

# Forming of Tailor-Welded Blanks Through Centerline and Offset Laser Welding

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## ABSTRACT

The forming of low and high strength tailor welded steel sheets into preferred three-dimensional shapes by a homogeneous distribution of plastic strain is highly difficult. In this work, the formability of tailor-welded blanks prepared using laser welding of low (IS 513 CR2, IS 513 CR3) and high tensile strength (AISI 304) steel sheets were analyzed, and the formation of the edge profile and weld line movement were also examined. The results showed a decrease in formability characteristics owing to the increase in strength ratio. Scanning electron microscope analysis of the fracture locations within unsuccessfully formed tailor welded blanks showed the presence of tempered martensite in the soft zone was found to be the most predominant factor affecting its failure. The formability characteristics of investigated tailored blanks were predicted using finite element simulation and compared with experimented results for validation.

## KEYWORDS

Abaqus, Automotive, Defects, Failure, Formability, Forming, Martensite, Sheet, Simulation, Steel

## INTRODUCTION

Sheet metal forming involves the forming of simple and complex components by the plastic deformation of a blank sheet till the required shape is achieved without any failures. The capability of a sheet metal to deform without any crack in sheet metal forming is called as formability (Kumar et al., 2021). The tool geometry, metallurgical and mechanical properties of the steel sheets, forming temperature and blank holder force, provide towards the success or failure during the forming of steel sheets. It is vital to understand the sheet material formability and thereby the development of components for several manufacturing and automotive applications (Natarajan et al., 2020; Mayavan et al., 2016; Hasan et al., 2017; Bagudanch et al., 2017; Hashemi et al. 2017).

The ever-increasing demand to improve the safety and comfort of automobiles has led to the addition of various electronic and other components (Allwood & Cullen, 2012; Satya et al., 2017; Ganesh & Naik, 2010; Hariharan et al., 2012). As a result, the weight of the automobile and the accompanied fuel consumption tend to increase. In addition Kishore and Jayasimha (2015) have observed that the need for fuel economy, safety and environmental mandates issued by the various governments in the recent years have caused the automotive industry to design light weight, high strength vehicles. Though low density materials such as aluminum lead to a weight reduction, their

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usage in automotive industry is limited owing to their low formability as stated by Kleiner (2013) and Raja et al. (2017). In addition to that, Karthikeyan et al. (2010) and Maji (2019) has found that the strength of sheet material reduces when subjected to welding owing due to the variations in their microstructure. This has led to development of tailor welded blanks (TWB) which optimizes the material thickness, improves the crash behaviour and reduces the overall component weight in automobiles (Xing et al. 2020).

The tailor welded blanks achieves these functions by applying engineering material requirements at exact locations instead of distributing it along the entire body panel (Kumar et al., 2017; Xinge et al., 2019; Satya et al., 2017; Swagat et al., 2018). Sangwook et al (2018) discussed the advantage of improving the process efficiency while reducing the number of stamped parts. Kinsey et al. (2000) have stated that under local dissimilar loading conditions, production cost is reduced by using tailor welded blanks.

Several studies explicate the importance of the study of the forming behaviors of TWBs fabricated using steels sheets in automotive industries. Vijay et al. (2018) & Su et al. (2019) has identified that formability of TWBs is highly influenced by the presence of the weld zone, the variations in thickness, and the high anisotropic behavior. Moreover their formability is limited by the material fracture and depends on the weld location in connection to the maximal strain. Mennecar at al. (2014) reported that a change in the location of the initial weld under deep drawing enhanced the forming characteristics of tailor welded HCT980X/HCT600X material.

Though several tests such as Limiting dome height test, Swift cup test, and Limiting drawing ratio tests are available to evaluate the formability of a TWB, the commonly used is LDR test owing to its simplicity and accuracy (Zadpoor et al., 2007; Zaeimi et al., 2015). Based on the literature study, it was identified that negligible research has been undertaken on the influence of WLM, and strength ratio on the formability of tailor welded blanks up of IS 513 CR2, IS 513 CR3 and AISI304 steel sheets. It was also identified that only stretch forming study on TWBs of the sheets has been carried out in the previous studies. This provides an immense scope to evaluate the forming behavior of steel sheets and TWBs of steel sheets which find extensive applications in the automobile industry.

