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FORMABILITY STUDIES ON AISI 304 STEEL SHEETS USING STRAIN BASED FORMING LIMIT DIAGRAM

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Abstract

The forming limit diagram is one of the most commonly used technique for evaluating the formability of sheet materials. Nonetheless, several recent studies suggest that it is not suitable for multistage forming processes due to its dependence on the forming history and strain path. In these cases, principal strain based forming limit stress diagramisfound to be more efficient. In this study, the formability of AISI 304 steel sheets has been assessed using strain-based forming limit diagrams and through Nakazima and Cup drawing tests. For validation, the experimental findings are compared to simulation results. Both finite element simulation and experimental results are in good agreement in terms of determining the locations, values of excessive thinning and forming limits.

Keywords: AISI 304, Formability, Forming Limit Diagram, Nakazima Test, Cup drawing test, Finite element simulation.

1 Introduction

AISI 304 stainless steel sheets are frequently used in the fabrication of diverse critical and general components such as automotive parts (fuel tanks and exhaust systems), aircrafts, medical apparatus, refrigerator parts, microwave body panels, nuclear vessels, cryogenic vessels, shipping drums, architectural panels, etc. All these applications necessitatebetter formability characteristics, high corrosion resistance,superior quality and durability. Moreover, certain fabrication processes, such as drawing, melt spinning etc.may initiate specific defects and textures in the material influencing their fracture behavior [1]. Thus, understanding the formability of AISI 304 steel sheets is critical to identify the range in which defect free components can be economically manufactured [2-8]. A standard method of determining the formability of sheet metal is to draw its forming limit diagram (FLD) 9-13] which provides the manufacturer apermissiblestrain limit below which failure will not occur under proportional loading. Yet various investigations haveestablished thatFLD depends on the forming history and strain paths of deformed materials.FLD is also found to be very sensitive to non-linear strain paths. In this investigation, the Forming Limit Diagram (FLD) was employed to investigate the formability characteristics of commercially available AISI 304 steel sheets. FLD ofAISI 304 steel sheets were constructed using Nakazima tests experiment and Cup drawing tests [14].

2. Experimental procedures

2.1 Material

AISI 304 steel sheets of thickness 0.8 mm were used as starting material.The chemical composition, mechanical properties and microstructure of AISI 304 steel sheetsat room temperature is shown in Table 1, Table 2 and Fig.1respectively. The microstructure was found to be normal for AISI 304 stainless steel with austenite grains and dispersed carbide particles.

Table 1 Chemical Composition [wt %] of AISI 304 steel sheet

C	Si	Mn	P	S	Cr	Ni	Iron
0.069	0.66	1.15	0.039	0.011	18.16	8.25	71.66

Table 2 Mechanical properties of AISI 304 steel sheet

S. No	Properties	Unit	Value
1.	Yield strength	kN/mm^2	0.258
2.	Ultimate strength	kN/mm^2	0.500
3.	Modulus of Elasticity	kN/mm^2	195
4.	Strength Coefficient	kN/mm^2	0.520
5.	Min. Elongation	%	60
6.	Strain hardening Index	No unit	0.245

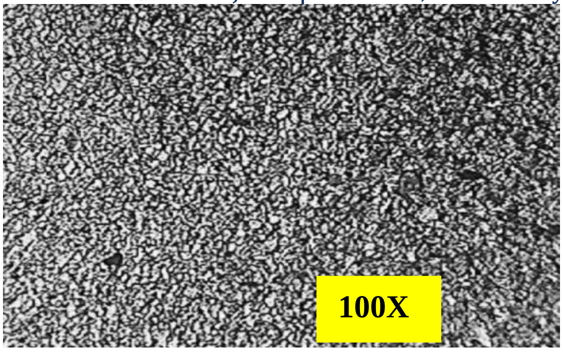

Fig. 1 Microstructure of the investigated AISI 304 steel sheet

2.2 Identification of Failure criteria

Various tests such as tensile, shear and Nakazima tests were carried out to identify the failure criteria of the investigated AISI 304 steel sheets. The geometries and images of the prepared specimens used for the tests are shown in Fig.2 (a-b) and Fig.3 (a-b) respectively. All the samples were prepared and tested according to ASTM E8 standards as proposed by Z.M. Yue et al [11].

