement of the weld line shifted from the stronger side to the weaker side at the cup bottom with increase in the thickness ratio as shown in Figure 5.1.



	TR=1	TR=1.25	TR=1.5
Without heating	-2.2	-0.7	0.65
With heating	-0.4	0.73	3.4

Figure 5.1: Variation of WLM at cup bottom

Pictorial representations of these figures are shown for thickness ratios of 1, 1.25 and 1.5 in Figure 5.2(a-d). Comparing the WLM at these temperatures, it is observed that temperature played an important role in the WLM. Higher is the temperature, greater is the WLM. Hence from the above cases, it can be concluded that it is better to vary temperature rather than varying thickness ratios. The WLM measured in the cup wall is more compared to that at the cup bottom, which can be observed from the Tables 5.1 and 5.2 respectively.



a) At 150⁰C and TR =1.25 b) At 150⁰C and TR =1.5

c) At RT and TR =1.25 d) At RT and TR =1.5

Figure 5.2: Pictorial views of WLM in the cup wall in TWB cups formed at different temperatures and thickness ratios

Figure 5.3 shows the bar chart regarding the influence of thickness ratio on the movement of weld line in the cup wall when formed at different temperatures. The WLM with negative values indicates that the weld line shifted laterally towards the high strength material side with respect to the centre. As the thickness ratio increased from 1 to 1.5, the shift in WLM is observed in the formed cups both at room temperature and elevated temperature. When the thickness ratio is 1, the WLM in the cups formed at elevated temperature is considerable less as compared to the WLM in the cups formed at room temperature. Maintaining a correct thickness ratio and forming at elevated temperature could reduce the movement of weld line to a great extent.

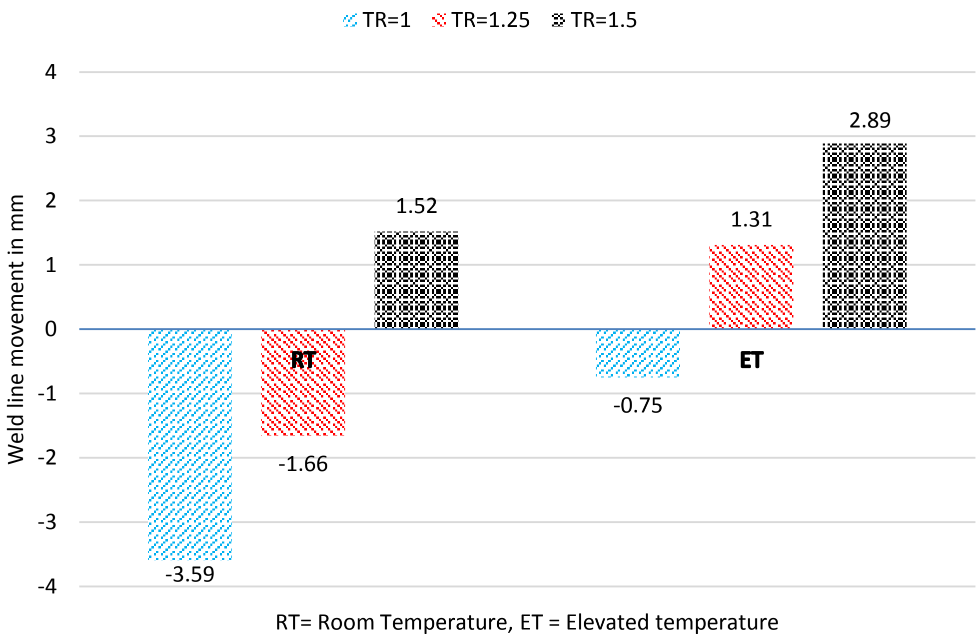
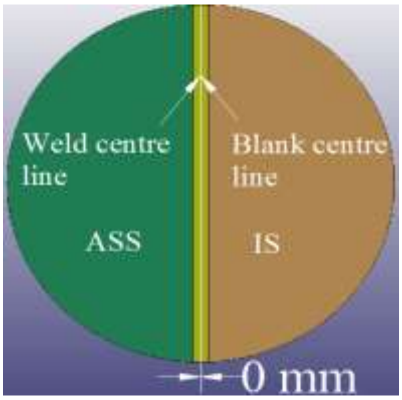


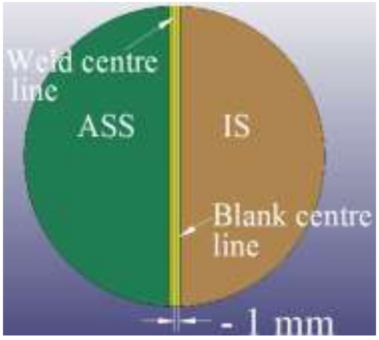
Figure 5.3: WLM in cup wall under the influence of thickness ratio at room temperature and elevated temperature

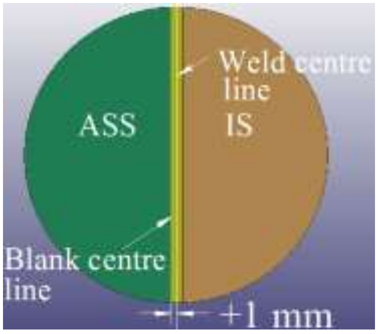
5.2 Effect of WLL on WLM

The initial WLL was placed at 0 mm, -1 mm and +1 mm from the centre of blank as shown in the Figures 5.4 (a-c) respectively. Laboratory experiments are conducted at room temperature as well as elevated temperatures for TWB forming by placing the weld line parallel to its original position at an offset distance of ± 1 mm from its centre.



(a)



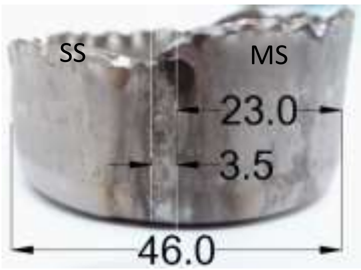


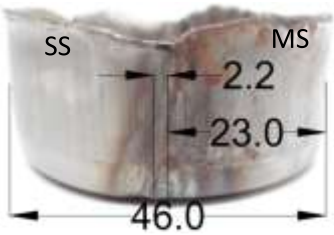
(b) (c)

Figure 5.4: Initial WLL placed at (a) 0 mm (b) -1 mm and (c) +1 mm

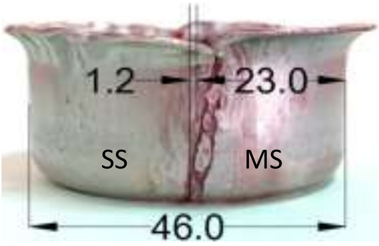
Results obtained from laboratory experiments

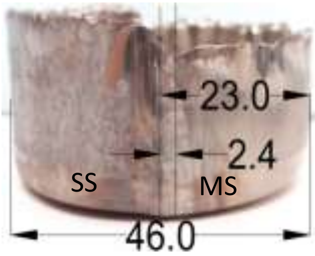
The cups are photographed and the images are imported into AutoCAD software for measuring the dimensions. A deviation of WLM from the centre line has been measured as shown in Figure 5.5(a and b). It is noticed that the effect of WLL on the WLM has been marginal. The weld line deviated in both cases. Placing the weld line at a distance of 1 mm towards the stronger material side resulted in a shift of 3.5 mm measured from centre line. It reduced to 2.2 mm when the weld line is placed at the same distance of 1 mm on the weaker material side.





(a) (b)





(c) (d)

Figure 5.5: TWB cups formed at room temperature for the weld line at placed at a)-1 mm b) +1 mm and at elevated temperature c) -1 mm d) +1 mm

The predicted values of the diameter of the cup as well as the WLM obtained from AutoCAD drawings are confirmed by measuring the cups using vernier callipers. Similar experiments are conducted at elevated temperatures as well for the same weld line positions as mentioned above and it has been noticed that the effect of WLL on the WLM is significant as shown in Figure 5.5(c and d) respectively. It is observed that there has been a transition with respect to the centre of blank which changed from negative value to positive value i.e. from -1.2 mm to +2.4 mm thus giving encouraging results.

Results obtained from simulation experiments

Experiments are also carried out on simulation model by placing the weld line at the same offset distance of ± 1 from the centre of blank. Pictorial representations of TWB cups formed at room temperatures are shown in Figure 5.6(aandb). In the case of the weld line placed on the stronger material side, the movement of weld line is 3.1 mm. When the weld line is placed at 1mm towards weaker material side, the movement of weld line is 1.1 mm. Hence, there is a good similarity between the simulation results and laboratory experiments.

Simulations were also conducted for the TWB formed at elevated temperatures and the results are shown in Figure 5.6 (c and d) respectively. In this case, weld line shifted by 1.1 mm when the weld line is located at 1 mm on ASS material side and it reduced to 0.4 mm when the weld line is placed at the same distance on the other side.

