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Artificial Neural Networks to the Analysis of AISI 304 Steel Sheets through Limiting Drawing Ratio Test

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Abstract: - Drawbeads are employed in the formation of intricately shaped draw pieces to modify the stress state in specific areas of the drawpiece or to equalize the material's flow resistance along its perimeter. A unique drawbead simulator for calculating the factor of friction on the drawbead is presented in this article. The objective of this manuscript is to employ artificial neural networks (ANNs) to comprehend the impact of the primary friction process parameters, namely sample orientation concerning the rolling direction of the steel sheets, counter-sample surface roughness, and lubricant conditions, on the rate of friction. The goal was to create a database that would be utilized to train ANNs. This paper investigates the influence of temperature gradients developed in the tool profiles on the forming characteristics of AISI 304 steel sheets, primarily employing the cup drawing test. To examine the formability characteristics of the investigated steel sheets, limiting drawing ratios test was conducted by isothermal and non-isothermal heating conditions on the prepared circular blanks. The experimental results also highlighted that maintaining a uniform tooling temperature does not lead to an enhancement in formability. Specifically during non-isothermal forming conditions, punch was purposefully kept at a temperature lower than the die / blank holder, LDR increased by 16 % in non-isothermal and 8 % in isothermal forming conditions.

Keywords: Artificial Neural Networks, AISI 304, sheet metal forming (SMF), limits drawing ratio, isothermal, non-isothermal.

I.INTRODUCTION

Forming plastic into sheet metals is a semi-finished product called sheet metal forming (SMF), which involves a variety of plastic working techniques primarily performed under cold-forming circumstances. Dies, which are often mounted on hydraulic or mechanical presses, are used in deep drawing operations. It is possible to shape using a rotating tool in unexpected ways. A smooth blank is converted into a three-dimensional, non-expandable drawpiece during the deep drawing process. Typically, drawbeads are needed by the dies for creating non-axisymmetric parts, particularly in the automotive sector. The material flow in specific parts of the drawpiece is restricted by the drawbead employed in the SMF process. A restricting force provided by the drawbeads or a blankholder tool is used to achieve this control 19, 20. As the sheet metal passes through the drawbead, the curvature of the sheet changes numerous times. In addition, the sheet material experiences frictional forces and plastic deformation. The final surface condition of the product and the drawbead height needed to achieve the right restraining force are determined by the friction conditions that occur on the drawbead. The drawbeads are

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an essential component in sheet metal developing, especially when it comes to creating intricately shaped drawpieces.

The foundation for creating simple and complex components is metal forming, which involves plastically deforming a sheet until the desired shape is flawlessly attained without the any failure. Many variables, including the tool, blank shape, forming temperature, punch force, and the force applied by the blank holder, affect the achievement of this goal 1, 18. In the manufacturing realm, material formability evaluation is a complex process that is usually achieved by forming methods such as Erichsen cup test, nakazima test and cup drawing test etc. Of these techniques, the cup drawing test holds a prominent position in the evaluation of sheet materials formability 2, 3. AISI 304 steel sheets are widely used in the production of a wide variety of both internal and external parts, including petrol tanks, starter end covers, structural parts, hinges, car frames and refrigerator panels. Nevertheless, their formability at ambient temperatures poses a challenge, primarily due to substantial deformation and elevated flow stress levels. Empirical evidence suggests that warm forming is a novel approach that enhances the formability of steel sheets by mitigating flow stresses and easing residual stresses. Consequently, deeper sketching and more material stretching are made possible. This, in turn, enables more drawing ratio and greater material stretching 4, 5, and 6.

Explorations into warm forming have disclosed an approximate 9% increase in the limiting drawing ratio (LDR) for extra deep drawing steel 7, 8. In-depth investigations concerning low carbon steel underline the substantial impact of forming temperature, particularly at reduced forming speeds, on restricting the drawing ratio 9, 10,11. It is noteworthy that finite element simulations have been performed for the following materials: AZ31 magnesium alloy, aluminium alloy, and EDD steel sheets 12, 13, 14.

While several investigations have delved into warm forming, extensive research concerning AISI 304 steel sheets under diverse process conditions, harmonizing with industrial demands, remains notably scarce. To close this information gap, the current study uses an LDR test to precisely establish the temperature requirements for AISI 304 grade steel sheet forming—a crucial process for the industry. Formability characteristics of AISI 304 sheets are thoroughly examined, with special attention paid to the existence of temperature gradients between the die, punch, and blank 15, 16, 17.