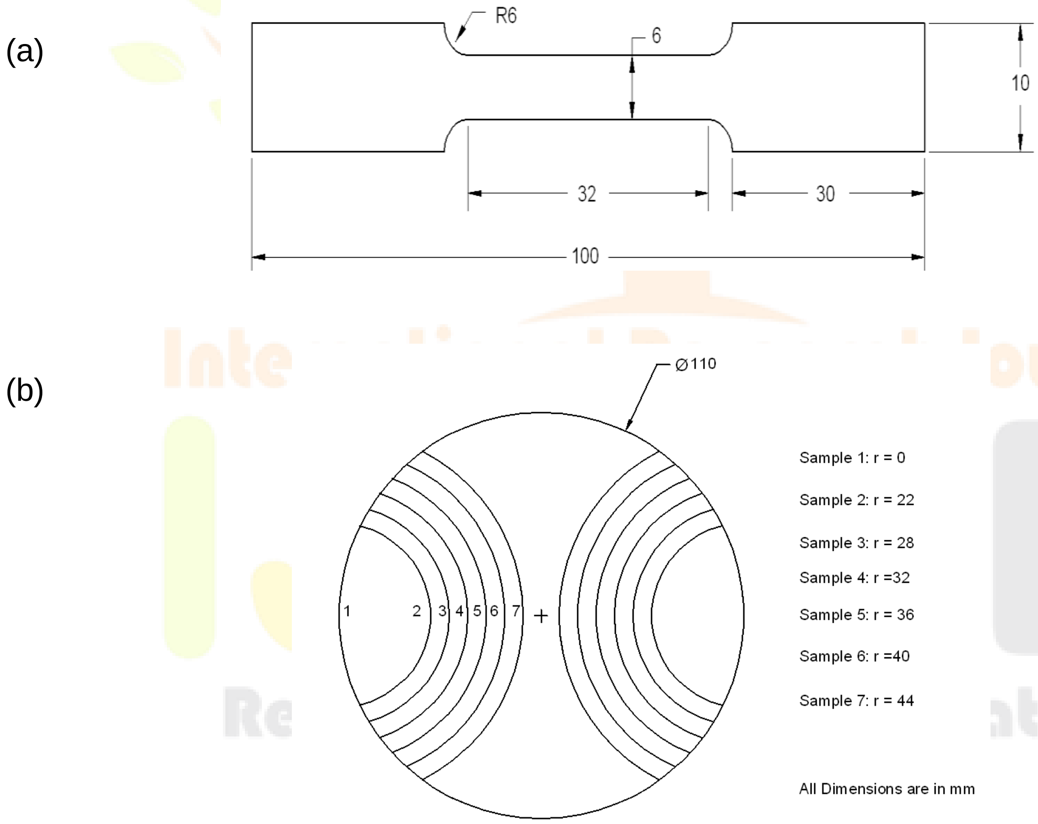

Fig. 2 Geometry of specimens a Tensile test b Nakazima test

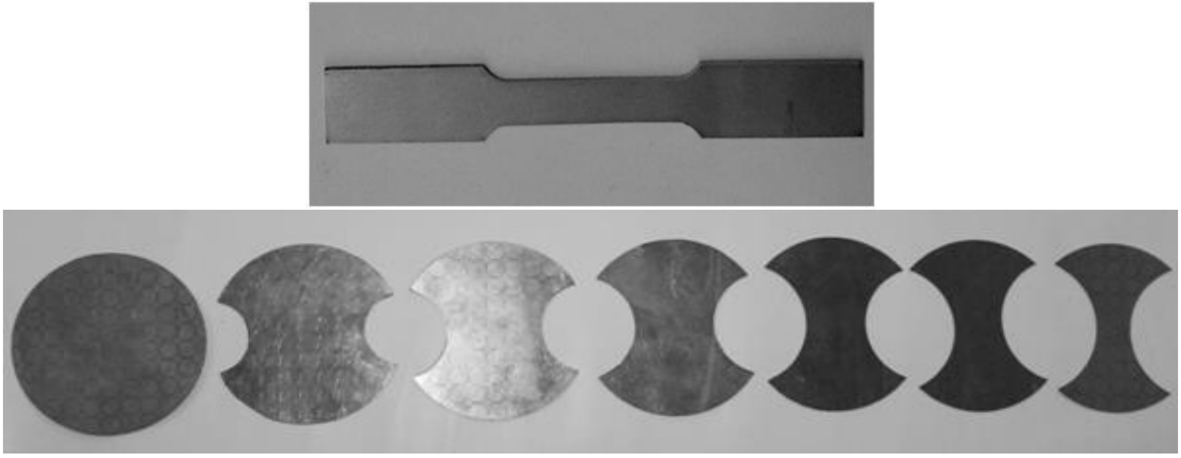

Fig. 3 Sample specimens a)Tensile test b)Nakazima test

2.3 Tensile test

Uniaxial tensile test was conducted at room temperature with a strain rate of $1s^{-1}$and a constant displacement of 0.3 mm/s in a universal tensile testing machine. The plastic flow curve of AISI 304 steel sheets after the testis shown in Fig.5. These tensile test specimens were loaded in three different directions namely longitudinal, transverse and diagonal directions to identify the anisotropic parameters of the investigated steel sheets.

2.4 Nakazima test

The formability of the sheet metals is usually predicted by FLD.FLD of the sheets are generally identified either by ‘Marciniak – in – plane’ test or ‘Nakazima–out- of plane’ test. In this work the FLD of the steel sheets was obtained by conducting Nakazima test in an 800 kN hydraulic press at room temperature as per GB/T 15825.8-2008 standards. The Nakazima test specimens were trimmed from 110 mm diameter blanks to form different shapes with a radius of 22 mm, 28 mm, 32 mm, 36 mm, 40mm, and 44mm. The varied specimen shapes describe the different states of stress and strain path during the forming process [14]. All these specimens were gridded with 12mm circles using laser technique to measure the major and minor strain.

Fig. 4 illustrates a schematic of Nakazima experimental setup. No lock bead was established between the blank holder and die as this study did not include stretching operation. During the test,the specimens were loaded and pressed between the die and the blank holders. A hemispherical punch of 50 mm diameter was used to deform the specimens till fracture. The punch speed and blank hold force employed during forming were0.2mm/sec and 250 kN respectively. Molykote was used as lubricant between blank and blank holder/die to minimize the friction between the moving parts. During the test the friction coefficient between blank and punch was maintained as 0.15 and the same was at 0.12 between blank and die/blank holder.

