FE modeling and experimental study of nonisothermal deep drawing under non-work softening temperature conditions

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Experimental and FEA of thermo-mechanical plastic deformation in nonisothermal warm deep drawing is investigated using SS304. A nonisothermal deep drawing tool is used in a servo-motor controlled press. Drawability of SS304 under elevated temperatures (25 C– 225 C), and low to high strain rates (drawing speeds of 2.5, 25 and 50 mm/s) were determined. Among various complex material models, an elastic-visco-plastic-thermal material model for non-work softening material behaviours, such as SS304, is found to be easily applicable and quite satisfactory. Tensile and equi-biaxial bulge tests were conducted for accurate flow stress data to be used in FEA. Measured punch load-stroke and cup's curvilinear thickness (rolling/transverse) curves were successfully compared with predictions from the nonisothermal deep drawing FE model.

Deep Drawing, Non-isothermal, Stainless Steel, Servo Press, Finite Element Analysis

1. Introduction

Demand for more formability requires alternative and advanced forming methods. Increasing formability of metals beyond the well-achieved limits is possible through advanced forming processes such as warm forming. While it is important to develop new processes, it is of utmost importance to also develop accurate and reliable finite element models of these processes with less complexity. Warm forming can be done isothermally or nonisothermally which requires different design and handling.

Among austenitic stainless steels, Type 304 is superior in formability and is most commonly used in parts for household and kitchen appliances. Studies have focused on improving the formability of austenitic stainless steels both by metallurgical considerations, such as varying alloy composition, and by mechanical considerations, such as using hot dies and cold punch. Formability of austenitic steels is strongly dependent upon alloy composition, strain state and strain path. During deformation, martensite formation takes place which is beneficial for formability. Angel (1954) has determined that martensite transformation is enhanced by high strains, low strain rates, low temperatures and lower nickel content. Sumitomo (1978) has investigated the effects of chemical compositions and manufacturing conditions on earing and delayed cracking of various alloy austenitic steel sheets. He concludes that in metastable austenitic stainless steel, used widely in deep drawing at room temperature, earing and delayed cracking can be improved by reducing the contents of carbon and nickel. At room temperature, Talyan et al. (1998), have investigated the forming behavior (at 10^{-1} /s, 10^{-2} /s, 10^{-3} /s) of austenitic and ferritic stainless steels at room temperature. In their study, measured in-situ temperature increase due to deformation and martensite content in tensile and dome tests have shown that temperature increases at higher strain rates thereby reduces the martensite transformation rate, strain hardening rate and hence formability.

Tague et al. (2008) have conducted formability tests between 15 C and 60 C and suggests selecting appropriate alloy austenitic steels under drawing, plane strain and biaxial stretching conditions. Peterson et al. (1997) showed that tensile tests for 304 gave maximum strains between 55 C and 80 C and showed no significant effect of strain rate.

Chang and Chou (1994) have conducted deep drawing tests by heating the sheet specimen outside of the tooling (in a furnace) and concluded maximum formability (achieved 50 mm cup height with a 50mm diameter punch) increase around 100 C. Punch-stretch tests to determine formability of type 304 stainless steel sheets were conducted using a hemispherical dome test by Coubrough et al. (1993). Takashi et al. (1998) has used ultrasonic vibration as an alternative method to increase formability, and achieved an LDR of 2.77. Kim et al. (1999), by changing the chemical composition of 304 and redrawing, has achieved LDR's up to 2.8. By redrawing/reverse drawing 304 sheets, an achieved 2.86 draw ratio is reported in PMA (1995).

Limited number of studies has been conducted for finite element analyses of SS304 at room temperature. Number of studies is even lesser especially under warm (within a heated tool) conditions. A two-phase metallurgical model was developed by Galee et al. (2007), to describe the behavior of AISI 304 at room temperature. By implementing this two-phase model into FEA, Galee and Pilvin (2010), has achieved successful thickness and punch load comparisons at room temperature. Deep drawing of 304 and 316 austenitic steels using finite element methods were modeled which included the effect of heating on transformation by Shinagawa et al. (1991). In Shinagawa et al. (1991), analyses were successful to predict failure locations in the deep drawn sheet under various temperatures and strain rates. Using the methodology in Shinagawa et al. (1991), finite

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element analyses were conducted in addition to the experimental forming limit study of 304 by Takuda et al. (2003). Takuda et al. (2003) has used hot dies and a cold punch and successfully predicted failure locations for the cups drawn at a punch speed of 2.5 mm/sec. While successful comparisons have been shown both in Shinagawa et al. (1991) and in Takuda et al. (2003), punch-load stroke curve comparisons have not been provided and only failure strokes during deep drawing were determined successfully.