## **BACKGROUND**

In the present investigation the formability characteristics of parent and laser butt welded blanks of IS 513 CR2, IS 513 CR3 and AISI 304 steel sheets were studied by subjecting them to LDR tests. The TWBs were prepared by center line and offset weld positions. The influence of strength ratio (SR) on formability ratio (FR) and WLM were studied. It was identified that the strength ratio of parent materials plays a significant role on the formability of tailor welded blanks. An enhancement of formability ratio and limiting drawing ratio was achieved for TWB (AISI 304-IS 513 CR3), by shifting the position of the weld line. The fracture was identified consistently in the soft zone of the weaker side due to the strain localization. The formability characteristics of the investigated TWBs were predicted using Abaqus/standard 6.12-1 and validated with experimental findings.

## **MATERIALS AND METHODS**

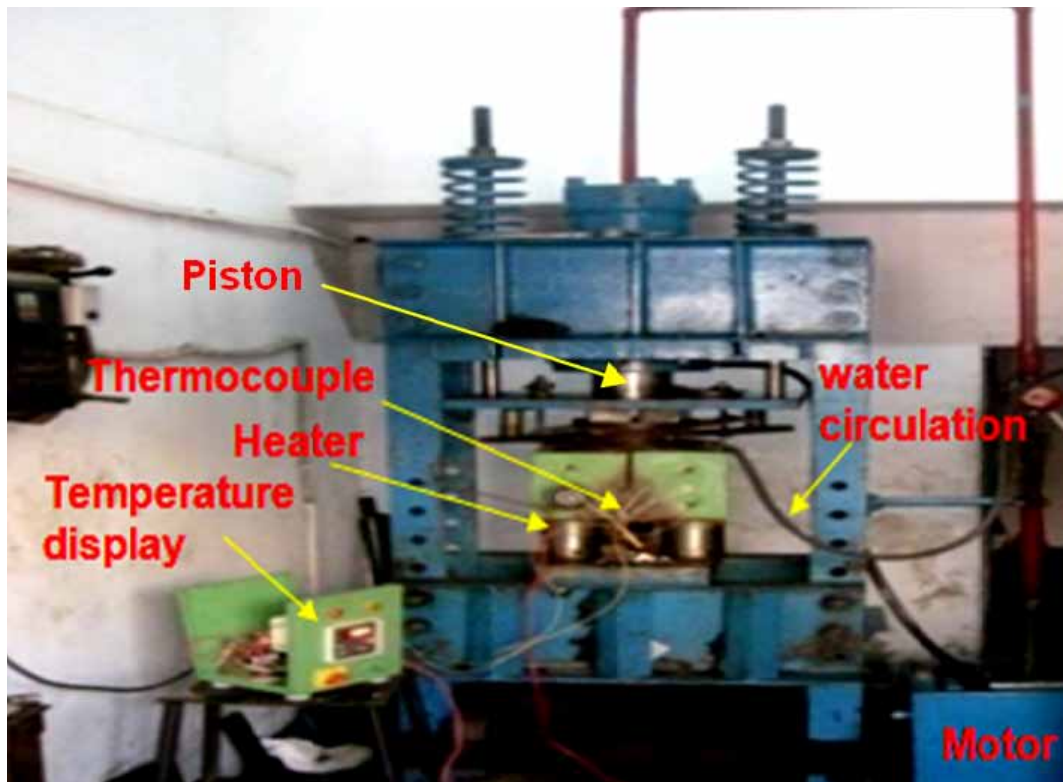
Two grades of steel sheets with moderate formability and low strength namely IS 513 CR2, IS 513CR3 and one high strength AISI 304 sheet were chosen as parent material in this study. The thickness of the sheet was 0.8 mm. Laser welding was employed to fabricate tailor welded butt joints under dissimilar material combinations, namely, IS 513CR2-AISI304 and IS 513CR3-AISI304. A 1.3 kW CNC controlled CO<sub>2</sub> ABB Robot laser machine of Japan make with specifications shown in Table 1 was used to perform laser welding.

Table 1. Specification of Laser welding

Frequency	Peak power	Max. Energy	Avg. Power	Clearance
19 Hz	1.30 kW	110 J	132.32 W	10 mm

The formability characteristics of parent materials and TWBs were investigated by subjecting circular blanks of diameter to a cup drawing test. Figure 1 shows a Jackson hydraulic press (make: India) with a capacity of 800 kN, motor power of 3 hp, piston stroke 400 mm was used to conduct the cup drawing test. Based on the trial experiments, the selected Blank holder force (BHF) were 15kN, 19 kN and 22 kN for IS 513 CR2, IS 513CR3 and AISI 304 parent materials respectively to avoid wrinkling in the flange region. However constant BHF of 22 kN was applied while forming of TWBs due to the presence of AISI 304 sheets in all the blanks. The moving parts were lubricated using Molykote during cup test. A velocity of 4 mm/s which is closer to general production conditions was maintained during punching. The tool dimensions and test conditions maintained are shown in Table 2.

