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An Experimental and Numerical Investigation of Formability of Tailor Welded Blanks in Conventional and Rubber Pad Sheet Metal Forming

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ABSTRACT— *In order to investigate behavior of sheet metals in forming, tailor welded blanks with different thickness is produced by Co2 laser welding were investigated. These blanks have been formed by two different methods of rubber pad forming and mandrel and matrix forming. The main purpose of this research is to investigate the effect of using rubber instead of matrix at tailor welded blank formability. Dome height test is done on the specimens with the thickness of 0.5, 0.6, 0.8 and 1 millimeter and result Formability for each case are compared. This is followed by a numerical and experimental study of formability. It is concluded that using rubber pad forming (RPF) causes a reduction in formability.*

Keywords— Tailor welded blank, Rubber pad forming, Formability, Press force

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1. INTRODUCTION

Sheet metal forming has a very important role in manufacturing complex automobile parts and other metal parts by minimizing the waste material and energy consumption and lets the designer use intrinsic properties of material. [1]

Rubber pad forming is a modern method for sheet metal forming is used in automotive, energy, electronics and space industries.

In the Compare with the mandrel and matrix forming process this method, based on shape of the part, only needs a rigid die and other tools are replaced by a rubber pad. This method can highly affect the formability of the blank because the contact surface between the rigid die and rubber pad is flexible. Thus rubber pad forming facilitates manufacture of sheet metal parts with complex bends and shapes. [2]

Aerospace and automotive industries always do activities to develop and use technology of products expense and weight reduction and according to reduction of energy use and environmental effects. Reduction weight of aircraft and vehicle by the use of advanced materials and manufacturing methods are noticed by all the manufacturers.

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]

Tailor welded blanks are consist of over two materials with similar or different strength and thickness joined together to form a single part before forming. The main advantage of using a tailor welded blank is that gives thicker or stronger materials at critical parts of the sheet metal blank so much increase the local stiffness. [4]

In the earlier papers the tailor welded blanks formability was compared with the conventional sheet metal forming methods and also some particular manufacturing methods like hydroforming, except rubber pad forming. There is no investigation about effect of rubber pad forming in formability of tailor welded blanks.

Review of the literature suggests that although some studies have been done on formability of aluminum tailor welded blanks, most prior formability studies have considered steel tailor welded blanks. In contrast to aluminum tailor welded blanks, 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 steel tailor welded blanks will behave significantly differently from tailor welded blanks is 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]. The lightness, strength, weldability, and corrosion resistance of the 6061-T6 alloy makes ideal it for heavy duty structures in marine applications.

Precipitation-treatable alloys, when peak 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 get the more efficiency of tailor welded blanks forming, various finite element analysis and experimental studies have been performed to specify mechanical properties of tailor welded blanks like formability, press force, weld line displacement in different materials like aluminum and stainless steel.

Though the tailor welded blanks have many advantages, but tailor welded blanks forming causes a significant reduction of formability and changes forming properties concerning the type of blank in different forming methods. Some of the important factors affecting the formability of this type of blank are material property changes in the weld and the heat-affected zone, non-uniform deformation because of the differences in thickness, forming process and properties and/or surface characteristics and location and orientation of the weld line 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.

2. TENSILE PROPERTIES

The aluminum alloy 6061 is composed of 97.5% aluminum, 1.0 % magnesium, 0.6 % silicon, 0.34 % iron, 0.3 % copper, 0.2 % chromium, and around 0.04 % zinc and titanium by weight. The T6 hardening treatment varies by manufacturer but it usually involves a solution treatment at 810 K is followed by quenching in water and then aging for a few hours at around 450 K. The solution treatment leads to a homogeneous supersaturated solid solution. The quenching step is performed to take the supersaturated solution to a two-phase region of the phase diagram. In the aging step, the magnesium silicide (Mg_2 Si) phase is precipitated in such a way that the precipitate is evenly distributed inside the grains. There is also some precipitation of AlFeSi at the grain boundaries. The precipitates inside the grains impede dislocation motion and make the alloy harder.

The strain in the specimen was measured with an axial INSTRON extensometer (0.5 inches) is attached to the specimen gage section. Before the experiments, the gage section was polished with water based diamond slurry with particles down to 3 µm in size to reduce stress concentration.