Nonisothermal forming is a forming process where hot dies and a colder punch are used. Modeling of nonisothermal warm forming is a rather complex process which requires accurate constitutive material models, heat transfer calculations and representation of the flow stress data. We know that, depending on the temperature levels and the alloy, materials can either work harden, work soften or both. These mechanical behaviours require different handling in finite element analyses to ensure accuracy. For example, an alloy such as SS304, known for its formability improvement at relatively lower temperatures (up to 150^{o}C) only work hardens and therefore we do not observe any work softening. Representation of the mechanical behavior of these types of alloys does not necessarily require rather complex constitutive models that have many parameters that need to be determined. An easier to use and convenient methodology for FEA of nonisothermal deep drawing of SS304 is demonstrated in thus study.

Also, in literature, predicted and measured thickness comparisons of drawn parts are quite common while punch load–stroke curve comparisons do not exist for warm forming of SS304. Punch load comparisons provided in literature are for room temperature processes, and there is no study that provides both punch load and thickness comparisons. Since punch load information is directly related to the flow stress, a predicted and measured punch load comparison shows the accuracy of the representation of the material behavior in FEA. Therefore, also in this study, finite element modeling and experimental study of nonisothermal warm deep drawing of SS304 alloy sheet is discussed. A commercially available FE code LS-Dyna is deployed and results are compared with measured experimental punch load-stroke and cup thickness curves.

2. Mechanical property tests, tooling, and experimental conditions

In metal forming, the most common way to obtain flow stress data to be used in finite element analysis is to conduct a tensile test. This test is a standardized test and is widely adopted by industry and academia. Another test is the equi-biaxial bulge test which gives higher strain values before fracture when compared to the tensile test but is more expensive and difficult to conduct. Both tests are conducted for the subject alloy of this study, SS304.

2.1. Tensile and bulge (equi-biaxial) tests

Tensile tests were conducted between room temperature and 125 C and at 0.0016 1/s, 0.016 1/s and 0.16 1/s strain rates. Tensile test specimens and procedures were planned according to ASTM E21-09. Equi-biaxial bulge tests were conducted only at room temperature to observe the variation of data from the tensile test data and to obtain higher strains. Tensile and bulge test sheet specimens were obtained from the same batch of the SS304 alloy. Details on calculations in equi-biaxial bulge test can be found in Gutscher et al. (2004). Flow stress curves obtained from these tests will be used in the finite element analysis. This is explained in further sections.

2.2. Nonisothermal warm deep drawing

Warm forming can be done isothermally or nonisothermally. In isothermal warm forming, die, blank holder and punch are heated. In nonisothermal deep drawing, die and blank holder are heated, punch is cooled, therefore the temperature of the sheet during forming is not constant. In other words, sections of the sheet are subject to different temperatures during the operation. This is due to having a cold punch (that is kept around room temperature by circulating water through it), a heated die and a heated blank holder. Nonisothermal warm forming process sequence (a-initial stage, b-dwelling/heating the blank, c-forming) is shown in Fig. 1. Initially the blank is placed on the bottom die/blank holder (Fig. 1a). The top ram moves down till it touches the blank and dwells (Fig. 1b). During this dwelling, the blank is heated to the required temperature by the heated die and the blank holder. After the dwelling period, the top ram moves further down against the stationary punch and the sheet is formed (Fig. 1c).

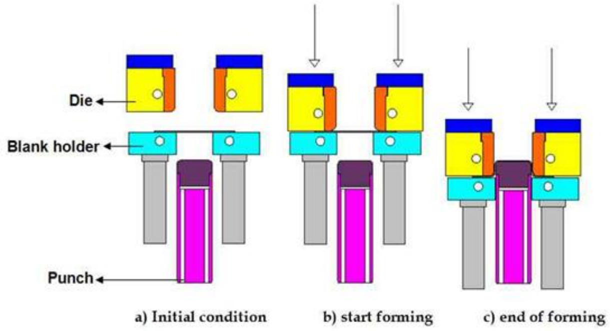

Fig. 1. Schematic view of nonisothermal deep drawing process sequence

2.2.1. Nonisothermal deep drawing tooling and machinery

A nonisothermal warm deep drawing tooling (punch shoulder radius:4 mm, punch diameter:40 mm, die shoulder radius: 6 mm, punch-die clereance:2.3 mm) is designed, shown in Fig. 2. Tooling consists of a blank holder and die, insulations, cartridge heaters, a temperature controller, a load cell, water circulation system and several thermocouples. This tooling was installed in a 110 ton servo–motor controlled industrial press manufactured by AIDA Corp.