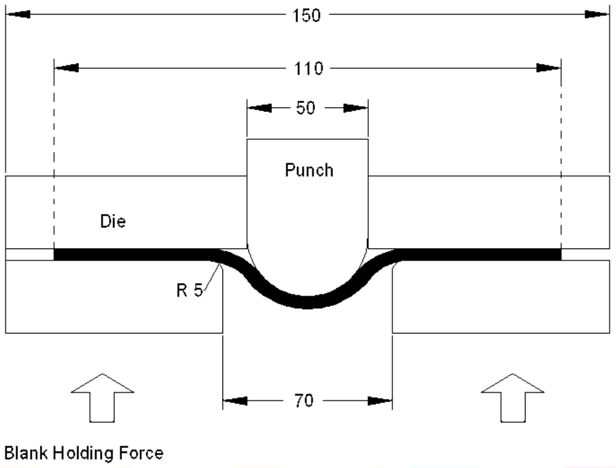

Fig. 4 Schematic of Nakazima test

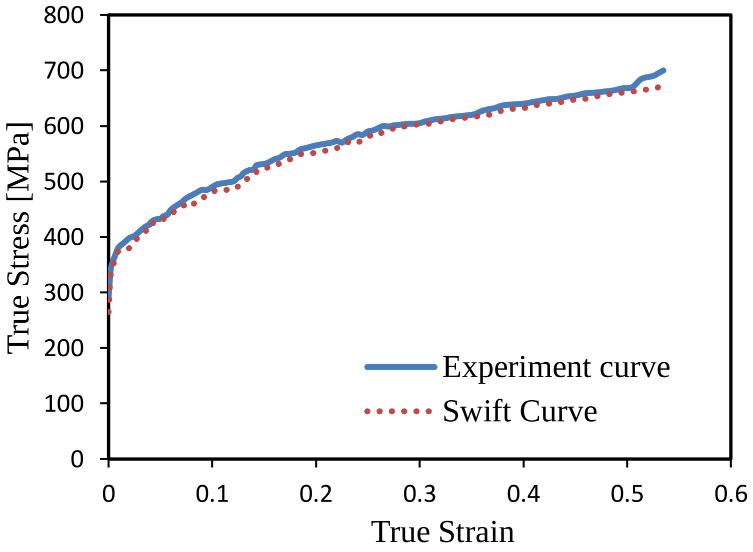

Fig.5 Comparison between experimental and numerical stress –strain curve

3. Evaluation of Formability by Nakazima test

A three dimensional (3-D) fully coupled thermo mechanical finite element analysis was developed using ABAQUS/ Standard 6.12-1 to investigate the formability characteristics of AISI 304 steel sheets. Die, punch and blank holders were meshed as analytical rigid surfaces and the trimmed circular blanks were meshed as thermally coupled and doubly curved thin/thick quad shaped S4R elements with 4-nodes. Blank, punch, die and punch holders were modeled separately and assembled in the pre processor with the required dimensions. The mechanical and thermal properties of AISI 304 steel sheets applied in finite element analysis are listed in Table 4. Failure locations and excessive thinning of sample 2 identified during nakazima testis shown in Fig.6.

Table 4 Material properties and process parameters used in simulation

S. No	Material properties and process parameters	Values
1.	Young's modulus (GPa)	195
2.	Poisson's Ratio	0.29
3.	Thermal Conductivity of sheet (W/m.K)	16.5
4.	Rockwell Hardness	68
5.	Specific Heat (J/g.K)	0.5
6.	Friction coefficient between blank and punch	0.15
7.	Friction coefficient between blank and die/blank holder	0.12
8.	Constants r_0, r_{45}, r_{90}	2.4, 2.1 & 2.8

Fig. 6 Identification of failure locations for Nakazima test

Post simulation the major and minor strain values were identified near the failure locations and FLD was constructed and compared with experimental FLD. Fig. 7 compares the strain based FLD obtained by experimental and by finite element studies. The identified finite element FLD is in good agreement with experimental results. A slight variation is observed between the simulated and experimental strain values on the left hand side of the FLD. This can be attributed to the reason that the predicted major and minor strain values in uniaxial tension (i.e. left hand side of the FLD), will normally be underestimated than the experimental strain values [15]. However for biaxial range, (samples 1-4) the predicted finite element strain values are in good agreement with experimental findings.