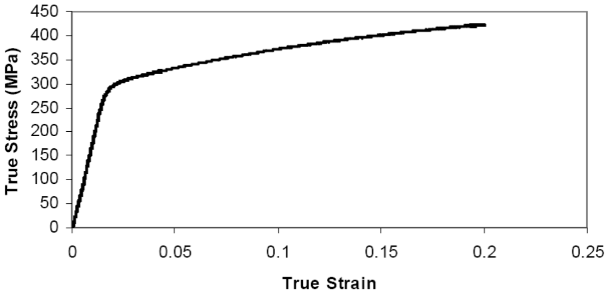

Figure 1: The true-stress true-strain behavior of 6061-T6 as determined by uniaxial tension test

True Stress-Strain curve of Al 6061-T6 is obtained from an INSTRON universal tension machine with load capacity 20 kN and deformation rate 2 mm/minute was employed in tension testing. Static tensile properties of Al-6061 were measured on the standard round-ended, miniature dog-bone tensile specimens as per ASTM standard E8M specification are shown in Fig.1. The tensile specimens have a 35 mm gage length and a 5 mm diameter.

The mechanical properties 0.2% yield strength (YS), ultimate tensile strength (UTS), % elongation and Young of the Al sheets are given in Table 1.

Table 1: Al6061-T6 mechanical properties

Mechanical Property	
Density	2700 Kg/cm^3
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

3. 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.

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 [8].

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. [8] 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.

Based on the result of the Shakeri et al. 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.

Table 2: Laser properties

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

Table 3: Thickness combination and thickness ratio of TWB

Thickness combination	
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
0.5 mm-1.2 mm (Just for Simulation)	2.4
0.5 mm-1.5 mm (Just for Simulation)	3

As result of Weston et al. [9] and S.K. Panda et al. [1] researches 3 kW Co2 laser beam is used for this study and the laser welding conditions are shown in table 2.

To ensure of the effect of thickness ratio in two welded sheets in TWBs, laser butt welded blanks with different thickness combination as shown in table 3 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.

4. LIMITING DOME HEIGHT TEST (LDH)

The formability of sheet metal is dependent on many factor such as its properties, microstructure, thickness and external factors. To understand formability of sheet metal is essential to define formability. Formability is loosely defined as a sheet metals ability to be mechanically shaped by plastic deformation without machining. Sheet metal forming occurs when a sheet is clamped around the edge of a die and a punch forces the sheet (form) through a cavity where the sheet is stretched to conform to the shape of the tools. To measure the formability of a metal, standardized sheet forming processes are used. There are many types of sheet metal forming processes used to measure formability, two well used forming operations are (1) stretch forming e.g. hemispherical punch test, and (2) deep-drawing [10].

The hemispherical punch of 50 mm diameter (out-of-plane stretching) until fracture is a type of limiting dome height (LDH) stretch testing equipment that has a high degree of reproducibility when compared to other stretch forming tests. In this test, draw-beads are used to hold the steel sheet firmly in place to prevent drawing in during forming process. The resulting form of the sheet metal is a rounded dome shape. There are also many studies done using this test to determine the formability of metal [10].

The geometrical models and processing conditions for the tooling system (i.e. punch, die and blank-holder) and the specimen of TWB used in the experiments in the conventional punch and die and rubber pad forming were established with the arrangement are shown in Fig. 2. Because no needs to use drawbead in rubber pad forming, in this study, did not install drawbead at the blank holder in conventional punch-die forming to unite the tests conditions.

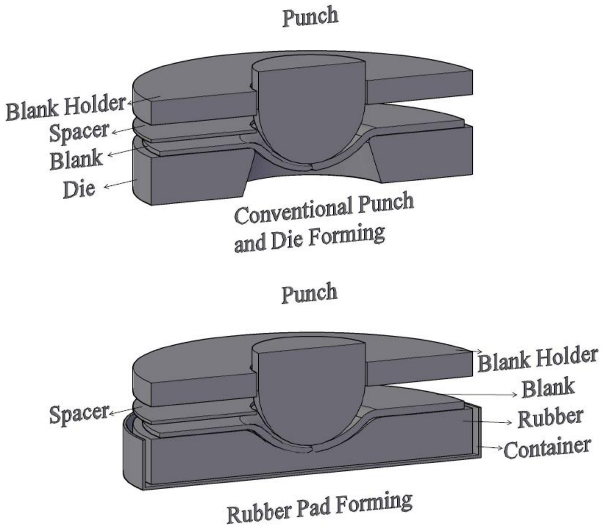

Figure 2: Schematic diagram of the tools used in the conventional punch and die and rubber pad forming experiments and simulations

In this study whether in the rubber pad forming or mandrel and matrix forming specimens are placed in the die in such a way that the weld line is along the geometrical center of punch. In order to completely observe the clamping process as seen in Fig. 2 in both forming methods the blank holder diameter is more than blank.

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 [11].

In this study a kind of polyurethane which is usually used in the rubber pad forming process has been chosen. Compression stress-strain curve and properties of this kind of polyurethane which has 90 shore A hardness has been indicated according to the manufacturer catalogue are shown in Fig. 3 and table 4. Thickness of this rubber is 30 millimeter and has a 10 millimeter distance from edge of the container.