Figure 1. Experimental setup for the cup drawing test



**Table 2. Tool dimensions and test conditions for the cup drawing experiments**

Sl. No.	Parameters	Units	Values	Increments
1.	Blank holder force (BHF)	kN	15/19/ 22	IS513 CR2/IS 513 CR3/ AISI 304
2.	Blank diameter (D)	mm	90 to 115	3
3.	Blank thickness (t)	mm	0.8	--
4.	Punch force	kN	0 - 30	Gradual increase and decrease
5.	Punch diameter ( $d_p$ )	mm	46	--
6.	Punch nose radius ( $r_p$ )	mm	5	--
7.	Die profile radius (r)	mm	12	--

## FINITE ELEMENT MODELLING OF TWBS

A three-dimensional fully coupled thermo-mechanical finite element analysis was conducted using Abaqus/Standard 6.12-1 to identify the formability characteristics of the fabricated TWBs. During FE simulation the tools used for the forming process such as punch, die, blank holder were meshed as analytical rigid surfaces and circular blank material was meshed as thermally coupled quad shaped elements with four nodes. Quad-shaped S4R elements with reduced integration, hourglass control, and S4RT elements were used during forming. Nearly 239825 elements with 66250 nodes were used to define a blank; rectangular elements were used on the surface, and triangular shapes on the edges. The blank holder force during the analysis varied according to the drawing ratio of the blank. During FE simulation Tsai-Hill failure criterion was used to identify the failure regions of investigated TWBs. Then the simulation was executed for the given input parameters and the parameters such as von mises stress distribution and surface defects were predicted. The thermal and material parameters of steel sheets used in FE simulation of TWBs is shown in Table 3.

**Table 3. Material properties and process parameters used in the finite element simulation**

S. No	Material properties and process parameters	AISI 304	IS 513 CR2	IS 513 CR3
1.	Young's modulus (GPa)	193	202	205
2.	Poisson ratio	0.3	0.29	0.28
3.	Thermal conductivity of sheet (W/mK)	17	85	93
4.	Specific heat (J/gK)	0.43	0.46	0.481
5.	Factor to convert plastic deformation energy to heat	0.92	0.80	0.78
6.	Friction coefficient between blank and punch	0.15	0.15	0.15
7.	Friction coefficient between blank and die/blank holder	0.12	0.12	0.12

## RESULTS AND DISCUSSION

### Plastic Flow Behaviours of Parent Materials and TWBs

Tensile tests were conducted for both parent & TWB samples to identify its plastic flow properties and to examine the failure location when subjected to transverse tensile loading. Tensile testing was carried out using a universal testing machine manufactured by Avto instruments limited (make: India). The tensile specimens were prepared as per ASTM E8 standard.

The mechanical properties of the parent materials required for forming study were evaluated using a uniaxial tensile test. In addition, tensile tests of both TWB samples (AISI304-IS 513CR2 and AISI304-IS 513CR3) were conducted to identify its strength, percentage of elongation and weld quality. The mechanical properties are listed in Table 4. The prepared parent and TWB tensile specimens are shown in Figure 2(a-c). Figure 2(d) compares the engineering stress and strain curve of the parent materials and prepared TWBs. The calculated plastic flow properties were used in finite element simulation.

Figure 2. a) Parent materials b) AISI304-IS513 CR2 c) AISI304-IS513 CR3 d) Plastic flow curves

