An Experimental and Numerical Investigation of Press Force and Weld Line Displacement of Tailor Welded Blanks in Conventional and Rubber Pad Sheet Metal Forming

Amir Ansari, Ehsan Shahrjerdi, and Ehsan Amini

Abstract—To investigate the behavior of sheet metals during forming tailor welded blanks (TWB) of various thickness made via Co_2 Laser welding are under consideration. These blanks are formed used two different forming methods of rubber as well as the conventional punch and die methods. The main research objective is the effects of using a rubber die instead of a solid one the displacement of the weld line and the press force needed for forming. Specimens with thicknesses of 0.5, 0.6, 0.8 and 1mm are subjected to Erichsen two dimensional tests and the resulted force for each case are compared. This is followed by a theoretical and numerical study of press force and weld line displacement. It is concluded that using rubber pad forming (RPF) causes a reduction in weld line displacement and an increase in the press force.

Keywords—Rubber pad forming, Tailor welded blank, Thickness ratio, Weld line displacement.

I. INTRODUCTION

SHEET metal forming has a very important role in the manufacturing of complex automotive and other sheet metal components in a manner which minimizes waste material and energy utilization and permits the designer to use the intrinsic properties of the material [1].

Rubber pad forming (RPF) is a novel method for sheet metal forming that has been increasingly used for: automotive, energy, electronic and aeronautic applications [2].

Compared with the conventional forming processes, this method only requires one rigid die, according to the shape of the part, and the other tool is replaced by a rubber pad. This method can greatly improve the formability of the blank because the contact surface between the rigid die and the rubber pad is flexible. By this way the rubber pad forming enables the production of sheet metal parts with complex contours and bends [2].

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The automotive and aeronautic industries are working continually to develop and apply technology that reduces the cost and weight of their products, thus minimizing the energy consumption and environmental impact of future products. Vehicle and aircraft weight reduction through the use of advanced materials and manufacturing methods is of interest to all major manufacturers [3].

Automotive engineers have also been successful in reducing weight, part counts, and cost and in streamlining the assembly process through the use of steel tailor welded blanks (TWBs) to replace multiple blanks that have to be stamped separately and then assembled [3].

A tailor welded blank (TWB) is composed of more than two materials with similar or different strengths or thicknesses joined together to form a single part before the forming operation. The main advantage of using a TWB is that gives thicker or stronger materials at critical parts of the sheet metal blank so as to increase the local stiffness [4].

Review of the literature suggests that although some studies have been done on formability of aluminum TWBs, most prior formability studies have considered steel tailor welded blanks. In contrast to aluminum TWBs, the weld and heat affected zone (HAZ) in steel tailor welded blanks are significantly stronger than the base material (in one study the welds and their HAZs were approximately twice as hard as the parent metal). Therefore, under common forming operations, it is reasonable to expect that steel TWBs will behave significantly differently from tailor welded blanks made of aluminum alloys. Although recent simulation and experimental study has clearly shown that aluminum alloy tailor welded blanks can be successfully deep drawn.

6XXX series of wrought aluminum alloys are widely used for automotive and aerospace structural applications due to their good extrudability, weldability, and excellent corrosion resistance. Aluminum 6061 is a typical alloy of this series that is used for applications such as canoes, railroad cars, towers, pipelines, and other medium strength structures where good weldability, good formability and excellent corrosion resistance are needed [5].

Precipitation-treatable alloys, when peak is aged (T6 temper), have an optimum distribution of precipitates that ensures the greatest strength for the material [6].

Thus 6061-T6 Al alloy has superior mechanical properties such as a high strength/weight ratio, good corrosion resistance, excellent weldability and deformability, it is considered for use in many advanced applications [7].

In order to achieve the maximum forming performance of TWBs, a variety of experimental studies and finite element analyses (FEA) was carried out to determine mechanical properties of the TWBs, as well as their formability, press force, weld line displacement in different material such as stainless steel and aluminum.