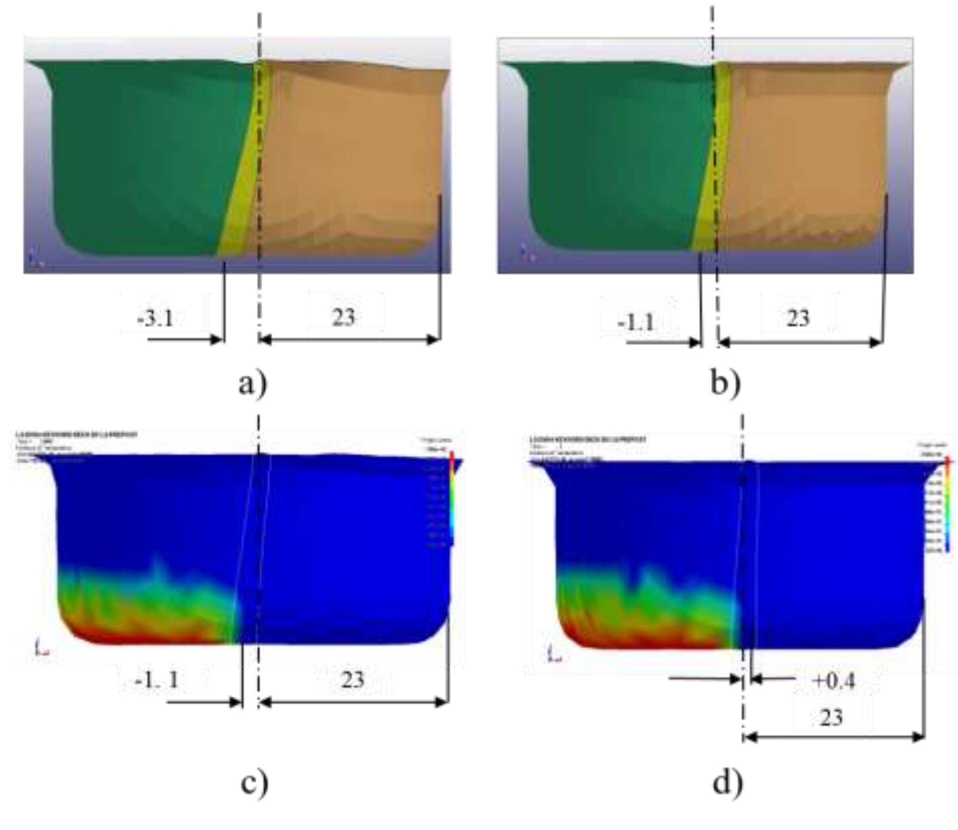


Figure 5.6: FE simulation on WLM in the TWB cup formed at (a and b) room temperature (c and d) elevated temperature by placing the weld line at ± 1 mm from TWB centre

Figure 5.7 shows the bar chart comparing the deviation of the in the TWB cups formed at different temperatures. The negative values indicate that the weld line shifted towards ASS material side and the shift towards IS material side indicate positive values. The deviation in the WLM is found to be marginal with relocating the weld line as compared to that of the WLM under the influence of thickness ratios.

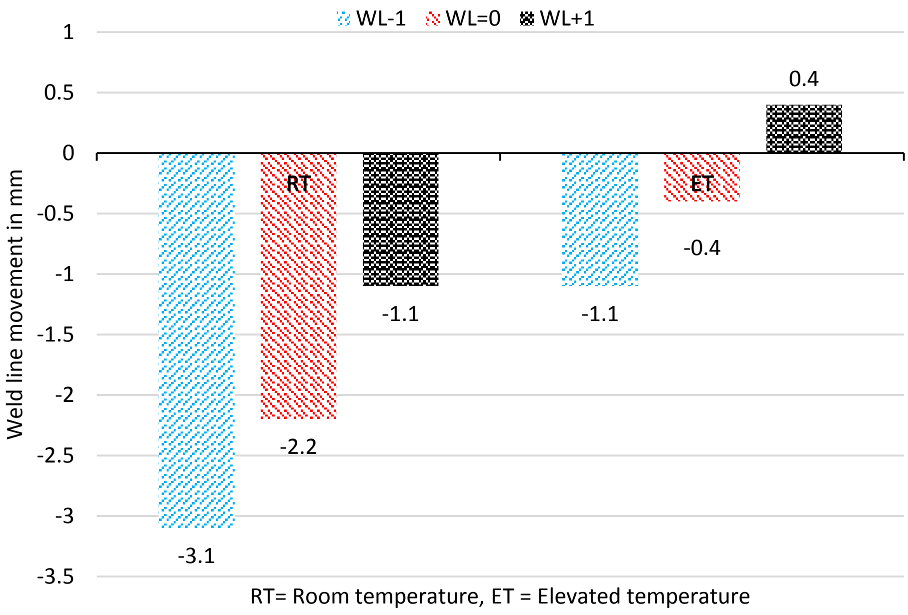
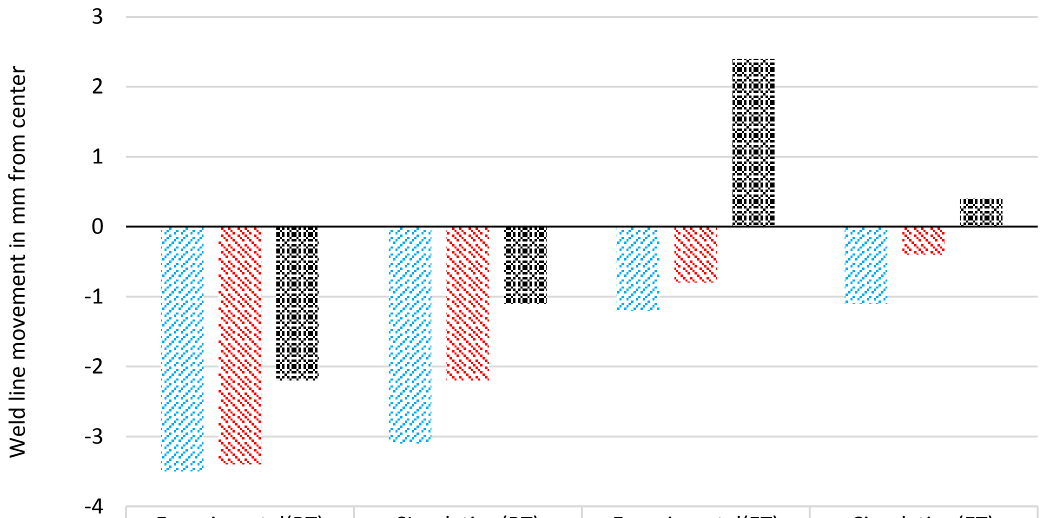


Figure 5.7: WLM under the influence of WLL at room temperature and elevated temperature based on simulation studies

<u>Comparison between experimental and simulation results</u>

Figure 5.8 gives the comparison between simulation and experimental results of WLM in the cup wall for the combined effect of temperature and WLL. There is no much deviation in the results, thus the validation of simulation results with experimental results can be justified. Comparing the WLM in the TWB cups formed at different temperatures and WLLs, it is observed that temperature played an important role in restricting the WLM towards stronger side of TWB. It has also been found that the effect of heating the stronger material have produced a greater influence on WLM as compared to the relocation of the weld line.

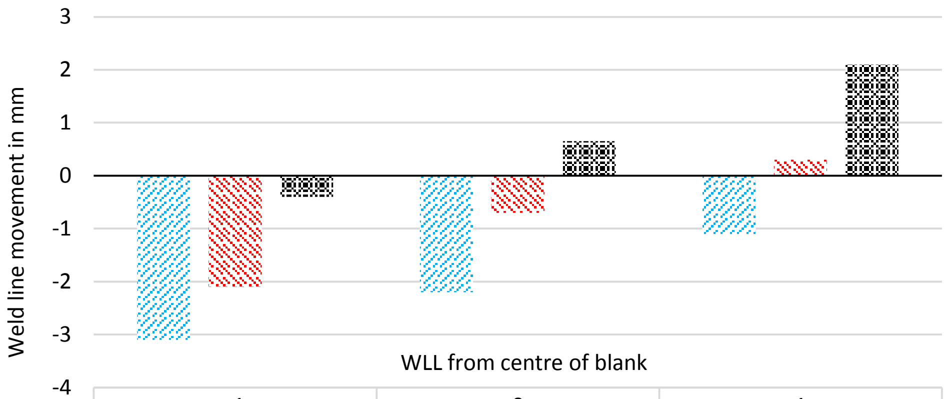


	Experimental(RT)	SImulation(RT)	Experimental(ET)	Simulation(ET)
WLL=-1	-3.5	-3.1	-1.2	-1.1
WLL=0	-3.4	-2.2	-0.8	-0.4
WLL=+1	-2.2	-1.1	2.4	0.4

Figure 5.8: Comparison between experimental and simulation results for various WLLs in the cup wall formed at different temperatures

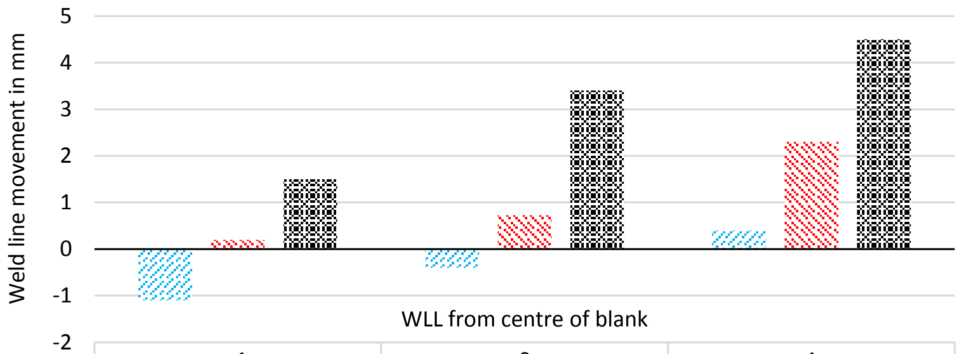
5.3 Combined effect of thickness ratio, temperature and WLL on WLM

The results clearly indicate that neither the thickness ratio nor the position of WLL could eliminate the WLM completely. Moreover, availability of sheet materials with correct thickness ratio may not be possible always. A combined approach involving all the three parameters may have a considerable effect in reducing the WLM. In practice, the choice between the parameters depends on many factors which include availability of raw materials with required thicknesses, tool costs, and the accuracy desired. Figures 5.9 and 5.10 show the combined effect of all the three parameters on the WLM in the TWB cups formed at room temperature and elevated temperature respectively



WLL from centre of blank	-1	0	1
TR=1	-3.1	-2.2	-1.1
TR=1.25	-2.1	-0.7	0.3
TR=1.5	-0.4	0.65	2.1

Figure 5.9: Comparison of WLMs with combinations of thickness ratio and WLLs in TWB cups formed at room temperature



WLL from centre of blank	-1	0	1
TR=1	-1.1	-0.4	0.4
TR=1.25	0.2	0.73	2.3
TR=1.5	1.5	3.4	4.5

Figure 5.10: Comparison of WLMs with combinations of thickness ratio and WLLs in TWB cups formed at elevated temperature

Comparing the results, it is observed that WLM has six negative values when TWB cup is formed at room temperature, which indicate that the weld line shifted more towards the stronger material side measured from the centre of cup as shown in Figure 5.9. When formed at elevated temperature, it can be observed that there are only two negative values as shown in Figure 5.10 which indicate that the weld line shifted more towards the weaker material side measured from the centre of cup. Thus, it is proposed that the WLM could be controlled more effectively by combining all the three parameters.