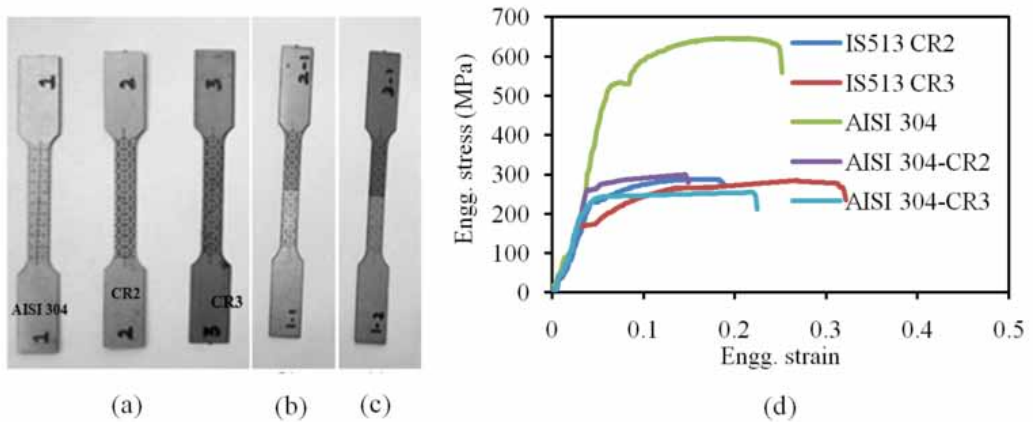


Table 4. Mechanical Properties of steel alloys

Materials: Grades	UTS (MPa)	Modulus of Elasticity (GPa)	Strength coefficient K- MPa	Strain hardening index (n)	Thermal Expansion (K <sup>-1</sup> )
AISI 304	505	193	1400	0.43	17.2x10 <sup>-6</sup>
IS513 CR2	370	202	545	0.27	12.2x10 <sup>-6</sup>
IS513 CR3	350	205	530	0.26	12x10 <sup>-6</sup>

## LIMITING DRAWING RATIO AND CUP HEIGHT

The maximum blank diameters that can be drawn successfully from tailor welded blanks AISI 304-IS 513 CR3 and AISI 304- IS 513 CR2 blanks are 98 mm and 103.5 mm respectively. The LDR value of AISI 304-IS 513 CR2 (2.07) TWBs was found to be 5.3% higher than that of AISI 304-IS 513 CR3 (1.96) TWBs. It is evident from the LDR results that the fatigue limit of tailor welded blanks was lesser than that of parent materials. It can also be inferred that different materials in TWBs achieved different heights in the formed cup based on the variations in their strengths. The obtained LDR values and depth of the formed cups of the TWBs are compared in Table 5.

**Table 5. Experimental LDR and cup height of parent and TWBs**

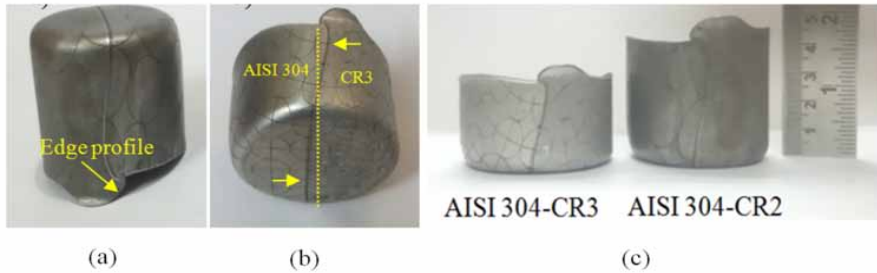
TWBs	LDR	Max. Height (mm)
AISI 304- IS 513 CR2	2.07	49.2
AISI 304- IS 513 CR3	1.96	33.1

During the forming of AISI 304-IS 513 CR3 TWBs the weaker IS 513 CR3 sheet attained a height of 33.1 mm and the stronger AISI 304 sheet attained a height of 27.5 mm. Similarly for AISI 304-IS 513 CR3 TWBs, the weaker IS 513 CR2 sheet reached a height of 49.2 mm and AISI 304 sheet reached a height of 45.5 mm. The reason for this difference in height is that the weaker IS 513 CR2 and IS 513 CR3 sheets easily flows into the die cavity as compared to the stronger AISI 304 sheet.