Despite TWBs' numerous benefits, forming TWBs is challenging due to significant reduction of formability and change in forming properties associated with this type of blank in difference forming process. Some important factors which influence the potential formability of the TWBs are: material property changes in the weld and the heat-affected zones, non-uniform deformation because of the differences in thickness, forming process, properties and/or surface characteristics and location and orientation of the weld with respect to the direction of application of load.

Different forming behavior and properties of TWBs in rubber pad forming (RPF) relative to conventional punch and die methods are expected to friction factor difference between die-blank and rubber-blank in addition to energy consuming for blank forming excessive energy consuming for rubber forming in RPF is considered. In this method, not only the blank, but also the soft tool has to be deformed. Therefore, in this study, properties such as press force and weld line displacement of AL 6061-T6 TWBs in rubber pad forming is researched.

II. EXPRIMENTAL WORK

A. Tensile properties

True Stress-Strain curve of 6061 Al alloy with the composition of Mg 0.84, Si 0.64, Zn 0.02, Cu 0.18, Cr 0.058, Fe 0.15, Ti 0.016, Mn 0.014, with the balance Al (all in mass pct) after heat treatment received in the aged T6 Temper (6061-T6) [7] obtained as per ASTM standard E8M specification shown in Fig.1 and The mechanical properties 0.2% yield strength (YS), ultimate tensile strength (UTS), % elongation and Young of the Al sheets are given in Table I.
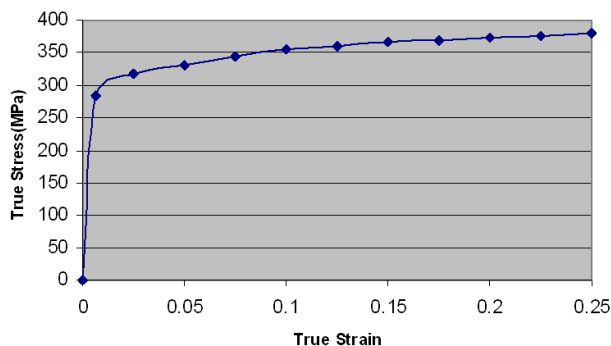
TABLE I
MECHANICAL PROPERTIES

Mechanical Properties	
density	2700 Kg/cm3
tensile strength, ultimate	310 MPa
tensile strength yield	276 MPa
young modulus	69 GPa
shear modulus	26 GPa
elongation at break	25%
poisson ratio	0.33

TABLE II
LASER WELDING CONDITIONS

Laser welding Conditions	
laser source	CO_2
beam power	3 KW
welding speed	1.5 m/min
argon gas flow rate	20 l/min
beam distance	6 m

B. Welding of specimens and TWB preparation

The quality of the weld in a TWB is critical for a successful forming operation. Although tailor welded blanks have been made using different types of welding techniques, the most common method currently in use is laser beam butt welding. With low divergence, laser beam can travel large distances without significant loss of beam quality or energy and can be focused to a very small spot resulting in very high power density. This energy can cause melting of the interfaces to be joined and not the surrounding area. Laser beam butt welding is a full-penetration fusion welding process that results in a high depth-to-width ratio and therefore generally produces a narrow weld seam [1].

With the use of the laser welding process, which creates a narrow weld and heat-affected zone (HAZ) at the junction of the dissimilar sheets, residual stresses and other welding defects can be introduced into a material [8,9].

But review of the literature suggests that although some studies have been done on formability of aluminum TWBs, most prior formability studies have considered steel TWBs. In contrast to aluminum TWBs, the weld and heat affected zone (HAZ) in steel TWBs are significantly stronger than the base material (in one study the welds and their HAZs were approximately twice as hard as the parent metal). Therefore, under common forming operations, it is reasonable to expect that steel TWBs will behave significantly differently from TWBs made of aluminum alloys [10].

There are also reports suggesting that the formability of the laser welds in TWBs is related to weld width and weld hardness. Weld width depends on heat input in the welding process and the hardness of weld/HAZ is mainly controlled by the composition of the base metal.

Although according to Shakeri et al. [10] the presence of defects in the welding techniques like non-vacuum electron beam (NVEB) specimens was much more pronounced than that in laser specimens and differences in welding conditions have produced only a marginal effect on formability of laser-welded TWBs [10].