Electro-mechanical servo-drives have been used in machine tools for several decades. Recently, several press builders, mainly in Japan and Germany, developed gap and straight-sided sheet metal forming presses that utilize the mechanical servo-drive technology. The mechanical servo-drive press offers the flexibility of a hydraulic press (infinite ram speed and position control, availability of press force at any ram position) with the speed and reliability of a mechanical press. Osakada et al. (2011) has reviewed this new drive technology and concludes that it has considerable potential in present and future applications in blanking, bending, stamping and coining. Aida Corp. and Nakagawa (2010) reported that more than 1000 servo-drive presses are already in operation in stamping and in automotive plants all over the world. This drive offers great flexibility and accuracy in controlling the speed and position of the press slide. The advantages of a servo-drive press in warm forming are mainly from the fact that a) the press can be programmed to stop during the stroke in order to heat the sheet (Fig. 1b) between the heated upper and lower tools (dwelling) and b) eliminating an outside furnace to heat the sheets (also eliminates the heat loss in the heated sheet while transferring it from furnace to the die and therefore eliminating improper deep draws due to the inhomogeneous temperature distribution) c) transfer of the sheet from furnace to the tool and related equipment d) the press

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motion can be programmed to achieve very accurate/high precision motion which provides highly controllable and repeatable speed, blank holder force/pressure.

Fig. 3 shows press motion curves specifically developed for warm forming that can be adopted for various types of experiments. For example; [123468] is a constant punch velocity forming process curve while [12345678] is a curve for variable forming velocity. For this study, [123468] motion was programmed. When the press ram reaches point 3, dwelling (heating of the sheet) starts and it ends at point 4. Please note that the sheet is heated within the tool by stopping the press between points 3 and 4. Further detailed explanation of the servo press motion in warm forming is given in Table 1 and by Kaya et al. (2008).

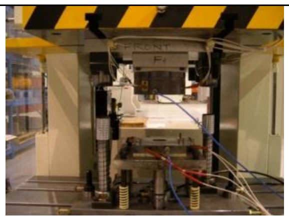

Fig. 2. Nonisothermal round cup tooling

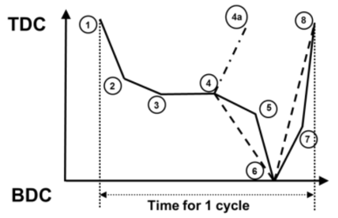

Fig. 3. Servo-drive press motion curves for warm forming

Table 1. Servo press motion explanation for warm forming

1-2	Fast approach
2-3	Slower approach reduces impact and vibrations. Both tools are in contact at 3.
3-4	Dwell (press is at a stop for a defined amount of time for heating of the blank)
4-4a	Return of the press ram to TDC (Top Dead Center)
4-5	Slower punch velocity for forming sharp corner radii
5-6	Higher velocity for faster forming. (6 is Bottom Dead Center.)
6-7	Slower exit from the tool reduces impact and vibrations
7-8	Faster return to TDC

2.3 Experimental conditions

Sheets having 0.87 mm thickness with diameters of 84, 92, 96, 100 and 108 mm targeting 2.1, 2.3, 2.4, 2.5 and 2.7 LDR's are studied experimentally. Tests are conducted at 2.5 mm/s, 25 mm/s and 50 mm/s drawing speeds and at various temperatures to determine the drawability window between strain rates of 10^{-1} 1/s and up to 20 1/s. Most literature provides strain rates in the range of 10^{-1} and 10^{-3}, and punch speeds of generally 2.5 mm/s which means a maximum strain rate of approximately 10^{-1} in the sheet. Therefore, by drawing at 25 mm/s (~10 1/s) and 50 mm/s (~20 1/s) formability of SS304 under nonisothermal conditions will be observed experimentally under relatively higher strain rates.