## WELD LINE MOVEMENT AND EDGE PROFILE IN TWBS

Two dissimilarities such as weld line movement (WLM) and edge profiles were observed on the fully drawn cups of the TWBs which were not evident during the forming of parent materials. The weld line follows a curvilinear path on forming of TWBs. During forming, the weld line shifts towards the stronger material (AISI 304) at the bottom of the cup and towards the weaker materials (IS 513 CR2 or IS 513 CR3) on the wall region of the cup. The stronger material offers higher resistance to the applied punch force which in turn supplies an additional pulling force on the weaker side of the cup formed using TWBs. Consequently the WLM reached a maximum on the weaker side of TWB. The shift in the weld line towards the weaker side contributes to an additional tangential compressive force leading to non-uniform deformation. This, 'edge profile' formed on the cup as shown in Figure 3(a-b) for both combinations. Figure 3(c) shows successfully drawn cups. Due to the presence of symmetry only one half of the welded line profile is shown. The shift in the weld line was observed to be maximum near the flange and bottom regions of the cup. Maximum weld line movement observed from AISI 304 steel towards IS 513 CR3 steel was 6.6 mm and IS 513 CR2 steel was 5.2 mm on wall region of the cup. This is due to a higher material flow on these sides. At the bottom region of the cup, only slight movement is weld line was observed towards AISI 304 from IS 513 CR3 (3.4 mm) and IS 513 CR2 (2.5 mm) materials.

Figure 3. a) Edge profile in AISI 304-CR2 b) Weld line movement in AISI 304-CR3 c) Drawn cups from TWB



The ratio of maximum to a minimum height of the fully drawn cups of TWBs and individual stronger and weaker sheets are shown in Table 6. Figure 4(a) compares the waviness of the heights measured on the strong and weak materials with respect to their distance from the weld position. The WLM of the formed TWBs is shown in Figure 4(b). It can be observed that the weaker materials have a larger variation in height as compared to the stronger material during the forming of TWBs despite the application of the same punch force in both the cases.

Figure 4. a) Comparison experimental cup heights with respect to weld line b) Weld line movement

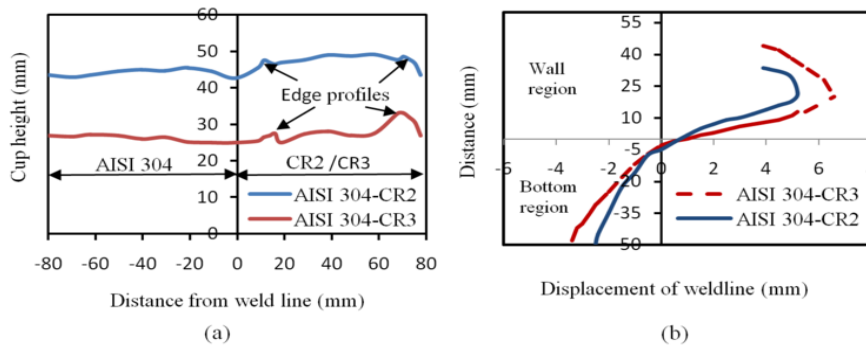


Table 6. Ratio of maximum to minimum cup height

TWBs	AISI 304-IS 513 CR2			AISI 304- IS 513 CR3		
Materials Measured	AISI 304	IS513 CR2	TWB	AISI 304	IS513 CR3	TWB
Ratio of Maximum to minimum height (%)	6.6	12.86	13.3	12.7	24.5	27.5

In order to compare the outer profile of the flange for stronger (AISI 304) and weaker materials (IS 513 CR2/IS513 CR3) with respect to cup center, flange drawn cups were formed from the prepared TWBs steel sheets. It was observed that during the forming the flow of material into the cup is not consistent on both sides of the welding. Due to the non-uniform flow of material neck formation takes

place in the weldment. In addition to that, the stronger side (AISI 304) of the TWBs is 3.5 mm and 3.8 mm less drawn compared with the weaker materials IS 513 CR2 and IS 513 CR3 respectively at right angles to weld due to the difference in strengths.