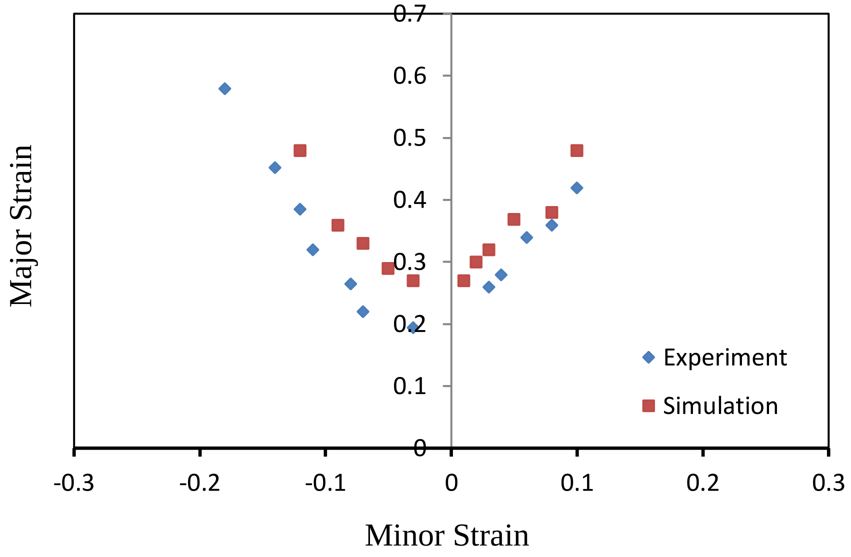

Fig. 7 Comparison of FEA and experimental FLD by Nakazima test

4. Evaluation of Formability of AISI 304 cup drawing test

In order to find the FLD of investigated AISI 304 steel sheets, the cup drawing test was conducted experimentally on the same material and simulated with the same input parameters using Abaqus 6.12.1. The purpose of the simulation was to estimate strain values at the critical failure area obtained from the experimental cup drawing test. During finite element simulation of the cup drawing test Tsai-Hill failure criterion was used to identify the failure regions of AISI 304 steel sheets. Failure locations of the cup drawing tests is shown in Fig.8.

Fig. 8 Identification of failure locations for cup drawing test

Fig.9 compares the experimental and numerical FLD withthe strain path of the crack initiating element obtained through simulation of cup drawing test. The crack initiating element was identified with the aid of experimental cup drawing test results. It is clearly seen that there is a deviation between the strain path identified by FEA of cup drawing test and the experimental FLD identified by Nakazima tests for the same material. This shows that failure criterion for this test is unable to predict the material failure accurately.

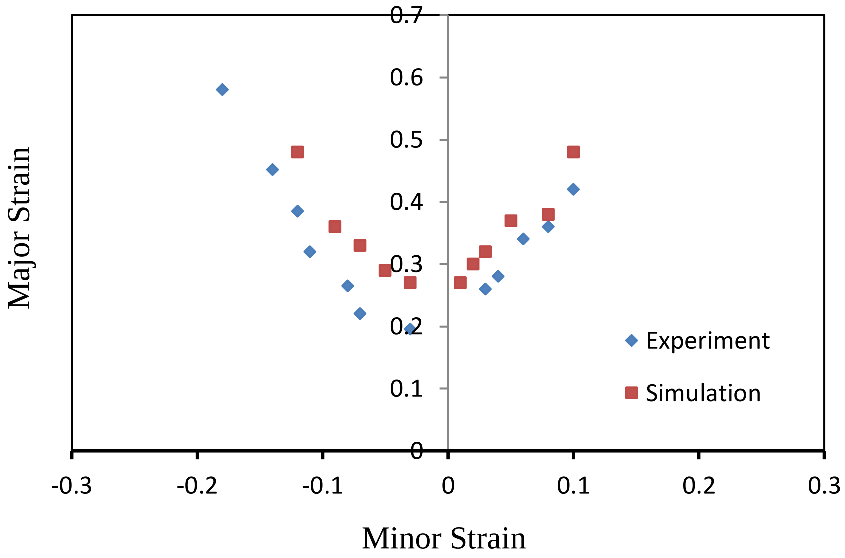

Fig. 9 Comparison of FEA experimental FLD by Cup drawing test

5. Conclusions

This study investigated the formability characteristics of AISI 304 steel sheets using FLD and FLSD.The FLD was plotted, by conducting the Nakazima test and by experimental approach. Simultaneously the test was simulated using Abaqus to identify the failure criterion. Finally, a cup drawing experiment was conducted on the same materialand the same experiment was simulated to demonstrate the accuracy of the predicted FLD. The results proved that the FLD identified by Nakazima test was in good agreement with cup drawing experiment. From the investigations it can be concluded that the FLDis able to predict the formability characteristics of AISI 304 steel sheets through Nakazima and Cup drawing tests.

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