It has been found that the WLM could be controlled to a certain extent by positioning the weld line at an offset distance from the centre line. Another approach is to maintain correct thickness ratio between the respective blanks.

Comprehensive understanding of the process parameters influencing the movement of weld line can only be possible by performing the DoE based study. In this work, the factors viz. thickness ratio, WLL and temperature which have the greatest influence on the WLM in TWBs are considered. Further, optimization of these process parameters values is also carried out to minimize the WLM.

5.4 Design of experiments

To understand the effect of various process parameters on the WLM, statistical techniques viz. Design of Experiments is used to arrive at the critical influencing parameters. The investigation has been extended in studying the effect of thickness ratio, WLL and temperature on the WLM. The situation is to choose the best possible value among thickness ratio and WLL under the influence of heat assisted forming of tailor welded blank (HAFTWB) to minimize the movement of weld line. The mathematical function in terms of WLM is obtained from the MINITAB statistical software by carrying out regression analysis.

This thesis is aimed at studying the effects of process parameters viz., thickness ratio, WLL and temperature on the WLM in a tailor welded blank

DoE is a statistical approach to study the effect of various process parameters on the quality of product by analyzing the data obtained by conducting experiments (Montgomery, 2007). The following steps help to understand the DoE with reference to the current research work.

1. Identification and problem statement: Based on the literature review, the problem definition is identified. It has been observed that there are many process parameters that influence the movement of weld line in TWB.
2. Choice of factors and levels : Among the various process parameters that are influence the quality of product, the present study is aimed at three factors viz. temperature, thickness ratio and WLL. Three levels have been considered for thickness ratio and WLL. The temperature is fixed, since forming is conducted at elevated temperature only.
3. Response variable selection: The response considered in this study is in terms of WLM in the cup wall measured in mm.
4. Conducting the experiment: Experiments have been conducted based on the above mentioned steps with the chosen process parameters, levels and range of values.
5. Analyzing the statistical data: The statistical data generates a regression equation, which further led to an output data in the form of graphs and reports. Through these graphs, the effect of each parameter on the response is known. It also showed that no interaction effects are present between the parameters.
6. Optimum design: The regression equation is further used to find the optimum parameters to arrest the WLM.

5.5 Formulation of optimization problem

Analysis of variance (ANOVA) based DoE study is carried out to find the effect of parameters on the WLM. The MINITAB statistical software is used in this regard. For developing a mathematical model, three independent variables viz. thickness ratio, WLL and temperature are chosen as design variables. The temperature has been kept constant at 150 ^{o}C while the other two parameters are altered. The thickness ratio of 1, 1.25 and 1.5 are chosen considering the thickness of high strength material to be 0.6 mm, 0.8 mm and 1 mm. The thickness of low material is kept constant at 1 mm. Similarly, the actual values of WLLs at -1 mm, 0 mm and +1 mm measured from the blank centre line are considered. A total of nine experiments are conducted using full factorial design. The input responses are supplied by the simulation studies conducted on LS-Dyna software as well as laboratory experiments for the WLM.

Using regression analysis, minimization of the WLM is used as a response criterion for solving optimization problem. Thus, the goal is to minimize the response, "WLM". The regression equation is expressed in terms of the geometric parameters viz. thickness ratio and WLL. The constraint equations have been formulated in terms of upper and lower bounds for these parameters.

5.6 Results and discussion

Results from the design of experiment study

A full factorial design involving nine runs has been conducted and the ANOVA procedure is used to judge the significance of regression model. The response data i.e., WLM measured in mm for various combinations of thickness ratio and WLL is fed into the model. The variation between the predicted values and the actual values is not much as listed in Table 5.3. Generally, two levels produce linear effects only, hence it is mandatory to choose three levels in order to capture non-linear effects.

Table 5.3 Responses obtained for WLM in TWB cup formed at elevated temperature for various combinations of parameter values

Experiment	Parameters used		Response of WLM at cup wall measured in mm	
	TR	WLL (in mm)	Predicted	Actual
1	1	-1	-1.569	-1.1
2	1	0	-0.469	-0.4
3	1	1	0.631	0.4
4	1.25	-1	0.181	0.2
5	1.25	0	1.281	0.73
6	1.25	1	2.381	2.3
7	1.5	-1	1.931	1.5
8	1.5	0	3.031	3.4
9	1.5	1	4.131	4.5

A response model in the form of a fitted equation is obtained for the input parameters for predicting the WLM given as under:

In terms of Actual values:

$$\text{WLM (in mm)} = -7.469 + 7.000\ \text{TR} + 1.100\ \text{WLL} \tag{5.1}$$

The model is being checked for fairness by plotting the normal probability plot of the residuals. The plot is a graphical representation of the data to know whether they are normally distributed or not. It can be concluded from the Figure 5.11 that the errors in the model are distributed normally, by the fact that the residuals are scattered over the straight line, which confirms that the model is adequate. The main effects plot of

WLM for the parameters viz. thickness ratio and WLL are shown in Figure 5.12. The WLM increased whenever there is an increase in either thickness ratio or change in WLL. Comparatively, the effect of thickness ratio is more than the effect of WLL on the WLM. This concept can be understood based on the high slopes of thickness ratios as compared to that of WLL as shown in Figure 5.12.

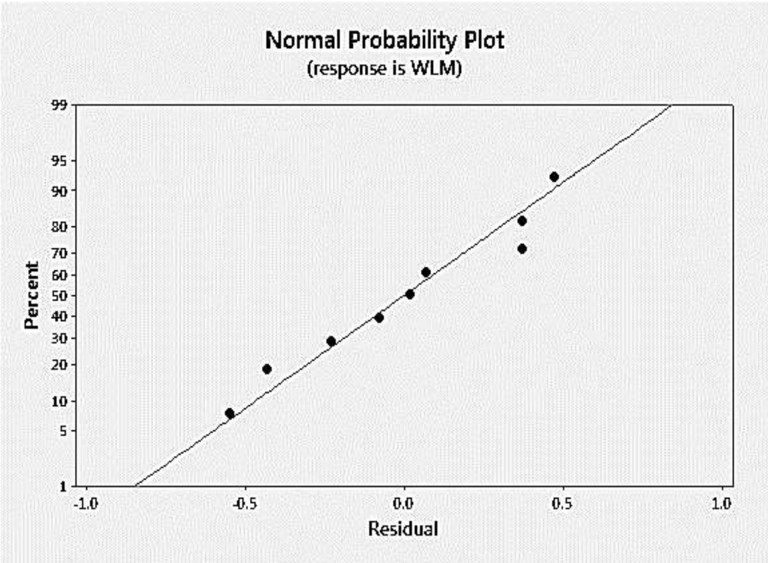


Figure 5.11: Normal probability plot of the residuals

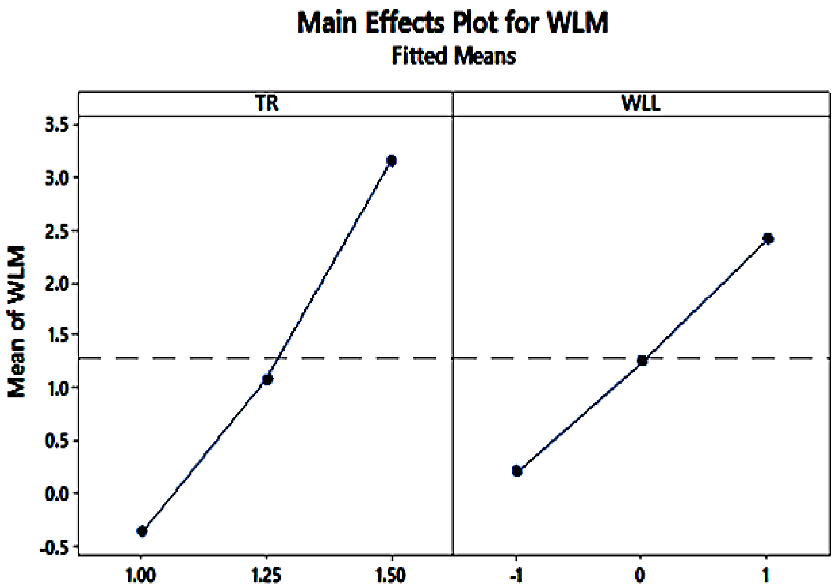


Figure 5.12: Main effects plot for WLM

Figure 5.13 shows the interaction plot among the parameters. It is noticed that the interaction effects between the two parameters viz. thickness ratio and WLL are not present in the model since the lines are not intersecting with each other. This is reflected in the regression equation as well, which also does not contain any interaction effect.