## FORMABILITY MEASURE OF TWBS RELATING TO STRENGTH RATIO

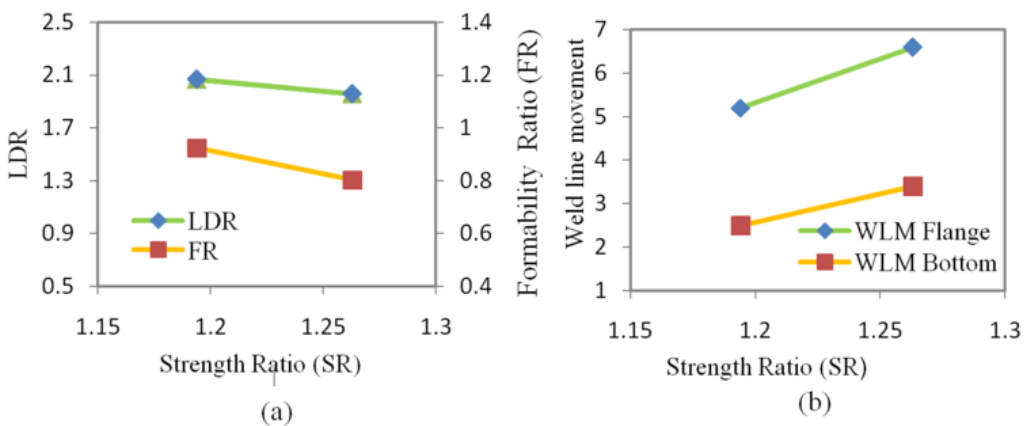
Owing to the variations in the developed stress and strain, it is difficult to evaluate the formability of TWB under the deep drawing and stretch forming process. As a result, the formability of the TWBs was evaluated with the help of formability ratio (FR) and strength ratio (SR). The SR and FR are defined as per the equations (5.1) and (5.2),

$$\text{Strength Ratio} = \frac{(\text{UTS} \times \text{Thickness})_{\text{strong}}}{(\text{UTS} \times \text{Thickness})_{\text{weak}}} \quad (5.1)$$

$$\text{Formability Ratio} = \frac{\text{LDR of TWB}}{\text{LDR of higher ductile material}} \quad (5.2)$$

It can be observed from Figure 5(a) that the LDR and FR values of TWBs increase from 1.96 to 2.07 and from 0.803 to 0.924 respectively while SR decreased from 1.263 (AISI 304-CR3) to 1.194 (AISI 304-CR2). Hence it can be concluded that the FR and LDR are inversely proportional to SR. In addition, it also affects the WLM of the cups formed from TWBs. Figure 5(b) shows the influence of strength ratio on the WLM of the individual materials of tailor welded blanks. At higher SRs the WLM is more. Due to the strain localization along the weaker side (IS 513 CR2/IS 513 CR3) the soft zone consistently exhibited a fracture. Since the differences in strength of the materials are high, the flow of low strength material is higher at the bottom of the cup allowing for a larger WLM towards the weaker side of the cup flange.

Figure 5. a) Influence of strength ratio on formability b) Influence of strength ratio on weld line movement



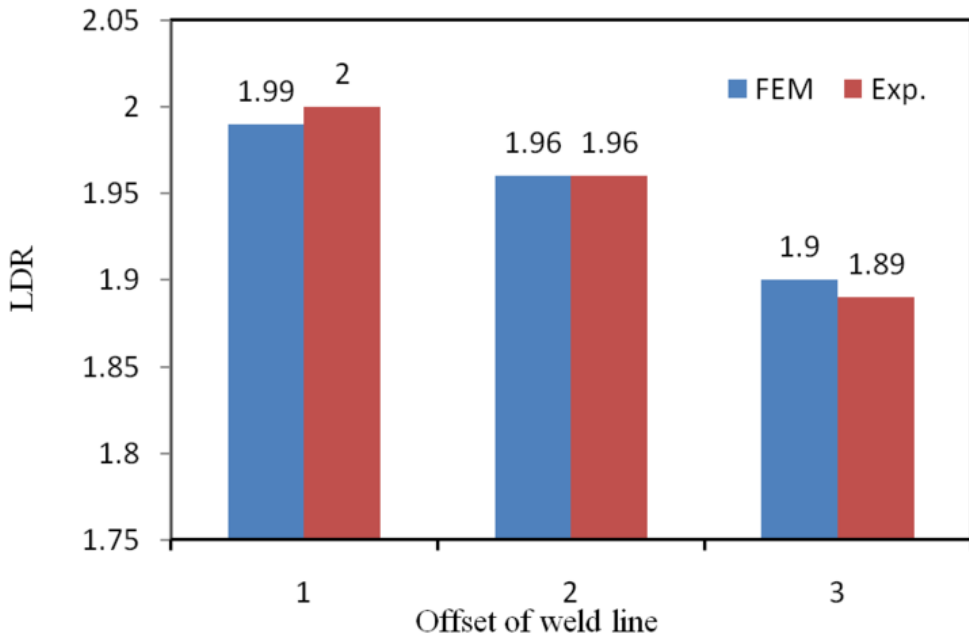


In the present study, the FR value of AISI 304-CR3 was 0.803 which is 13% lower than the FR value of AISI 304-CR2. This is due to the existence of high SR value between the materials. However, the formability of the TWB cups can be improved by shifting the position of the weld. Finite element simulation was done to identify the best position of weld for achieving higher LDR. During the FE simulations, the weld line shifted towards left (AISI 304) and right side (IS 513 CR3) at 12 mm, 24 mm and 36 mm away from the centre line of the TWB.