II.EXPERIMENTAL PROCEDURE

2.1 Material and Experimentation

In this investigation, we employed cold-rolled AISI 304 steel sheets, the chemical composition of which is outlined in Table 1. It is noteworthy that stress levels substantially decrease as the temperature rises from 30°C to 225°C. The sheet's elongation grows steadily to 37.37% when the temperature reaches 225°C, yet its strength gradually decreases from 221 MPa to 176 MPa within this temperature range. Conversely, samples subjected to temperatures exceeding 250°C exhibit fractures and minimal elongation. As a result, the room temperature to 250°C temperature range was established for the formability study, a measure designed to pinpoint the optimal forming conditions for AISI 304 steel sheets.

Table 1. Compositions of AISI 304 Grade Steel Sheet

Name of the material	Percentage (in Weight)								
	C	Si	Mn	S	Cu	P	Cr	Ni	Fe
Stainless steel:AISI 304	0.07	0.66	1.15	0.01	-	0.04	18	8.25	Rest

Tensile tests were performed on the examined steel sheets in order to ascertain their plastic flow properties and to pinpoint the point of failure under transverse tensile pressure. Avto Instruments Limited (make: India) produced a universal testing apparatus that was used for these tensile tests. As seen in Figure 1, the tensile specimens were painstakingly constructed in compliance with the ASTM E8 standard. Figure 2 shows the prepared tensile specimens. The uniaxial tensile testing was used to carefully evaluate the mechanical properties of the source materials, which were important for the forming studies that followed. The mechanical properties acquired through the tensile tests are comprehensively detailed in Table 2. The procedures for determining material constants, such as strength coefficient (K), strain hardening component (n), closely adhere to the methodology proposed by Fekete et al. (Ref 1)

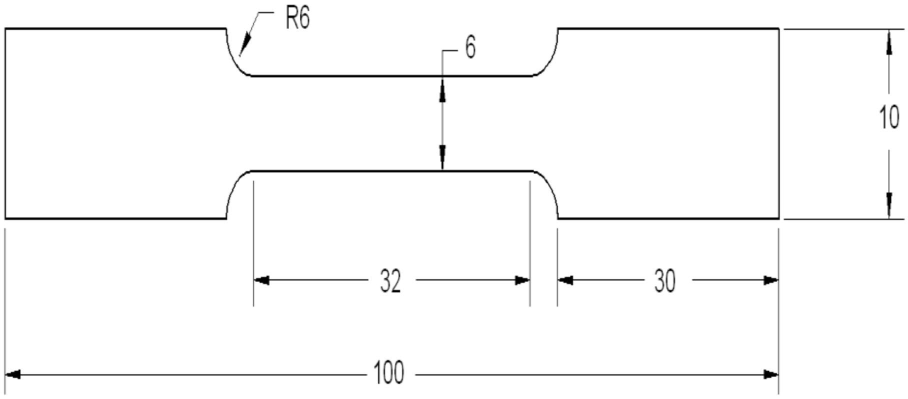


Figure 1. Geom9etry of the Specimen for Tensile Test

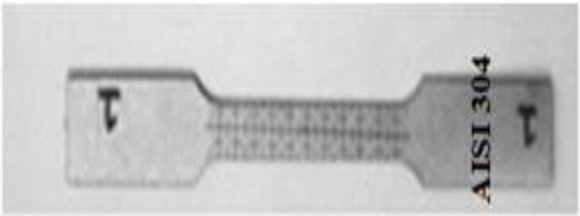
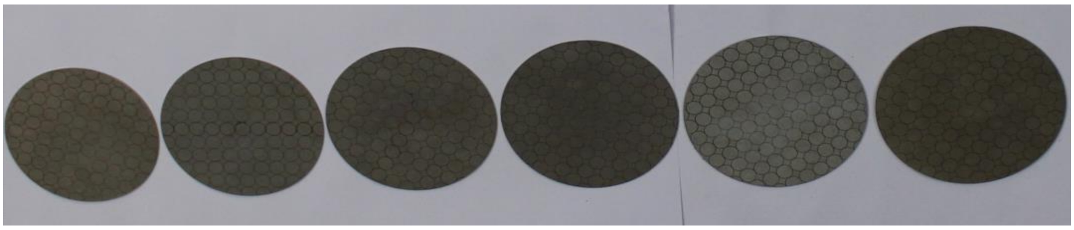


Figure 2. Tensile specimen of AISI 304

For the LDR test, rigorous preparation was done on circular blanks of diameters between from 10.5 cm to 13 cm with a thickness of 0.8 mm. All these specimens were precisely gridded with 12 mm circles using laser technology to facilitate the measurement of major and minor strains. Figure 3 visually presents the blanks which were employed in the LDR test.