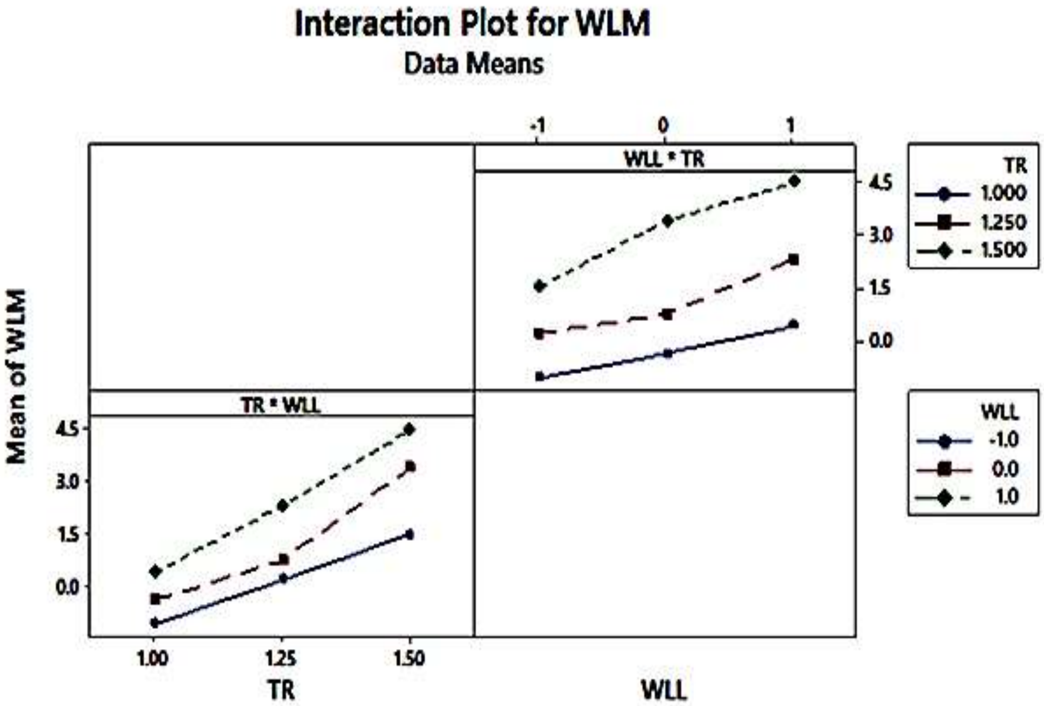


Figure 5.13: Interaction effects plot

The ANOVA results are tabulated in Table 5.4. To test the significance of the parameters with the probability value, the technique of ANOVA is used. A desired confidence level of 95% is taken to test the significance of the model. The results shown in Table 5.5 are found to be adequate at 95% confidence level with the 'P- value '< 0.05.

Table 5.4: ANOVA test results for the regression model developed for WLM

Source	DF	Adj SS	Adj MS	F-Value	p-Value
Regression	2	25.635	12.8175	73.47	0.000
TR	1	18.375	18.3750	105.33	0.000
WLL	1	7.260	7.2600	41.62	0.001
Error	6	1.047	0.1744		
Total	8	26.682			

Optimization results

Optimization of the process is carried out by using the response optimizer in Minitab statistical software. The value of the parameters obtained for an optimized design is thickness ratio = 1.0, WLL = 0.02 mm to achieve a target of zero WLM between the range of parameter values. The minimum WLM that has been predicted with these optimum parameters is 0.000 mm. The validity of the optimum values and the regression equation is checked by conducting simulation experiment. The optimization problem is formulated as follows:

Minimize:

WLM (in mm) = -7.469 + 7.000 TR + 1.100 WLL

Subjected to:

Thickness ratio (TR) of 1, 1.25 and 1.5 and WLL of -1 mm, 0 mm and 1 mm

Sheet metal manufacturers produce sheets with standard specifications. However, it is very difficult to maintain correct thickness ratio for the TWB. In this context, if several options are available based on thickness ratio, Weld Line Location (WLL) and heating conditions, it would help the designers to choose the best possible combination of parameters to solve the problem of WLM. Thus, a combined effect of thickness ratio, selective heating and WLL would result in minimizing the WLM to a great extent. A feasible zone is created in Figure 5.14 with a target value of ± 0.1mm to choose the parameter values as per convenience.

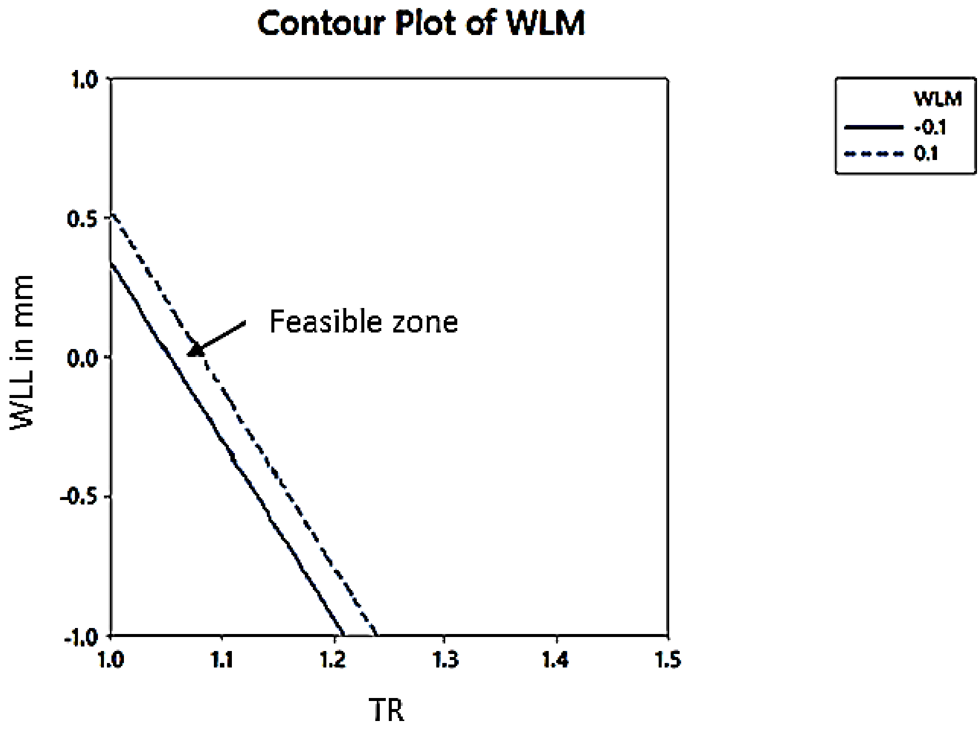


Figure 5.14: Feasible zone for choosing parameters

In order to correlate the predicted optimum values by the ANOVA technique, a simulated experiment has been carried out based on the optimized parameters. They are incorporated in the FE simulation model. The results show that the optimum values obtained from this study could achieve a near zero WLM at the cup wall as shown in Figure 5.15(a). In contrast, the WLM achieved by incorporating actual values produced a large deviation as shown in Figure 5.15(b). Therefore, the experiments conducted at elevated temperatures and room temperature with optimum parameter values resulted in a considerable change in the WLM.

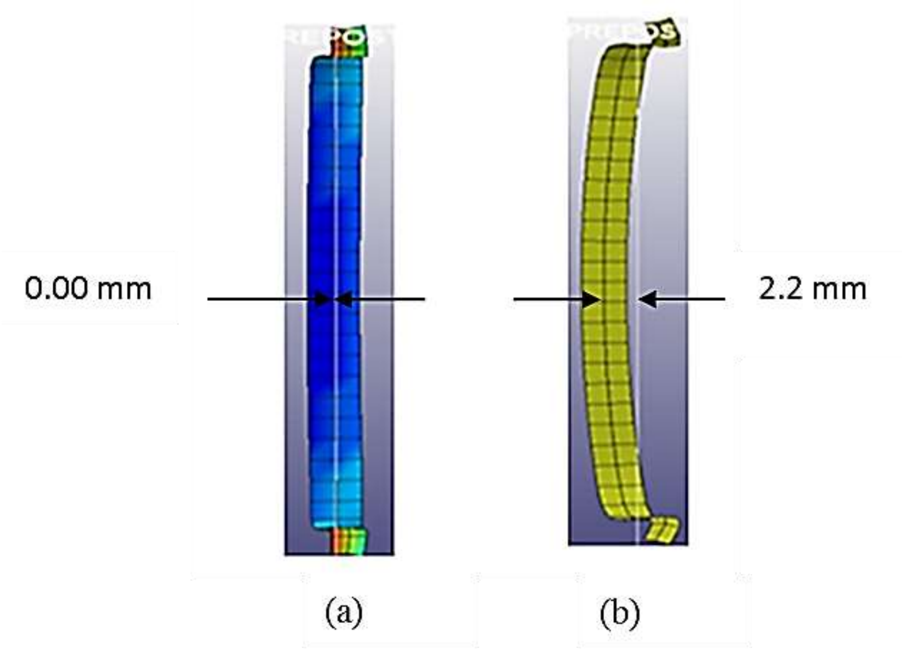


Figure 5.15: WLM in the weld at cup bottom for a) optimized design b) initial design

In this chapter, the effect of WLL, thickness ratio and heating of the stronger material on the WLM in the forming of TWB cups is discussed. TWBs consisting of different combinations of the above parameters are studied in addition to the effect of each independent parameter on the WLM. A combined effect of all the parameters on the WLM has also been undertaken. Observations are carried out in the cup wall as well as at the cup bottom. It has been noticed that the deviations of WLM in the cup bottom are marginal compared to the deviation in WLM in the cup wall. Heating of one part of TWB favoured the formability with considerable control in WLM. It is noticed that the influence of heating the stronger material and weld line offset made a significant impact on the WLM. It is observed that the influence of temperature had a large impact on WLM compared to the other factors like thickness ratios and weld line offset. Since temperature is playing a significant role in controlling the WLM, the selective method of heating the stronger material may be used in the stamping of the automotive components involving TWBs.

The results clearly indicate that neither the thickness ratio nor heating the stronger material nor placing of WLL could control the movement of weld line completely. A combined approach involving all the three parameters gave more options in controlling the WLM to a large extent.