## FORMING ENHANCEMENT OF TWB THROUGH OFFSET WELD

The finite element simulation results predicted a slight improvement in the formability of AISI 304-CR3 steel sheets with a shift of 24 mm in the weld line towards the material with higher tensile strength (IS 513 CR3). This is indicated in Figure 6. The positions 1 and 3 shows the weld line offset towards the left and right-hand side to the blank center and position 2 shows the weld line at the center.

Figure 6. Comparison of LDR for AISI 304-CR3 with different weld position



For experimental validation of FE simulation results towards the improvement of formability, the TWBs (AISI 304-CR3) were prepared with diameters of 92 and 94 mm keeping the weld line 24 mm to the left of the centerline (position 1). The experimental result showed that blank with a diameter of 92 mm was successfully drawn with increased LDR of 2. But the blank with a diameter of 94 mm confirms that the fracture occurs near the weld in the weaker IS 513 CR3 side Figure 7(a). Figure 7(b) shows the successful prediction of the fracture locations by finite element analysis for the above experimental conditions. Figure 8(a-b) shows the finite element simulations of failure zones of TWBs for center weld positions. Similar to microstructural studies, excessive stress regions within the weaker materials causing the failure of formed cups were seen in the finite element analysis too.

The failure locations identified under experimental conditions were more or less similar to finite element simulations.

The fractured surfaces of the TWB cups were sectioned and examined by SEM. Figure 9 (a-c) shows the SEM images of the tailor welded blanks after forming. The tempered martensite present within the soft zone of the weld was found to be the most predominant factor affecting the fatigue life and joint strength at this region. Owing to the localization of strain along the weaker side (IS 513 CR2/IS 513 CR3) the soft zone consistently exhibited a fracture. The same results were observed by Bandyopadhyay et al. (2017) during the formability of laser welded dual phase steel sheets.

Figure 7. Excessive stress identification a) Wall region of offset weld of TWBs- Experiment b) Wall region of offset weld of TWBs- FEA

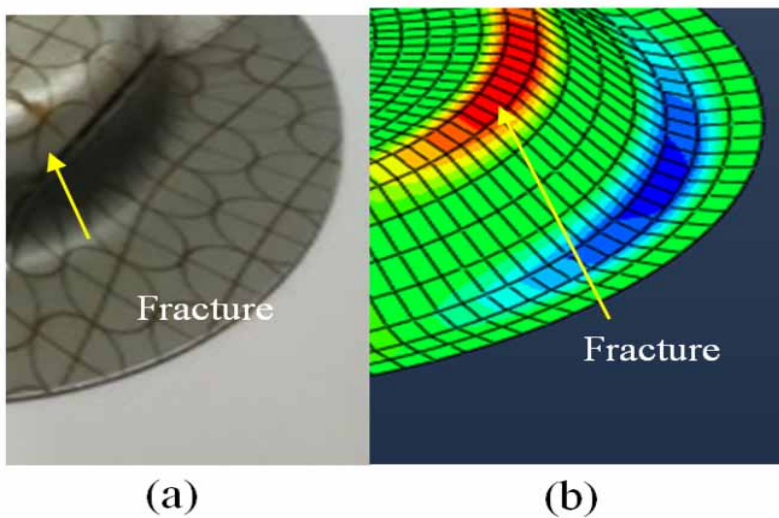


Figure 8. Excessive stress identification a) Soft zone of IS 513 CR2-FEA b) Soft zone of IS 513 CR3-FEA