Table 2. Mechanical Properties of AISI 304

Young's Modulus (GPa)	Thermal Expansion (K^{-1})	Strength coefficient K-MPa	Strain hardening index (n)	UTS (MPa)
191	17.1×10^{-6}	1395	0.42	630



105 mm 110 mm 115 mm 120 mm 125 mm 130 mm

Figure 3. Specimens for LDR Test

2.2 Limiting Drawing Ratio Test

In order to assess the influence input parameters on the forming characteristics of AISI 304 steel sheets, these prepared blank sheets were subjected to a LDR test in a as shown in 800-kN hydraulic press as shown in Figure 4(a). The schematic representation of the experimentation of the LDR test is shown in Figure 4(b). Three separate sets of heaters were included in the testing apparatus. One set was affixed to the blank holder to heat the blank, and the other set was firmly fixed to the bottom die to keep the die material at the proper temperature. Molykote lubricant was applied between moving parts to reduce friction. The speed of punch is consistently maintained at 0.4 cm/s, a rate closely mirroring typical production scenarios (Ref 14).

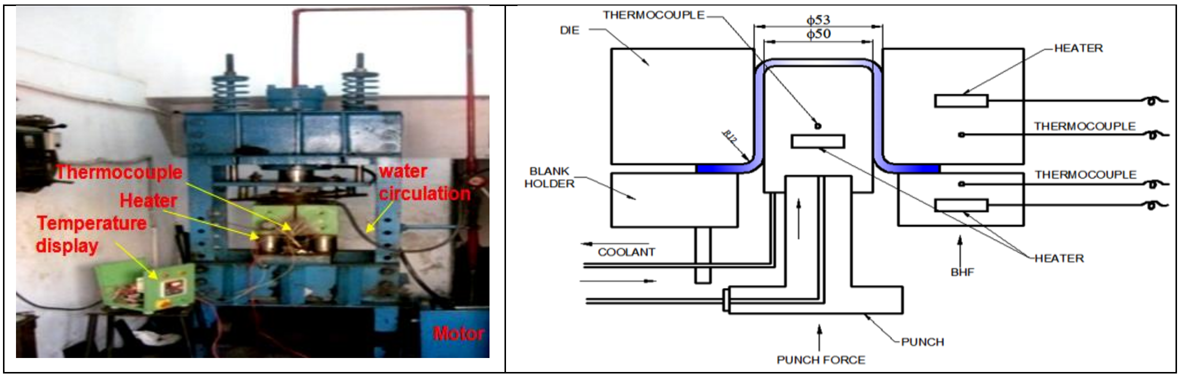


Figure 4 a). Experimental Setup for the LDR Test b) Schematic of for the LDR Test

2.3 Input parameters and warm forming strategies

At the specified temperature, blanks were subjected to the LDR test. Through preliminary experiments, the Blank Holder Force (BHF) was determined to be 15 kN, a decision taken to stop the flange area from wrinkling. The diverse input parameters employed during the warm forming experiments are comprehensively detailed in Table 3. The Limiting Drawing Ratio (LDR) test encompassed a total of eight distinct experimental sets, each characterized by varying tooling temperatures. In the first four experiments, the blank holders, punch and die were kept at constant temperatures under isothermal conditions.

Table 3. Input parameters of LDR Test

Sl. No.	Input Parameters	Range
1	Punch diameter (d_p)	50 mm
2	Die profile radius (r)	12 mm
3	Tool temperatures (Punch , Die & Blank holder)	30°C - 250°C
4	Punch nose radius (r_p)	5 mm
5	Blank holder force	15 kN – 22 kN
6	Blank thickness (t)	0.8 mm
7	Blank diameter (D)	110 to 130
8	Punch force	0 kN – 30 kN

In contrast, Experiments 5 to 8 were carried out under non_isothermal conditions. This decision was guided by prior research, which indicated that maintaining higher temperatures in the blank holder and die, as compared to the punch, led to smoother material flow into the die cavity. A comprehensive breakdown of the isothermal and non-isothermal tooling temperatures is provided in Table 4. Table 5 lists the summary of experimental conditions for LDR test for AISI 304 steel sheets.