The next chapter deals with the geometric accuracy of the TWB components and its dependence on movement of weld line. It also discusses about the energy analysis carried out on the HAFTWB process.

Chapter 6

Geometric Accuracy and Energy Analysis of HAFTWB Process

Geometrical measurements viz. roundness, cylindricity and perpendicularity measurements are carried out experimentally. In the literature, no attempt has been made to check the geometric accuracy of TWB. Hence an investigation in this area is strongly needed. Under warm forming conditions, several authors have shown improvement in the cup height of TWB cups, However there is no mention of geometric accuracy especially in terms of cylindricity, roundness and taper measurement. Very few investigations have explored geometric effects other than those induced by sheet thickness. The accuracy of the products affects significantly due to the occurrence of size effects in forming process.

Cylindrical and circular features of stamped products are fundamental in nature with respect to geometric form features. Cylindricity error causes hindrances during the assembling of components which in turn affect the performance of the TWB products. Coordinate Measuring Machines (CMMs) or form measuring instruments can evaluate geometric form error. The CMM data contains details viz. form, position and size. Misalignment between the actual centre/axis of the geometric feature and the instrument centre/axis influences the form error values.

The degree of out-of-roundness (ovality) is measured by the difference in the minor and major axis in a single cross section using the Minimum Zone Circle criteria (MZC) for measurement of ovality. For measuring the cylindricity, the difference in diameters at subsequent locations along the axis is measured. The taper is evaluated by the angle generated between the wall of the cup and its base i.e. in this case TWB cup bottom for the two materials separately.

The, surface quality, geometric accuracy and the microstructure of a component manufactured through sheet metal forming process also depends on the heat transfer between tools and work piece, and the elastic deflection of the equipment. In turn, these interactions depend on tool wear, surface oxidation and lubrication. These mechanisms may vary throughout processing, hence not include in the scope of study.

6.1 Theoretical background of geometric accuracy measurements

Roundness measurement

It is important to measure the out-of-roundness in the component in addition to the measurements of their diameter or position. It can be measured by theoretically as shown in Figure 6.1 (Venkaiah N and Shunmugam MS, 2007a) and also by specialized measuring devices, depending on the time of the measurement and uncertainty in the measurement values.

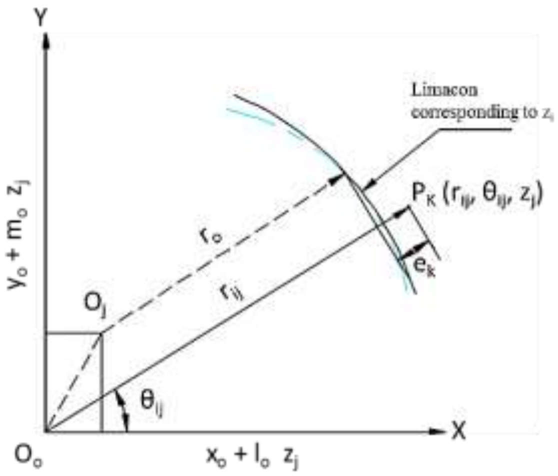


Figure 6.1: Calculation for roundness measurement

The roundness measurement can be approximated and modeled as the sum of the components of the origin (x_0, y_0) and the radius (r). The deviation of a point (r_i, θ_i) on the profile measured represented as $r_o + x_0 \cos(\theta_i) + y_0 \sin(\theta_i)$ is given by

$$e_i = r_i - [r_o + x_0 \cos(\theta_{ij}) + y_0 \sin(\theta_{ij})] \quad (6.1)$$

<u>*Cylindricity measurement*</u>

The recommendations and parameters for measurement of cylindricity are described in the Geometrical Product Specifications (GPS) – Cylindricity under ISO/DIS 12180-1, 2: 1999 standards. According to the standard, a deviation from cylindricity can be considered as a cylindricity deviation in a longitudinal section. (Venkaiah N and Shunmugam MS 2007b) has presented the mathematical relations to measure the cylindricity values based on the Figure 6.2.

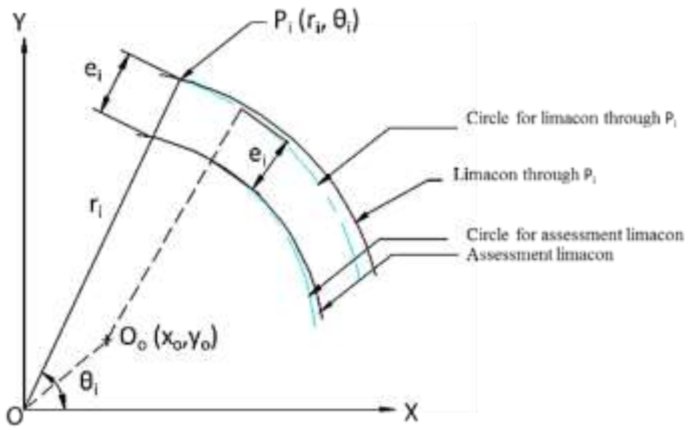


Figure 6.2: Calculation for cylindricity measurement

The deviation of a point (r_{ij}, θ_{ij}) on the profile measured at *j*th section (z_i) from the limacon-cylinder represented as

$$r_o + (x_0 + l_o z_i)\cos(\theta_{ij}) + (y_0 + m_o z_i)\sin(\theta_{ij})$$

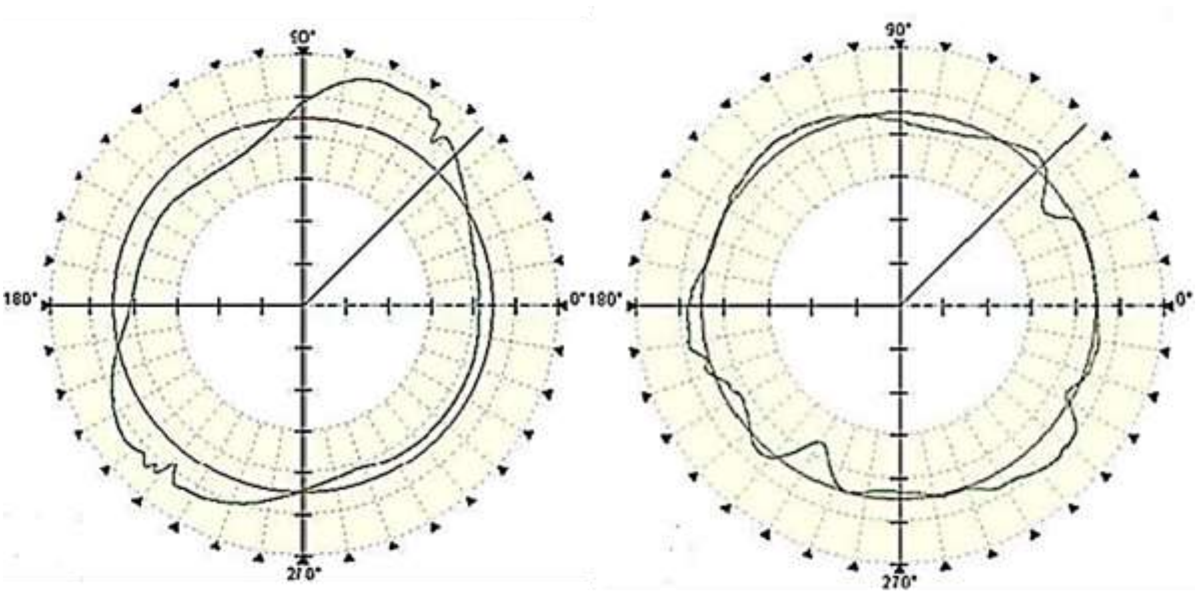
is given by

$$e_{ij} = r_{ij} - [r_o + (x_0 + l_o z_i)cos(\theta_{ij}) + (y_0 + m_o z_i)sin(\theta_{ij})] \qquad (6.2)$$

6.2 Experimental results of geometric measurements

Roundness measurement

The roundness of the TWB samples has been measured using a ultra-precision roundness tester (Talyrond 290) measuring instrument. Figure 6.3 (a) shows the roundness of the TWB cups formed at room temperature and Figure 6.3 (b) shows the roundness of the TWB cups formed at elevated temperature. It is found that the roundness accuracy of TWB cup formed at room temperature as shown in Figure 6.3(a) has a value of 0.3378 µm which is greater as compared to the sample formed at elevated temperature which is 0.2768 µm as shown in Figure 6.3(b). Based on the experimental result, it has been observed that the part formed at elevated temperature has good geometric accuracy as compared to the part formed at room temperature.