All blanks are cut by wire EDM to eliminate unwanted burr at edges. During the deep drawing tests, a PTFE film with a melting temperature of 350 C was used as lubricant. Sheets were kept at the heated tooling for at least 90 seconds to reach desired temperatures. 90 seconds was found sufficient after conducting measurements with thermocouples. Table 2 shows the process parameters used in the experimental study.

3. Experimental results

3.1 Tensile and bulge tests

In tensile tests, it was seen that strain rate did not have a significant effect on stress levels. Therefore, Fig. 4 shows the flow stress curves under various temperatures at 0.016 1/s.

Table 2. Experimental matrix for drawing

Die& Blank holder temperature (C)	LDR	Forming velocity [mm/s]	Blank holder force [kN]	dwell time [s]
between 25 C and – 225 C	2.1	2.5/25/50	10	90
	2.3			
	2.4			
	2.5			
	2.7			

Fig. 5 shows the comparison of room temperature tensile and bulge tests for SS304. As seen, curves are quite close except that strain obtained in bulge test is around 0.57 compared to 0.43 obtained in tensile test.

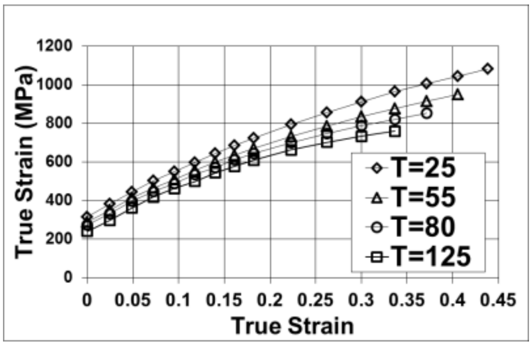

Fig. 4. Tensile tests conducted at various temperatures

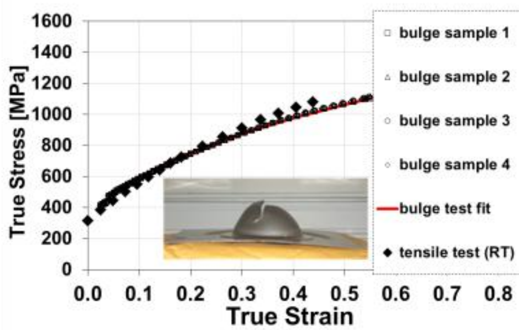

Fig. 5. Flow stress obtained from bulge and tensile tests

3.2 Deep drawing process windows

Fig. 6, shows the change in LDR with die and blank holder temperature at punch speeds of 2.5, 25 and 50 mm/s.

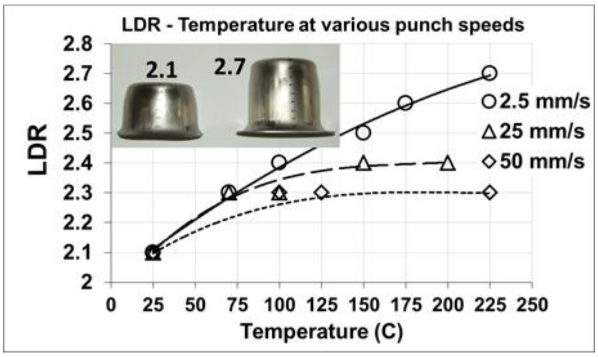

Fig. 6. LDR change with die and blank holder temperature

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Successfully drawn cups are cut for thickness measurements along the rolling direction *(RD)* and the transverse direction *(TD)*. Also, punch load- stroke curves are recorded via a load cell. These curves are compared with the numerically predicted data in Section 5.

4. FE model of nonisothermal deep drawing

4.1 Material model selection

In FE modeling of warm forming, the flow stress equation usually needs to take work hardening/softening, strain rate and temperature into account. Commercially available FE code Ls-Dyna was used as solver and Ls-Prepost as post-processor.

All plastic-thermal material models available in LS-Dyna are reviewed and three material models (*Mat_Elastic_Plastic_Thermal, Mat_Johnson_Cook* and *Mat_Elastic_Visco_Plastic_Thermal)* that could potentially represent the thermo-mechanical material behavior were determined. Since only *Mat_Johnson_Cook* and *Mat_Elastic_Visco_Plastic_Thermal* material models can take the effect of strain rate into account, *Mat_Elastic_Plastic_Thermal* was eliminated in the initial review.