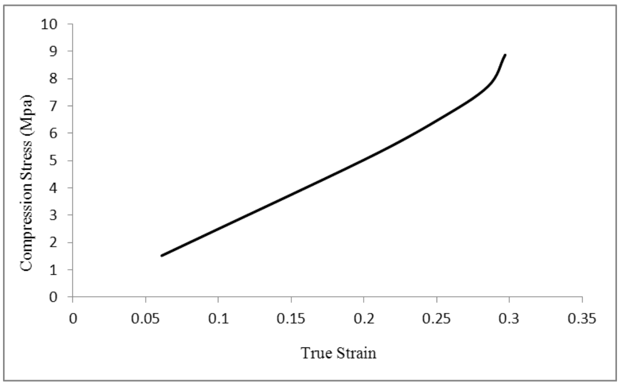

Figure 3: Compression stress-strain curve of polyurethane produced by manufacturer

Table 4: Mechanical properties of the polyurethane

Mechanical Property	
Density	1250 Kg/m3
Hardness	90 shore A
Maximum deformation	30%
Maximum working temperature	50oc
Young modulus	27.3 MPa
Poisson ratio	0.475

There exists a gap between the die and the thinner part of the tailor welded blank due to the thickness difference in the tailor welded blank 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 blank holder and the thinner part of tailor welded blank. This balanced the force on the tailor welded blank during blank holding and yielded smoother material flow in the forming operation [4].

To reduce the friction all the LDH experiments were conducted in dry condition at a punch speed of 2 mm per minute. The experiments were stopped when a visible neck or initiation of fracture was observed on the specimens. The dome height of the specimens was measured by a height gauge of least count of 0.02 mm. An optimum blank holding force in the range of 10–12 tonnes was applied on the upper die in all cases.

5. THE FINITE ELEMENT MODELS

The conventional and rubber pad forming of tailor welded blanks models were incorporated into 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) and validated against experimental data.

Results of Raymond et al. [12] 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 related 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.

So 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.

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.

6. RESULTS AND DISCUSSION

Limiting dome height tests were used to test the formability of the TWBs in conventional punch and die and rubber pad forming processes. In all cases, the failure of the TWBs was parallel to the weld line and perpendicular to the principal strain. It occurred at the thinner part of the TWBs. Generally, a thinner material resists a much smaller force than a thicker material. When the thinner material undergoes plastic deformation, the thicker one is still deforming in the elastic region. This implies that the thinner material has a lower strength in the rubber pad forming process just like conventional forming than the thicker material. This is why the TWBs fail at their thinner region, this result agreeing with the findings in [4].

Figure 4 shows the numerical and Fig. 5 shows experimental limiting dome hights 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 according to Raymond et al. [12] most punch traveling of this blank is expected.

A lower thickness ratio (smaller thickness difference of the TWB) will reduce the difference in formability between the welded materials. The materials on both sides of the weld share the plastic deformation if the materials have similar thicknesses. Therefore, a lower thickness ratio increases the formability of the TWB in rubber pad forming process just like conventional forming as shown in S. M. Chan et al. [4] investigations.

As shown in Fig. 4 and Fig. 5, in experimental and numerical investigations the AL 6061-T6 TWBs of all thickness ratios yield the higher LDH in conventional forming thus rubber pad forming process decreases formability of the AL 6061-T6 TWBs as about 5-10 percent in all thickness ratios.

Figure 6 shows the difference of limiting dome hight between experimental and analytical results for each thickness ratio according to table 3 in both conventional and rubber pad forming. The tendency of analytical result was in good agreement with experiment but the amount of experimental limiting dome height is approximately 10-15% smaller than analytical result in each thickness ratio.

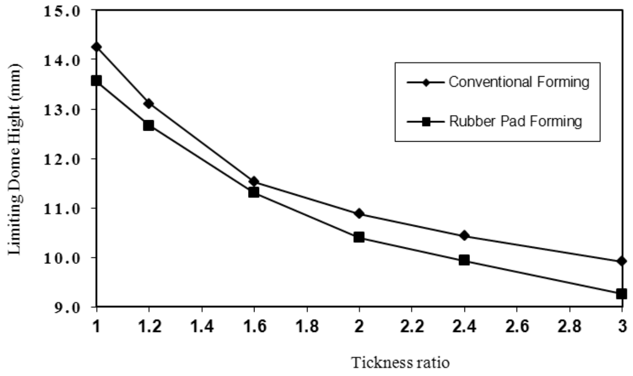

Figure 4: Comparison of the limiting dome hight causing failure in numerical investigations