Fig. 1 True Stress-Strain curve of 6061 Al alloy in axial tensile test

Based on the result of the Shakeri et al. [10] investigation, welding defects dominate when the weld line and loading direction are parallel. When the loading axis is perpendicular to weld line, other parameters including the thickness ratio, amount of reinforcement at the top and/or bottom of the weld and presence or absence of superficial defects such as undercuts also play an important role on overall properties. Therefore for aluminum tailor welded blanks the laser welded specimens exhibit better performance in the absence of weld failure than other welding techniques.

Because of aluminum`s high reflectivity, effective coupling of the laser beam and aluminum requires a relatively high power density.

As result of Weston et al. [11] and S.K. Panda et al. [1] researches 3 kW Co_2 laser beam is used for this study and the laser welding conditions are shown in table II.

To ensure of the effect of thickness ratio in two welded sheets in TWBs, laser butt welded blanks with four thickness combination as shown in table III were made. The blanks were cut circular with the diameter of 120mm from the laser welded specimen and the weld bead position was located at the centerline of the blanks in the point of punch force.

To avoid the effect of sharp edges on the fatigue strength and stress concentration, the gauge area of all the specimens was slightly smoothed out by hand polishing with a 084 fine (#400) emery paper.

TABLE III
THICKNESS COMBINATION AND THICKNESS RATIO OF TWBS

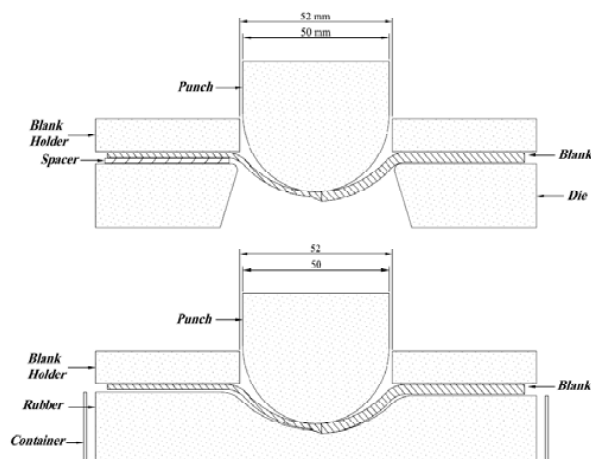| Thickness Combination (mm)	Thickness Ratio
0.5 mm-0.5 mm	1
0.5 mm-0.6 mm	1.2
0.5 mm-0.8 mm	1.6
0.5 mm-1 mm	2

Fig. 2 Schematic diagram of the tools used in the conventional punch and die and rubber pad forming experiments and simulations

C.Limiting dome height test (LDH)

The biaxial stretch forming tests were done according to the ASTM E643 using a spherical punch of 50 mm diameter on a double action hydraulic press. The schematic diagrams of the tools arrangement used in the experiments in the conventional punch and die and rubber pad forming is shown in Fig. 2.

In this study, did not install drawbead at the blank holder in conventional punch-die forming to unite the tests conditions because no needs to use drawbead in rubber pad forming.

In the case of conventional forming, specimens were placed on the lower die such that weld line was at the middle of the die opening and in the other case (RPF); specimens were placed on the rubber that was in the container such that weld line was at the middle of the punch. Since the specimens' diameter is smaller than the blank holder diameter, it ensures complete clamping of the blank at the blank holder and hence samples were subjected to biaxial tensile stresses.