(a) (b)

Figure 6.3: Graphs plotted for roundness measurement of TWB cups using talyrond instrument (a) without heating (b) with heating

Cylindricity measurement

The cylindricity of the TWB samples is measured using a coordinate measuring machine (CMM) instrument and plotted as shown in Figure 6.4. It shows the cylindricity of the TWB cups formed at room temperature and elevated temperature. Based on the experimental result, it has been found that the cylindricity value of the TWB cups formed at room temperature is 0.4459 μm which is greater than the value obtained for sample formed at elevated temperature which is 0.3745 μm. Thus, there is an improvement in the cylindricity of the TWB cups formed at elevated temperature

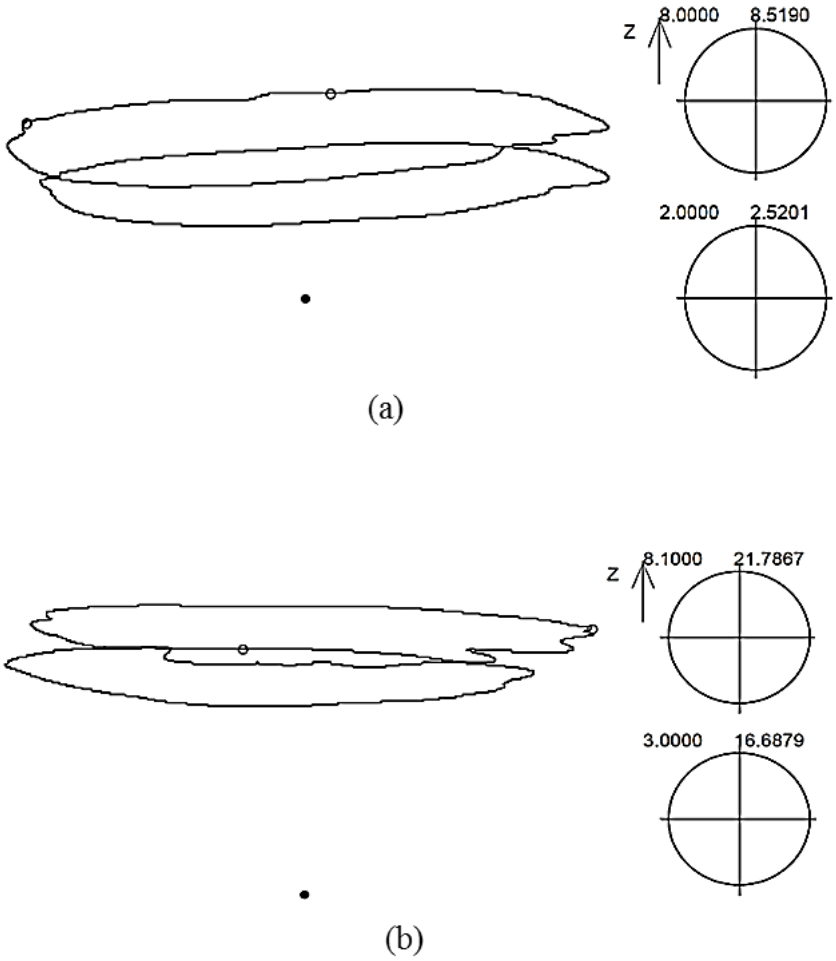


Figure 6.4: Graphs plotted on CMM for cylindricity measurement of TWB cups (a) without heating (b) with heating

Perpendicularity measurement

The perpendicularity measurement in a component is measured with the help of a profile projector, which is used to measure two-dimensional contours in a specimen. The part to be measured has been magnified and projected on a screen by an optical system. The dimensions of the component are visible on the screen. The particulars of the profile projector are listed in Table 6.1. A Profile Projector which is also known as a simple optical comparator is a device that uses the principles of optics in the measurements of manufactured parts. It can measure length and width simultaneously in a two dimensional space unlike the micrometers and callipers, which measure only one dimension at a time.

Table 6.1: Specifications of the profile projector

Make	Metzer
Model	Metz-401
Magnification	10X-100X
X axis	25 mm
Y axis	25 mm
Least count	0.005 mm
Angular scale	0- 360^0

Perpendicularity measurements which are carried out on a profile projector on ASS 304 side and IS 513 side separately and the values are shown in Table 6.2. It has been found that on both sides, the perpendicularity measurements of TWB cup formed at room temperature are greater than the measurements obtained for cup formed at elevated temperature. In other words, it can be understood that the TWB cup formed without heating has more taper than the cup formed with selective heating.

6.3 Discussion on geometric measurements

The phenomenon leading to the improvement in geometric accuracy can be understood from the fact that there is a tendency for more plastic deformation due to thinning of ASS material upon heating. It is noticed from the Table 6.2 that the perpendicularity measurements of TWB formed at room temperature have less value compared to the measurements of TWB cups formed at elevated temperature. This effect may give rise to spring back problems. In a stamping operation, if spring back is not compensated, it may cause problems in maintaining geometric and dimensional accuracy of parts. Some of the methods suggested by researchers to compensate spring back effect are to arrange variable blank holder force or using a direct water quenching technique immediately after the cup is formed.

Table 6.2 Perpendicularity measurements in TWB cups

Material	Without Heating		With Heating	
	Expt.	Simulation	Expt.	Simulation
ASS 304 side	91.3°	90.7°	93.8°	91.7°
IS 513 side	92.5°	90.7°	93.2°	92.0°

Perpendicularity in the TWB cups is also measured using CMM. The perpendicularity is measured on either side of cup. It is noticed that of the perpendicularity measurement is less on the ASS 304 side compared to the IS side as shown in Figure 6.5. Without heating the perpendicularity measurement on ASS side is 0.3508 μm and on IS side it is 0.4104. With heating, the perpendicularity measurement reduced to 0.1688μm on ASS side and 0.2326μm on IS side respectively. Thus an improvement in the perpendicularity results is noticed when the TWB cup is formed at elevated temperature.

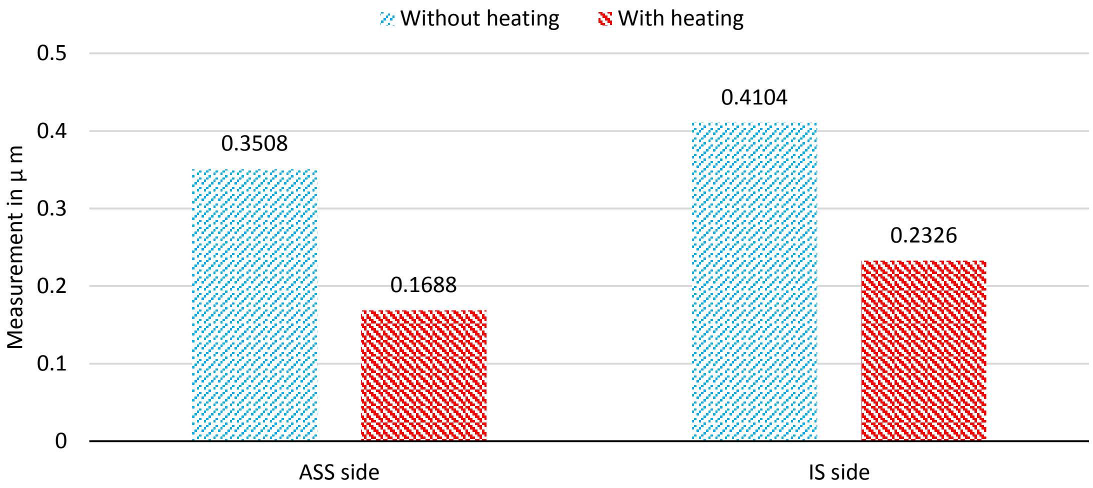


Figure 6.5: Comparison of perpendicularity on either side of TWB cups formed with and without heating

Figure 6.6 shows the comparison of TWB cups formed at room temperature and elevated temperature between cylindricity and roundness for the samples. TWB cup formed at room temperature resulted in cylindricity measurement of 0.445 µm and it reduced to 0.374 when formed at elevated temperature. Similarly the roundness measurement in the cup formed at room temperature is 0.337 µm and it reduced to 0.276 µm in the TWB cup formed at elevated temperature.

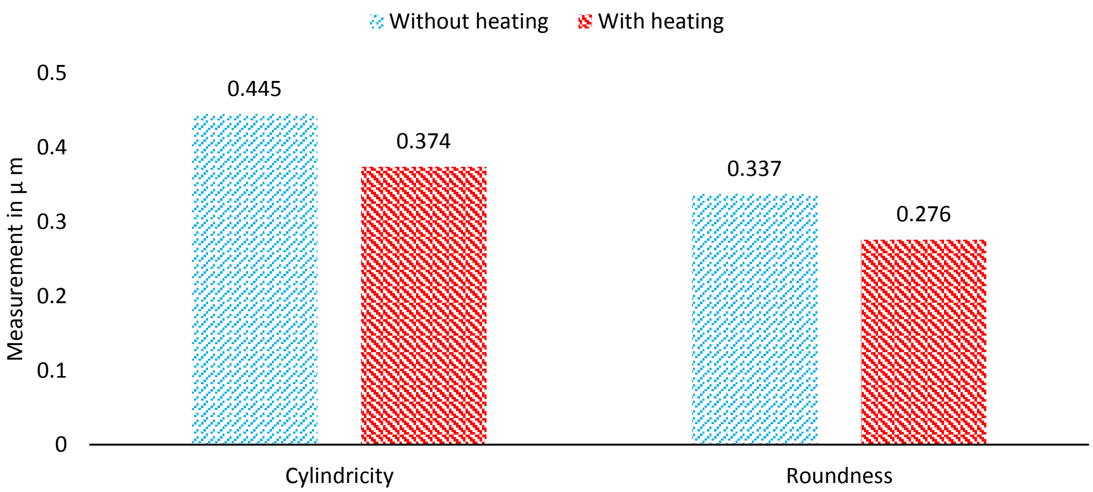


Figure 6.6: Comparison among cylindricity and roundness values for TWB cups formed with and without heating

Selective method of heating played a significant role in improving the geometric accuracy of components. The performance of the TWB components has been evaluated by the geometrical measurements viz. roundness, cylindricity and perpendicularity using high precision measuring instruments. Based on the experimental results, it is found that cylindricity and perpendicularity measurements shown good results, while roundness measurement has slightly improved. Geometric accuracy between the parameters showed an improvement when the TWB has been subjected to heating. Since heating resulted in an improved accuracy and also minimized the WLM, geometric accuracy in the component need not be compromised with the WLM.

6.4 Discussion on Energy Analysis in HAFTWB process

Sustainable manufacturing issues related to energy analysis in sheet metal forming processes are widely investigated. Ingarao et al (2012) investigated sustainability aspects in sheet metal forming processes. They focused on the efficient use of energy and material savings in stamping process based on the initial blank design. They concluded that different methodologies need to be applied for energy and material savings and both cannot be clubbed. Cooper et al. (2017) studied the traditional and latest methods of sheet forming based on the electrical power requirements in the die design. Their results showed that idling consumed more electricity. They found that there are significant potential savings for small production runs, consistent with part development/prototyping. However, these savings varied depending on the part size. The results of their study highlighted that for small production numbers over the die lifespan, the impacts of die-making are important. However, as production numbers increase above one hundred parts per die-set, the impacts of making the sheet metal become dominant. It is therefore concluded that researchers interested in reducing the environmental impacts of sheet metal forming concentrate on innovations that would reduce sheet metal blanking and post-forming trimming losses.