Johnson-Cook material model (*Mat_Johnson_Cook*) is known to take work softening, strain, strain rate and temperature into account. However, it requires numerous experiments to determine five parameters (A,B,c,n,m) it has.

Reviewing the flow stress curves obtained in Fig. 4, it is seen that no work softening exists in SS304 due to maximum testing temperature of 125 C, which is quite low. Therefore, the flow stress equation that represents the mechanical behavior does not need to take into account any work softening behavior. It was observed from tensile tests that the effect of strain rate was also negligible. Since the only parameter that affects the mechanical behavior in this study is temperature, *Mat Elastic Visco Plastic Thermal* was selected to input flow stress data. This model was preferred over the others since it gives the user more flexibility in fitting the experimental data for different values of temperatures. The flow stress (σ_{eq}), as function of strain (ε_{eq}), strain rate ($\dot{\varepsilon}_{eq}$) and temperature (T), is calculated using the formula below:

$$\sigma_{eq}\left(\varepsilon_{eq},\dot{\varepsilon}_{eq},T\right) = \underbrace{\overbrace{MFS(\varepsilon_{eq})}^{\boxed{\text{I}}}}_{\boxed{\text{Master flow stress}}} \times \underbrace{\overbrace{SF(T)}^{\boxed{\text{II}}}}_{\boxed{\text{Effect of Temp.}}} \times \underbrace{\overbrace{\left[1+\left(\frac{\dot{\varepsilon}_{eq}}{C(T)}\right)\right]^{\frac{1}{P(T)}}}^{\boxed{\text{III}}}}_{\boxed{\text{Effect of strain rate}}}$$

A total of four tables are provided in this material model, which are MFS (ε_{eq}), SF(T), C(T) and P(T).

I. The first component in the formula is the "master flow stress", MFS (ε_{eq}). This is provided in the form of a table that has room temperature stress-strain data.
II. The second component, SF(T), scales the masters flow stress(MFS) values to account for temperature effects.
III. The last component has the so called viscous parameters "C and P" to take strain rate effects into account. C(T) and P(T) are also input in tabular form, if the effect of strain rate is taken into account.

4.2. Flow stress of SS304 used in FE model

Since strain rate effects were negligible, only two tables were needed to accurately represent the SS304 behavior in our study. These are the master flow stress MFS(ε_{eq}) and the SF(T) tables. Fig. 7 shows the scaled flow stress curves. Master flow stress curve is given a scaling factor of 1. With the increase of temperature, the master flow stress decreases, therefore scaling factors of 0.94, 0.86 and 0.7 were determined for temperatures of 55 C, 80 C and 125 C, respectively.

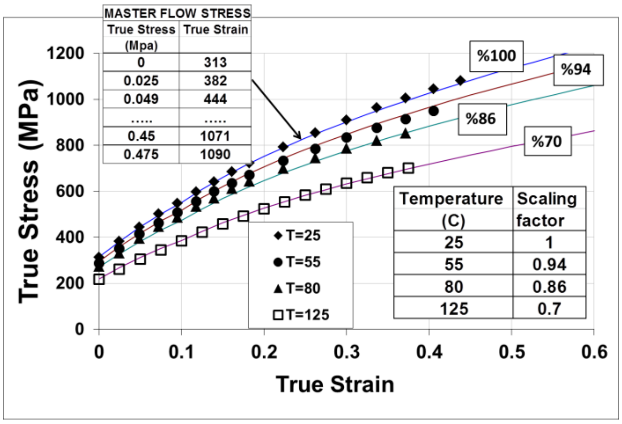

Fig. 7. SS 304 flow stress data represented using elastic visco plastic thermal material model

4.3. Simulation matrix

Table 3 shows the selected forming conditions for the FEA. It must be noted that same forming conditions were simulated using the data obtained from the tensile test and the bulge test.

Table 3. SS 304 simulation matrix

	Draw Ratio ($DR=d_{punch}/d_{die}$)	**Die/BH temperature**	**Forming velocity (mm/s)**	**Flow stress**	
Case 1	2.1	Room Temp.	2.5	Tensile test	Bulge test
Case 2	2.3	70 C			
Case 3	2.4	100 C			

Thermal conductivity and specific heat are 16.3 W $m^{-1}C^{-1}$ and 502 J $kg^{-1}C^{-1}$ respectively. Interface heat transfer coefficients for sheet-punch, sheet-die, sheet-blank holder and sheet - environment are selected as 5000 W m^{-2} C^{-1}, 1000 W m^{-2} C^{-1}, 1000 W m^{-2} C^{-1}, 50 W m^{-2} C^{-1}, respectively.