Urethane is usually used in practice due to its special properties like good wear resistance, oil and solvent inertness, thermal stability and very high load-bearing capacity [12]. The polyurethane chosen in our research is most frequently used in rubber pad forming processes. According to manufacturer catalogue, compression stress-strain curve and the properties of this type of polyurethane are shown in Fig. 3 and table IV. The rubber was placed in container and there was 10mm clearance between rubber and container.
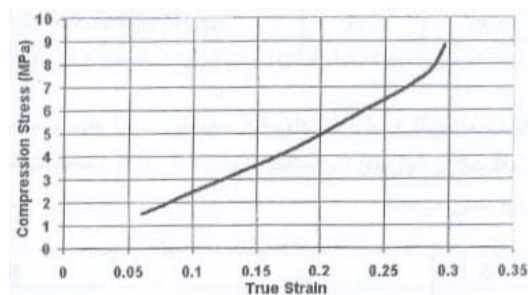

Fig. 3 Compression stress-strain curve of polyurethane produced by manufacturer

TABLE IV
MECHANICAL PROPERTIES OF THE POLYURETHANE

Properties	
density	1250 Kg/m^3
hardness	90 shore A
maximum deformation	30%
maximum working temperature	$50^{o}c$
young modulus	27.3 MPa
poisson ratio	0.475

This table's data were gathered according to manufacturer's catalogue based on ASTM rubber tests.

There exists a gap between the die and the thinner part of the TWB due to the thickness difference in the TWB in the conventional forming case. In order to compensate this gap, an aluminum 6061 sheet of the same thickness as the gap was inserted between the die and the thinner part of TWB. This

arrangement balanced the forces on the TWB during blank-holding and yielded smoother material flow in the forming operation [4].

A punch speed of 2mm/min was used for the LDH experiments and no lubricant was used to reduce the friction. Specimens were either tested to failure or were unloaded at predetermined dome heights prior to necking. Specimens of different TWBs in both cases (conventional and rubber pad forming) were tested to failure or interrupted prior to failure, selected specimens sectioned and examined by optical microscope.

III. Finite element analysis

Simulation of conventional and rubber pad forming of tailor welded blanks was done by using a commercially available finite element code ABAQUS (an explicit dynamic FE solver which is used to solve dynamic, non-linear large deformation events and processes including quasi-static sheet metal forming problems). Material and geometrical non-linearities can be handled well in this software.

In the finite element models, in the case of conventional forming, the TWB, the blank holder, the spacer, the die and the punch and in the case of rubber pad forming rubber and container instead the die were formed the main components. In the model definition in ABAQUS, the die, blank holder, container, spacer and punch were defined by rigid surfaces. The sheet and rubber were represented by a deformable mesh. C3D8R elements with fine mesh with ABAQUS's tutorial recommendation were used to mesh the tailor welded blank. C3D8R is 8-node linear brick, reduced integration with hourglass control element. Due to the asymmetry of the tailor welded blank, the whole components were modeled.

Results of Raymond et al. [9] investigation that is an examination of the effects of weld modeling techniques on the results of FE simulations of TWB forming operations, indicate that there are a number of relatively subtle effects associated with the manner in which the weld is modeled. Most of these effects relate to the constraining effect of the weld line with respect to strain along the axis of the weld line. Based on these results in FE model, modeling the weld prevents approximately 10 percent error in weld line displacement and punch travel at failure.

Zhao et al. [13] were presented various finite element models for TWB including weld and HAZ. Based on this research, HAZ can be neglected safely in real applications when blank size is large enough compared to the size of HAZ. Because shell element modeling of TWB has the advantage of much less computing time and fairly good accuracy compared to 3-D solid element, Zhao et al. were used shell element with weld line modeling. But in this investigation, to prevent any error result in shell element, was used 3-D element to mesh the each blank and weld geometry.

The simulation begins with the die in contact with the blank. The punch then moves down in Z direction with a velocity of 2mm/min to form the blank in each case. The interface between the die and the blank, and between the blank and the punch and between blank and rubber are modeled using an automatic surface to surface contact algorithm.

IV. Results and discussion

A. Weld line Displacement

Fig. 4 shows the numerical and Fig. 5 shows experimental weld line displacements in conventional and rubber pad forming of tailor welded blanks forming for each thickness combination. The thickness ratio 1 is a non tailor welded blank without weld and no movement in center of this blank is expected. Fig. 6 shows the difference of weld line movements between experimental and analytical results for each thickness ratio according to table III in both conventional and rubber pad forming. Every case shows that the weld line moves to the thicker parts of TWB which can be explained with different strength and formability and every thickness combination shows that this movement is smaller in rubber pad forming than conventional method and weld line movement difference between rubber pad forming and conventional methods increased as the difference of thickness increased. It seems that area contact in rubber pad forming more than conventional and friction coefficent difference between blank-rubber friction coefficent and blank-die, increase the restraining force and as a result the weld line movement is reduced.