Pereira and Rolfe (2014) studied the frictional heating aspects occurring during stamping operation which are responsible for high die temperature. They have carried out both simulations involving thermo-mechanical finite element model and experiments. They concluded that the process speed and blank material strength strongly influence maximum temperatures. The results showed direct influence of temperature on tool wear performance during stamping operation. Hon (2002) discussed that the maximum force measured on a TWB does not lie halfway between the maximum forces of both materials, but that the higher strength steel contributes 40% and the lower material contributes 60% of the maximum force of the TWB. He explained that since the hard material displaces the soft material and consequently, the hard material requires less force for being formed.

Mayyas et al. (2012) discussed on the use of stronger materials which have a high and sustained work hardening effect for producing light weight structures. It allows the automobile manufacturers to use thinner materials resulting in less weight. They also suggested using TWB to custom make the thickness of blanks according to their location performance criteria. Krause and Seliger (1997) studied the influence of weld position on the environmental aspects during the forming of TWB. They studied the simple life cycle energy model and concluded that it is better to reduce the product weight rather than reducing the waste weight.

Power consumption in HAFTWB process

Load displacement graph obtained for TWB cup formed at room temperature is shown in Figure 6.7.The punch travel was limited to 20 mm. Nearly 38% of load is saved when the samples are tested at the temperature of 150 °C as compared to the load required for forming at room temperature.

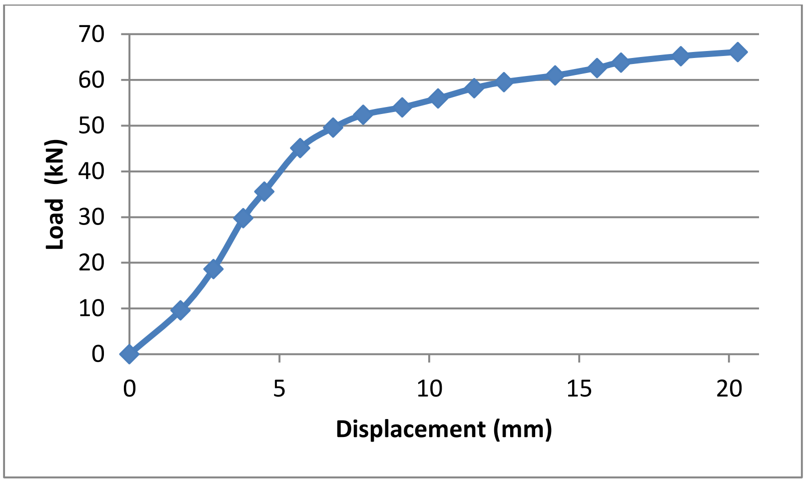


Figure 6.7. Load displacement graph of TWB cup formed at room temperature

The power consumption during forming can be calculated as:

Power = Energy consumed * time in sec

Comparisons were made with respect to the power consumed in forming of TWB component at different temperatures as shown in the Figure 6.8. The initial peaks are due to the limiting friction between the punch and the sheet material. It can be observed that the energy required to overcome limiting friction is more in case of cups formed with heating as compared to the cups formed without heating. However, the total energy consumed for the products formed at room temperature is more than that of the products which are formed using the heat assisted forming method.

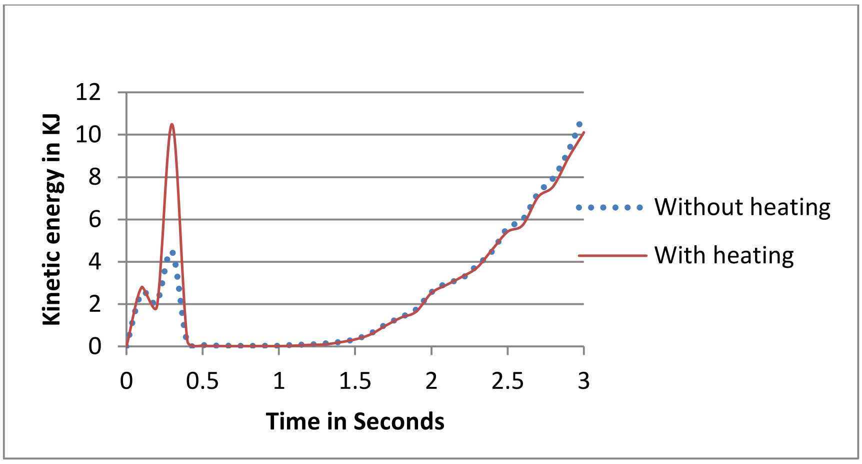


Figure 6.8 Power consumed during the punch travel of a stamped TWB cup

Total energy consumed in the forming of TWBs

The energy balance equation in the HAFTYWB process can be deduced as, Energy balance = Amount of thermal energy supplied + amount of mechanical energy supplied – reduction in the plastic deformation energy requirement due to reduced flow stress in the stronger side.

This sum may turn out non-zero and largely positive value. Surely, we must supply net energy. However, it is important to understand that the *primary* purpose of this selective heating mechanism is to achieve part accuracy (with minimized weld-line movement), and not to save on the energy of forming.

In general the total energy is the sum of internal energy+ kinetic energy + contact (sliding) energy + hourglass energy + system damping energy+ rigid wall energy. Internal energy includes elastic strain energy and work done in permanent deformation. The total energy is equated to the total work done by the system. External work includes work done by the applied forces and pressures as well as work done by velocity, displacement or acceleration boundary conditions. The following equation should hold at all times during an analysis.

$$\underbrace{E_{kin} + E_{int} + E_{si} + E_{rw} + E_{damp} + E_{hg}}_{\text{Total Energy } E_{total}} = E^0_{kin} + E^0_{int} + W_{ext} \quad (6.3)$$

Where E_{kin} = current kinetic energy, E_{int} = current internal, E_{si} = current sliding energy (including friction), E_{rw} = current rigid wall energy, E_{damp} = current damping energy, E^0_{kin}= initial kinetic energy, E^0_{int} = initial internal energy, W_{ext} = external work

The total energy required to form a TWB component using heat assisted forming is less than the energy required to form at room temperature as shown in the Figure 6.9.

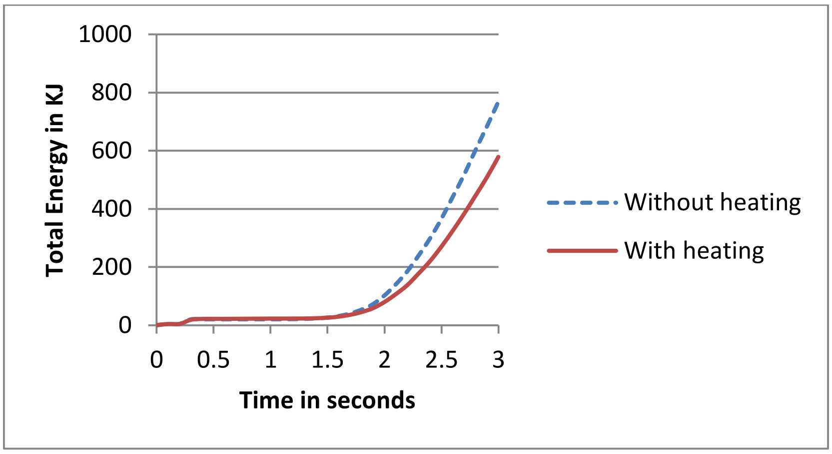


Figure 6.9 Comparison of total energy consumed in the stamping of TWB cup formed at different temperatures.

Numerical simulations were conducted at different temperatures and thickness ratios to study the sustainable aspects involved with energy and material savings. The results show a reduction of punch load to an extent of 75% and material saving of nearly 33%. Overall, heat assisted forming of TWBs reduced the weld line movement, improved accuracy and saved material and energy in the manufacture of TWB components.

Chapter 7

Conclusions and Future Work

In this research work, an elaborate study has been conducted on the problems faced with weld line movement (WLM) in the forming/stamping of tailor welded blanks (TWBs).

7.1 Conclusions and specific contributions to research

Based on the work carried out and results obtained, the following conclusions have been drawn:

- New combinations of materials such as Austenitic stainless steel and mild steel (ASS-IS) are successfully tested to obtain defect free TWB cups through simulations and laboratory experiments by adopting the novel heat assisted forming of tailor welded blank (HAFTWB) process.
- Formability of tungsten inert gas (TIG) welded TWBs is equally good as compared to the laser welded TWBs. Therefore, TIG welding is recommended as a low cost welding method for forming of TWBs.
- From the simulation study of HAFTWB process, it has been found that the WLM showed a reduction of 87% at the cup bottom and 75% in the cup wall. These results were in good agreement with experimental results.
- An experimental setup for HAFTWB process with a split punch in which one part of the punch is heated and the other part is cooled has been developed and successfully tested. The heated part of the punch has been in contact with the stronger material (ASS) to reduce its flow stress.

- To find out the effect of thickness ratio and weld line location (WLL) on the WLM, a parametric study on HAFTWB process has been conducted. Based on this study, it has been found that the effect of thickness ratio is greater than the effect of WLL on the WLM; however, independently neither the thickness ratio nor the WLL could restrict the WLM completely. An optimum study based on the combined effect of all the above mentioned parameters could minimize the WLM to a great extent.
- With respect to the geometric accuracy, in comparison to the conventional forming of TWB, cylindricity and perpendicularity of the components formed with HAFTWB process have greatly improved, while roundness in the components has slightly improved.

Overall, the HAFTWB method of forming resulted in improved geometric accuracy and minimized the WLM.