Table 4. Isothermal and Non isothermal forming - Experiment strategies

Experiment Number	Drawing Ratio (DR)	Speed of Punch (mm/sec)	Temperature Gradient of Blank and Tools	
			Punch °C	Die/Blank Holder °C
Isothermal forming conditions				
1	2.1 to 2.6	4	30	30
2	2.1 to 2.6	4	100	100
3	2.1 to 2.6	4	150	150
4	2.1 to 2.6	4	200	200
Non-isothermal forming conditions				
5	2.1 to 2.6	4	30	250
6	2.1 to 2.6	4	100	250
7	2.1 to 2.6	4	150	250
8	2.1 to 2.6	4	200	250

Table 5. Experimental Conditions of LDR test for AISI 304 Steel Sheet

Expt. No.	Tool Temperature (°C)		Max. Punch Force-kN	Max. Blank Holder Force-kN	Speed of Punch - mm/s	LDR
	Punch	Die and Blank holder				
1	30	30	30	22	4	2.25
2	100	100	28	22	4	2.2
3	150	150	28	22	4	2.2
4	200	200	28	22	4	2.2
5	30	250	33.3	22	4	2.44
6	100	250	30	22	4	2.3
7	150	250	28	22	4	2.3
8	200	250	28	22	4	2.3

III.RESULTS AND DISCUSSIONS

3.1 Punch Force

Figure 5 (a-b) compares the punch load requirements with respect to displacement of the punch for isothermal and non-isothermal forming conditions for the investigated AISI 304 steel sheets. From the graph, it is evident that the required punch forces progressively increases for all forming conditions and then slowly decreases at the end owing to lower blank holder forces experienced at flange region. The maximum punch force required for successful forming under isothermal and non-isothermal forming condition for AISI 304 steel sheets was identified as 30 kN and 33.3 kN respectively.

Due to the higher tensile strength and formability characteristics of the investigated steel sheets, the required drawing load and corresponding punch force more. Furthermore, in both the simulated and actual data, the punch force needed for isothermal forming (experiments 1-4) was less than that for non-isothermal forming (experiments 5-8). This could be explained by the fact that at higher temperatures, flow stresses are reduced and residual tensions are relieved (Ref 4).

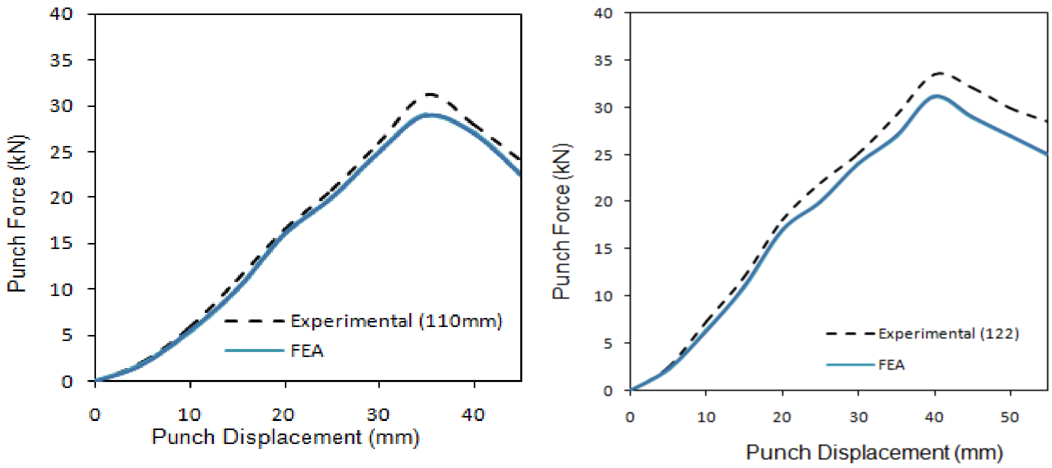


Figure 5. Punch forces Vs displacement for AISI 304 (a) isothermal forming (LDR 2.25) (b) non-isothermal (LDR 2.44)