Based on previous experience, sheet-punch interface heat transfer coefficient (HTC) was chosen five times higher than the sheet-die and the sheet- blank holder; this was done to emulate the effect of the higher sheet-punch contact pressure on HTC value. Friction coefficient value of 0.08 was used based on previous modeling experience using PTFE lubricants. It is a bit lower than what is normally reported in literature (from 0.1 to 0.16) because of the low friction PTFE film lubricant used during experiments.

5. Comparison of FE predictions and experimental results

Punch load - stroke and cup thinning curve comparisons obtained from FE predictions and experimental results are provided in Fig. 8, Fig. 9 and Fig. 10.

It is seen from the comparisons of cup thickness and punch load curves that FE predictions are quite satisfactory. Punch load comparisons show that values using the selected material model and methodology are quite acceptable and practical to use.

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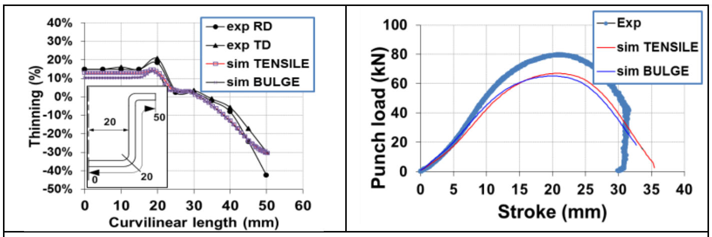

Fig. 8. Thickness and punch load curve comparison (RT, 2.1)

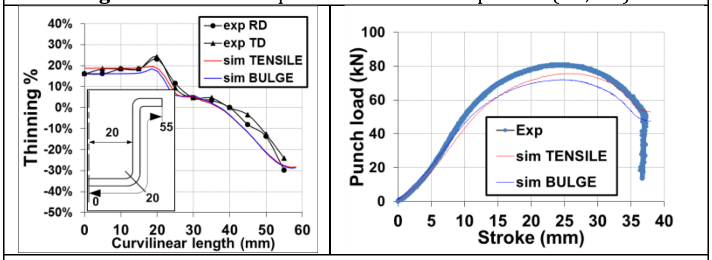

Fig. 9. Thickness and punch load curve comparison (70 C, 2.3)

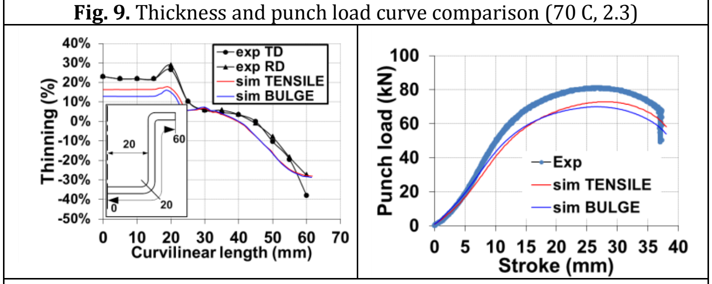

Fig. 10. Thickness and punch load curve comparison (100 C, 2.4)

6. Summary and conclusions

1. Nonisothermal warm deep drawing of SS304 is conducted and LDR's of 2.3, 2.4 and 2.7 are achieved at drawing speeds of 50 mm/s, 25 mm/s and 2.5 mm/s, respectively.

2. A servo-motor controlled press was successfully deployed using a nonisothermal warm forming tooling. Sheet specimens were heated within tooling by programming the servo press accordingly.

3. In all experimental thickness measurements, as LDR increased, maximum thinning of 30% is observed at the bottom corner of the cup, not at the cup wall. Thickness measurements along the rolling direction (RD) and transverse direction (TD) were found to be quite close.

4. A practical and easy to apply FE methodology is demonstrated successfully for thermo-mechanical modeling of non-work hardening metals using an elastic visco plastic material model.

5. Room temperature tensile testing and equi-biaxial bulge testing of SS304 did not show significant variation in hardening behavior. Only difference was observed at achieved maximum strain levels at necking. Therefore, punch load – stroke and cup thickness comparisons using tensile and bulge test data did not vary significantly.

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