It is shown that the forming method had a reduction effect of weld line movement therefore weld line displacements can be controlled by rubber pad forming.

In Fig. 6 the tendency of the analytical results was in good agreement with experiment but the amount of movements were overestimated.

Heo et al. [14,15] investigations on effect of drawbead and its dimensions on weld line movement at steel tailor welded blank show that the weld line movement is smaller when drawbeads were presented and the weld line movement decreases as the size and the hight of the drawbead increase. Fig. 7 shows that weld line movement decrease in existence of drawbead. In Fig. 7 "L" is the initial of the weld line from the center of the blank.
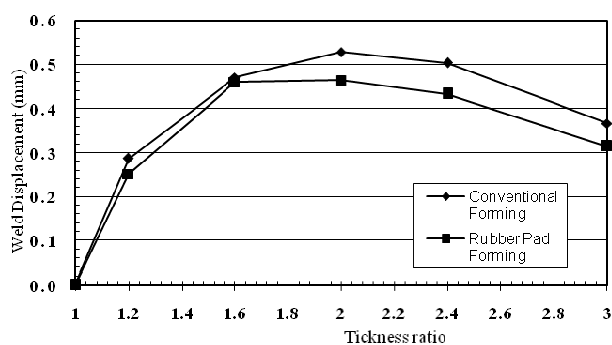

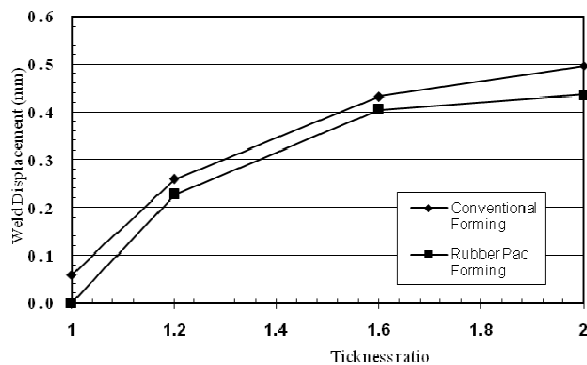Fig. 4 Weld displacements at failure of difference thickness ratio in numerical results

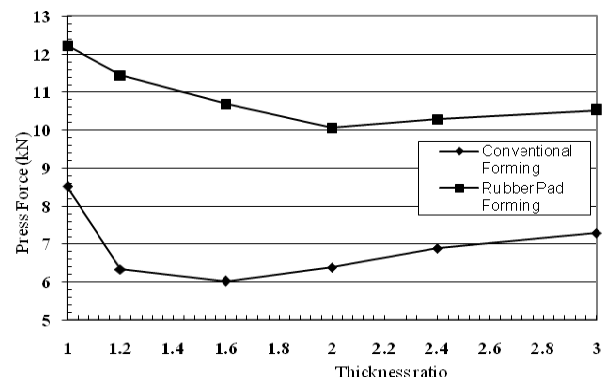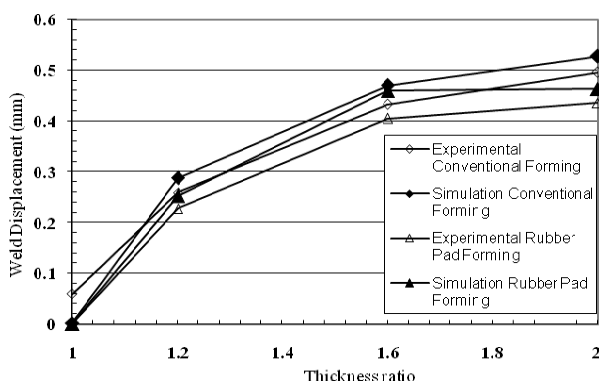Fig. 5 Experimental weld displacements at failure of difference thickness ratio