3.2 Limiting Drawing Ratio

A limited drawing ratio test was performed on the prepared blanks to examine the impact of both isothermal and non-isothermal forming conditions on the formability of the AISI 304 steel sheets. The LDR values attained for the AISI 304 steel sheets formed by isothermal (Experiment 1 to 4) and non-isothermal (Experiment 5 to 8) forming conditions are shown in table 6. The ranges of blank diameter that can be successfully formed under isothermal conditions are 105 mm (DR 2.1) to 112.5 mm (DR 2.25). The blank diameters above this range fractured at the punch corner region. The maximum cup height achieved was 47.2 mm for experiment 1. During non - isothermal forming the LDR value of AISI 304 steel sheets reached its peak value of 2.44 for 30°C/250°C heating conditions (Experiment 5). Compared to 30°C and isothermal forming, the LDR value attained with non-isothermal forming is increased by 16% and 8%. On the other hand, the LDR for trials 6 through 8 was 2.3, which is 3% more than isothermal formation.

Table 6. Results of Isothermal and Non-Isothermal LDR tests on AISI 304 Sheets For Experiments 1-8

Experiments	Drawing Ratio S= Success ; *F* = Failure							LDR
	2.10	2.20	2.25	2.30	2.35	2.44	2.50	
Isothermal Forming								
1	*S*	*S*	*S*	*F*	-	-	-	2.25
2	*S*	*S*	*F*	-	-	-	-	2.2
3	*S*	*S*	*F*	-	-	-	-	2.2
4	*S*	*S*	*F*	-	-	-	-	2.2
Non-Isothermal Forming								
5	*S*	*S*	*S*	*S*	*S*	*S*	*F*	2.44
6	*S*	*S*	*S*	*S*	*F*	-	-	2.3
7	*S*	*S*	*S*	*S*	*F*	-	-	2.3
8	*S*	*S*	*S*	*S*	*F*	-	-	2.3

Figure 6. Successfully formed cup of AISI 304with maximum LDR
a) Isothermal Forming (a) Non- Isothermal Forming

Figure 6 shows the successfully formed cups by isothermal and non-isothermal forming conditions respectively. During isothermal heating conditions the improvement of LDR was minimum. Though during non-isothermal forming results (30°C /250°C) prove that the Limiting Drawing Ratio value is remarkably greater than the room temperature forming and isothermal conditions. Experiments also show that the temperature gradient is indispensable for the high formability due to the prevention of localized necking by minimizing the flow stress of the sheet metal. This is a beneficial conclusion for the practical drawing of stainless steel sheets. The drawing limit and failure initiation was successfully predicted using FEA.

IV.CONCLUSIONS

In contrast to isothermal forming, non-isothermal forming significantly improved the formability of all the steel sheets, especially when there was a larger temperature differential between the blank holders, die and punch:

- Under isothermal heating condition, a blank diameter of 112.5 was successfully formed with an LDR of 2.25. The blanks above this range fractured near the punch corner. During non-isothermal forming, the LDR value attained in experiment 5 was 2.44 at 30°C/250°C, which was 16% higher than in regular forming.
- In contrast to isothermal forming, non-isothermal forming significantly improved the formability of all the steel sheets, especially when there was a larger temperature differential between the blank holders, die and punch.
- The fracture was typically seen close to the punch corner under isothermal heating conditions. Fracture at the cup wall near the punch corner results from the cup wall region needing more strength to survive the critical punch force. On the other hand, as the temperature in this area is relatively higher at non isothermal forming, the fracture was found near the die corner, or top segment of the cup wall.

- The drawbead used in the SMF process limits the material flow in particular areas of the drawpiece. To accomplish this control, a blankholder tool or the drawbeads' restricting force is employed. The sheet metal undergoes multiple curvatures as it travels through the drawbead. Frictional pulling and plastic deformation are also experienced by the sheet material. The friction conditions on the drawbead determine the end product surface condition and the drawbead height required to obtain the proper restraining force. In metal sheet developing, the drawbeads are a crucial part, particularly when making precisely curved drawpieces.
- A blankholder device or the limiting force of the drawbeads is used to achieve this control. As the sheet metal passes through the drawbead, it curves in several different directions. The sheet material also undergoes plastic deformation and frictional tugging. The end product surface state and the drawbead height necessary to achieve the appropriate restraining force are determined by the friction characteristics on the drawbead. Drawbeads are an essential component in the process of producing metal sheets, especially for creating perfectly curved drawpieces.

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