7.2 Limitations of the current study

The following are the limitations in the current study:

- In this research work, the HAFTWB process has been carried out only for one material combination, i.e., ASS-IS.
- In the development of TWB, manual TIG welding has been used and so the surface finish of TWB has been found moderate.
- In HAFTWB experiments, the heat transfer rate between the punch and TWB has been relatively slow, which made it difficult to control the differential heating of two sides of TWB.
- In the development of HAFTWB experimental setup, the temperature measurements have been done by thermocouples due to their economic viability, however these resulted in slow measurement and difficult temperature control.

7.3 Recommendations for future work

Based on the above mentioned conclusions and limitations of the study the following recommendations have been suggested for carrying out future work.

- Future research can be extended to the currently used industrial materials viz. Dual phase steels and interstitial free steels for stamping of TWBs using HAFTWB method.
- To improve the productivity and surface finish of TWBs (Spotll and Mohrbacher, 2014), an automated TIG welding process could be used.
- To increase the heat transfer rate between the punch and TWB, the pencil heater can be replaced by an induction heater coil in the punch.
- For quick temperature measurement, thermistors can replace thermocouples in the HAFTWB process.
- Non-linear weld profiles viz. circular, elliptical, spline curve etc. can also be attempted in future work to solve the problem of WLM. A correlation between the WLM and the weld profile can be established
- There are some more important challenges not yet addressed by literature such as controlled warm forming and hydro warm forming, solving which require extensive experimental facilities and a lot of material data. Thus, in future, these works can also be undertaken with available experimental facilities and raw material

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List of Publications

SCI/SCIE Peer-reviewed International Journal Publications

1. **V.V.N. Satya Suresh**, Srinivasa Prakash Regalla, Amit Kumar Gupta (2017) "Combined effect of thickness ratio and selective heating on weld line movement in stamped tailor-welded blanks" *Materials and Manufacturing Processes*, 32(12), 1363-1367.
2. **V.V.N. Satya Suresh**, Srinivasa Prakash Regalla, Amit Kumar Gupta (2018) "Optimum parameters to minimize weld line movement in the warm forming of tailor-welded blanks" *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 40 (4), 234.
3. **V.V.N. Satya Suresh**, Srinivasa Prakash Regalla, Amit Kumar Gupta (2018) "Minimization of weld line movement in heat-assisted forming of tailor welded blanks" *Proceedings of Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* (Article first published online: November 7, 2018).

Scopus Publications through Peer-reviewed International Conferences

1. **Vakada Venkata Naga Satya Suresh,** Srinivasa Prakash Regalla (2017) "Investigations on dimensional accuracy of stamped tailor welded blanks under warm forming conditions" *ASME Proceedings of the International Mechanical Engineering Conference and Exposition 2017, Paper No. IMECE2017-72478, pp. V002T02A071* . doi: 10. 1115@IMECE2017-72478.
2. **Satya Suresh V.V.N**, Srinivasa Prakash Regalla, Ratna Sudheer G (2016) "Effect of localized heat treatment on the weld line shift in deep drawing of tailor welded blanks (TWBs)"*AIP conference proceedings*, **1769**, 100015 (1-10).
3. **Satya Suresh V.V.N**, Srinivasa Prakash Regalla, Amit Kumar Gupta, Padmanabham G (2015)" Weld line shift in the case of Tailor welded blanks subjected to differential

strengths with respect to TIG and Laser welding, *Materials Today Proceedings*, 2, pp 3501-3510.

Other Peer-reviewed International Journal Publications

1. **Satya Suresh V.V.N**, Srinivasa Prakash Regalla, Amit Kumar Gupta (2017)“ Influence of geometric parameters on weld line movement in the selective heating of tailor welded blanks” *Advances in Materials Processing Technologies, 3, 385-392 (Taylor and Francis)*

Other Publications through Peer-reviewed National/International Conferences

Arman Khan, **V.V.N. Satya Suresh,** Srinivasa Prakash Regalla (2014) “Effect of thickness ratio on Weld Line Displacement in Deep Drawing of Aluminium Steel Tailor Welded Blanks’ *Procedia Materials Science, 6, pp 401-408 (Elsevier)*

Satya Suresh V.V.N., Srinivasa Prakash Regalla, Uday kumar R (2014) “Experimental investigations, Modeling and Simulation of Tailor welded blanks: A review” *International Journal of Current Engineering and Technology,* Special issue-2, 141-146.

Satya Suresh V.V.N., Srinivasa Prakash Regalla, Amit Kumar Gupta “Influence of weld profile shape on the weld line movement of Tailor welded blanks” at *Sheet Metal Forming Research Association (SMFRA’16)* Conference held at IIT Bombay between 7th-9th December, 2016.

V.V.N. Satya Suresh, Srinivasa Prakash Regalla “Comparison of welding processes in the forming of tailor welded blanks” in the *6th WRCC* organized by International Institute of Welding during 7-9 April, 2016 at Hyderabad

V.V.N. Satya Suresh, Srinivasa Prakash Regalla, Amit Kumar Gupta "Minimization of weldline movement and improvement of geometric accuracy in the forming of Tailor welded blanks using finite element methods" at *International Symposium for Research Scholars (ISRS)* at IIT Madras, December 11-13, 2014

V.V.N. Satya Suresh, Srinivasa Prakash Regalla "A combined FEA and design of experiments approach for the design and analysis on the weld line movement in localized warm forming of Tailor Welded Blanks" at *DPLC, 2016* conference held in BITS-Pilani, Hyderabad campus, March 20, 2016.

V.V.N. Satya Suresh, Srinivasa Prakash Regalla "Effect of weld line position and thickness ratio on the movement of weld line in the warm forming of Tailor welded blanks" at *RAMR, 2016* conference held in BITS-Pilani, Hyderabad campus, April 22-23, 2016.

Satya Suresh V.V.N., Srinivasa Prakash Regalla "Approximation of perform shape for the Minimization of weld line shift in deep drawing of Tailor welded blanks in the *Advances in Materials Joining Technologies* [AMJT 2015] organized by Indian Institute of Welding, Hyderabad branch on 29th May 2015

Satya Suresh V.V.N., Srinivasa Prakash Regalla "Minimization of weld line movement by the approximation of weld in the forming of Tailor welded blanks (TWB) using finite element simulation" in the workshop on *Advances in Welding and Surface Engineering* (AWSE) organized by IIW, Hyderabad branch in October 2014

Patents filed: 01

Vakada Venkata Naga Satya Suresh, Srinivasa Prakash Regalla "A Novel Deep Drawing Tooling With Selective Heating And Cooling For Tailor Welded Blanks (TWBs)" Indian Patent Application No. 4038/CHE/2015, August 04, 2015

Grants received: 02

1) **V.V.N. Satya Suresh** received research grant of Rs. 4.8 lakhs from UGC towards minor research project titled "Evaluation of formability characteristics of Tailor welded blanks to satisfy performance criteria and optimize the Deep Drawing process parameters using Design of Experiments (DoE) and comparing with the Finite Element simulation model" with grant no. F MRP-6160/15 (SERO/UGC) for the period between Jan '15-Jan'17

2) **V.V.N. Satya Suresh** received travel grant from UGC towards presenting paper at the 19th ESAFORM conference held at Nantes, France between 27-29th April, 2016

Brief Biography of the Candidate

V.V.N. Satya Suresh is currently working as Associate Professor in the Department of Mechanical Engineering at Mahatma Gandhi Institute of Technology (MGIT), Hyderabad, India. He has two years of industrial experience and teaching career of 20 years. He taught Engineering mechanics, Strength of materials, CAD/CAM, Computer graphics, Finite element methods and Engineering drawing courses for the under graduate students. He also taught Advanced CNC technology, Autotronics and Vehicle intelligence courses to the graduate students.

He obtained his Master's degree with specialization in CAD/CAM from Jawaharlal Nehru Technological University, Hyderabad (JNTUH) in the year 1997. He worked on the project titled "Optimization of tall chimneys subjected to dynamic loads" in his Master's degree. He has another Master's degree and PG diploma in value education and spirituality from Annamalai University. His research area includes Material characterization, Finite element modeling, Sheet metal forming and CAD/CAM.

Brief Biography of the Supervisors

1) Prof. Srinivasa Prakash Regalla is a Professor in Mechanical Engineering Department, coordinator of the Center for Product Design and Realization (CPDR) and Associate Dean of Work Integrated Learning Programmes at BITS Pilani, Hyderabad campus. He has Ph.D. from IIT Delhi, M.Tech. from IIT Kanpur and B.Tech. from Kakatiya University, Warangal, all in Mechanical Engineering. He has been a guest researcher at NIST, Gaithersburg, MD, USA during 1998. He completed several funded research projects from government agencies and industry as a principal investigator. Recently, he completed as the principal investigator and project coordinator a DBT/BIRAC/BIG-5 project on 'innovative and affordable 3D printing technologies to manufacture artificial limbs for disabled in India'. He published 55 peer-reviewed international journal papers, presented papers in over 32 international conferences, authored 2 books, delivered several invited talks and filed 3 patents. He guided 4 Ph.D. students and is currently guiding 5 Ph.D. students. His research areas are additive manufacturing, sheet metal forming, CAD/CAM, medical devices, metal working tribology.
2) Prof. Amit Kumar Gupta is the Head and Professor in the Department of Mechanical Engineering in BITS Pilani, Hyderabad campus. He graduated in Mechanical Engineering from the Indian Institute of Technology (IIT Delhi) and obtained his Ph.D. from Nanyang Technological University (NTU), Singapore. He has authored about 90 publications in reputed international journals and conferences. He has completed several funded research projects from government funding agencies, such as DAE, DST, UGC, DRDO as a principal investigator. His areas of research include sheet metal forming, tensile testing, constitutive modeling, production scheduling and predictive modeling and optimization of manufacturing processes.