Fig 6. Weld line movements between experimental and analytical results in both conventional and rubber pad forming
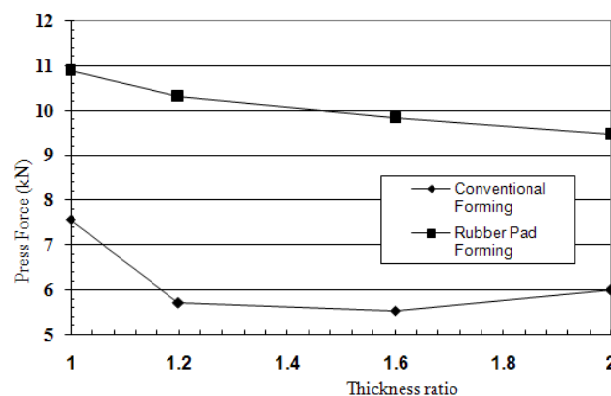

Fig. 7 Comparison of weld line movement of existence of drawbead in Heo et al. investigation [14]

Fig. 8 Press force at failure of difference thickness ratio in numerical results

Fig. 9 Experimental press force at failure of difference thickness ratio

Fig 10. Press force between experimental and analytical results in both conventional and rubber pad forming

B. Press Force

Fig. 8 shows the numerical and Fig. 9 shows experimental maximum forming force in conventional and rubber pad forming of tailor welded blanks for each thickness ratio.

Increasing the restraning force in rubber pad forming and because amount of energy, moreover blank forming energy, for rubber forming is Needed, more maximum force for an ordinary blank forming to failure in rubber pad forming
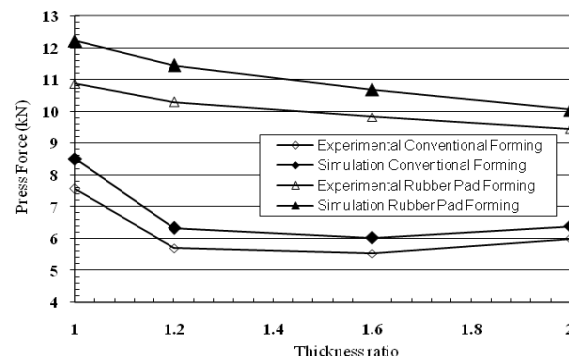
relative to conventional methods is needed as shown in Fig. 8 and Fig. 9. In this study, the maximum press force in conventional forming was approximately 7.6 kN and this amount is 10.9 kN at a non tailor welded blank in rubber pad forming therefore 3.3 kN force was consumed for rubber pad forming. So the maximum press force to failure is smaller in conventional forming methods.

Numerical and experimental results shown that the

maximum forming force to failure in a tailor welded blank relative to an ordinary blank is reduced. This reduction is cuased by stress concentration in joint of two blanks in a tailor welded blank due to transiguration and reduction of TWB formability relative to ordinary blanks. Because energy consuming increased in order to increasing the ticker part thickness in tailor welded blank forming, the maximum press force to failure increased as the difference of thickness increased but the forming force difference between rubber pad forming and conventional method is reduced in thickness ratio increasing.

Fig. 10 shows the difference of weld line movements between experimental and analytical results for each thickness ratio according to table III in both conventional and rubber pad forming.

V. CONCLUSION

In this paper, the weld line displacement and press force of tailor welded blank in two forming method, conventional die and punch forming and rubber pad forming was investigated theoretically and experimentally. Four thickness combinations in experimental work and difference thickness ratio in numerical analysis of aluminum 6061-T6 tailored welded blanks were used. From the study, the following are concluded:

1) The weld line movement of a TWB is smaller in rubber pad forming than conventional method in each thickness combination.
2) Weld line movement difference between rubber pad forming and conventional methods increased as the difference of thickness increased. Therefore forming method had an effect of weld line movement in tailor welded blanks.
3) Weld line displacements can be controlled by forming methods like rubber pad forming.
4) The maximum forming force to failure in a tailor welded blank is smaller than this forming force in ordinary blank and the forming force difference between rubber pad forming and conventional method is reduced in thickness ratio increasing.

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