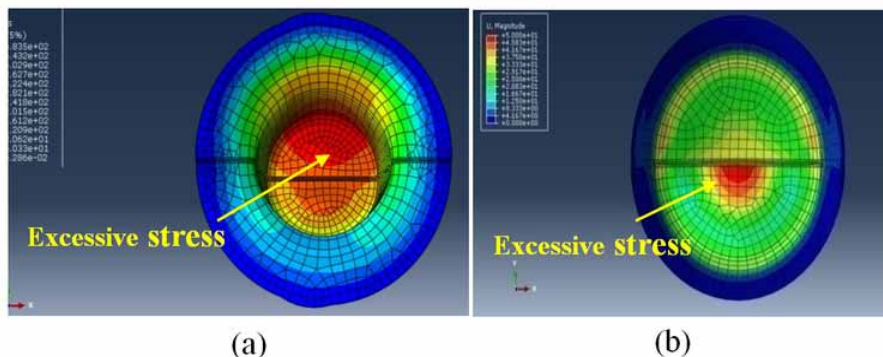
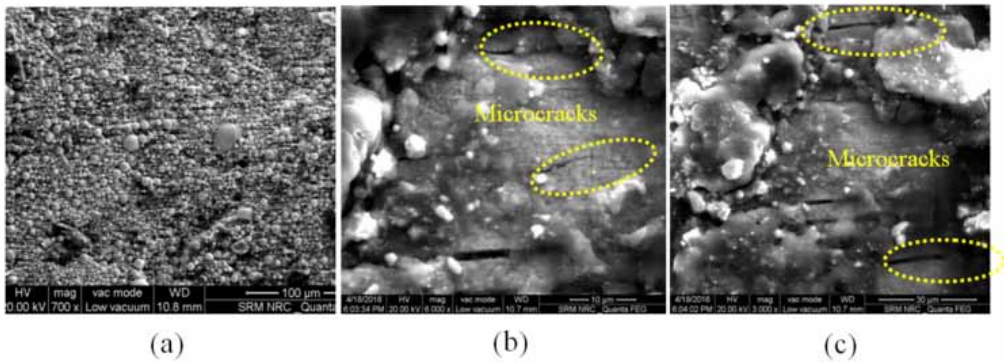


Figure 9. SEM images a) Hard zone of AISI 304b) Soft zone of CR2 c) Soft zone of CR3



## CONCLUSION

Tailor Welded Blanks were prepared using laser butt welding of AISI 304 & IS 513 CR2 and AISI 304 & IS 513 CR3 steel sheets. Being the unique materials the fabricated TWBs were subjected to formability studies as they have several forming applications owing to their locally different properties. The nature of the fracture surfaces of the formed steel sheets and TWBs were studied using SEM. Apart from process characterization by experimental study, the formability characteristics of the tailor welded sheets were predicted using analytical studies and finite element analysis using ABAQUS (Version V 6.12.1). The predicted results were then validated with experimental results. On the basis of the obtained results it can be concluded that,

- § The LDR value of AISI 304– IS 513 CR2 tailor welded blank was found as 2.07, which is 5.3% higher than that of AISI 304– IS 513 CR3 (1.96).
- § The maximum cup height of fully drawn cups with regard to minimum cup height for AISI 304- IS 513 CR3 was observed as 27.5%. However, this ratio was higher (24.5%) for weaker material (IS 513 CR3) when compared with stronger material AISI 304 (12.7%). Similarly, the ratio was observed as 13.3% for AISI 304- IS 513 CR2, out of which weaker material (IS 513 CR2) contributes 12.86% and stronger material (AISI 304) contribute only 6.6%.
- § During the forming of TWBs, the weld line moved 2.5 mm (AISI 304- IS 513 CR2) and 3.4 mm (AISI 304- IS 513 CR3) towards the stronger material (AISI 304) at the bottom of the cup and 5.2 mm (AISI 304- IS 513 CR2) and 6.6 mm (AISI 304- IS 513 CR3) towards the weaker materials (IS513 CR2/ IS 513 CR3) on the wall region of the cup.
- § An increase in the LDR from 1.96 to 2.07 and formability ratio (FR) from 0.803 to 0.924 were observed in TWBs AISI 304- IS 513 CR3 and AISI 304- IS 513 CR2 respectively while the strength ratio decreased from 1.263 to 1.194. It can be concluded that the formability of TWBs increases with a decrease in SR.
- § During the forming of the TWBs, the non-uniform material transfer leads to the non-uniform flange profile.
- § The stronger side (AISI 304) of the TWBs was 3.5 mm less drawn as compared with the weaker IS 513 CR2 and 3.8 mm less drawn than the weaker IS 513 CR3 steel sheets due to the difference in the strengths.
- § Owing to the localization of strain along the weaker side (IS 513 CR2/IS 513 CR3) the soft zone consistently exhibited a fracture. The SEM images reveal the development of microcracks on the surfaces of the soft zones of weaker materials.

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Publisher has waived the Open Access publishing fee.

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