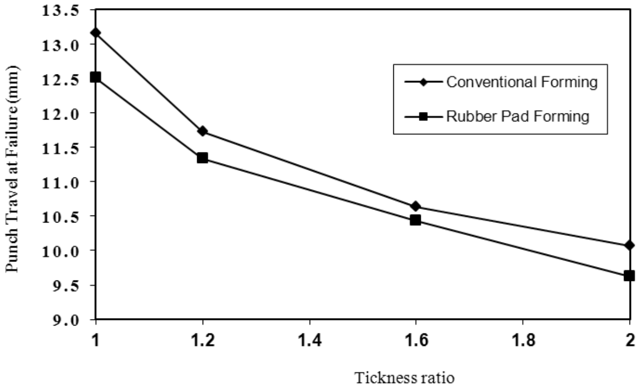

Figure 5: Comparison of the limiting dome hight causing failure in experimental investigations

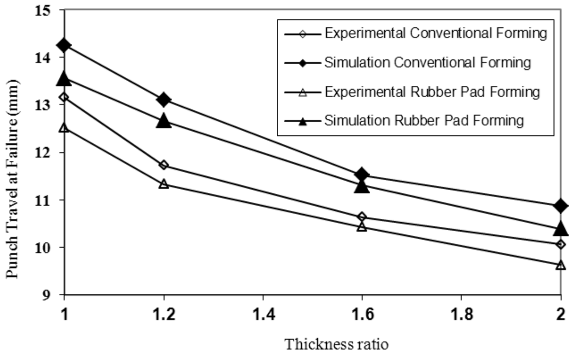

Figure 6: Limiting dome height of experimental and analytical results in both conventional and rubber pad forming

Figure 7 shows the numerical and **Fig.** 8 shows experimental maximum forming force in conventional and rubber pad forming of tailor welded blanks for each thickness ratio.

Increasing the restraining 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.** 7 and **Fig.** 8. In this study, the maximum press force in conventional forming was approximately 11.8 kN and this amount is 16.9 kN at a non tailor welded blank in rubber pad forming according to **Fig.** 9 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 thicker 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.

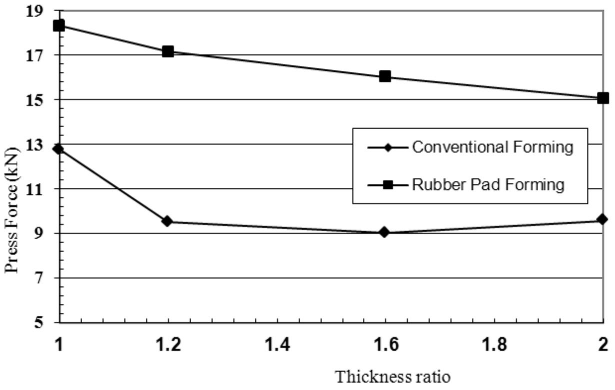

Figure 7: Press force at failure of difference thickness ratio in numerical results

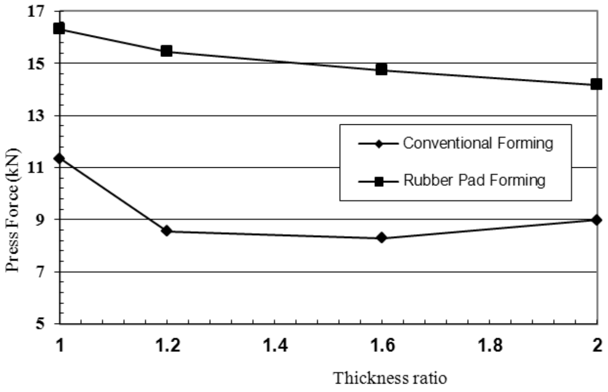

Figure 8: Experimental press force at failure of difference thickness ratio

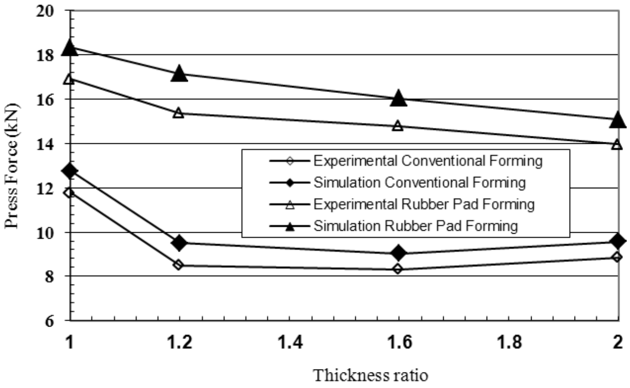

Figure 9: Press force between experimental and analytical results in both conventional and rubber pad forming

7. CONCLUSION

In this paper, the formability 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:

The formability of a TWB is smaller in rubber pad forming than conventional method in each thickness combination.

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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