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# Warm Deep Drawing of AISI 304: Thermo-Mechanical Simulation with a Temperature-Dependent Barlat Yield Law

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**Abstract**
Austenitic stainless steel AISI 304 is widely used in sheet components but its drawability at room temperature is limited by strain-induced martensite and anisotropy. This study examines warm deep drawing through coupled thermo-mechanical finite-element analysis and experiments. A plane-stress Barlat yield function with temperature-dependent parameters is identified from directional tensile tests and implemented in LS-DYNA. Simulations reproduce measured thickness profiles and predict a peak limiting drawing ratio near 150 °C. At higher temperatures the response deteriorates, consistent with dynamic strain aging. The results define a practical process window and highlight the need to calibrate anisotropy at each temperature.

Keywords: AISI 304; deep drawing; warm forming; Barlat; anisotropy; forming limit diagram; LS-DYNA.

## 1. Introduction

AISI 304 provides corrosion resistance and weldability, making it a common choice for formed sheet parts. At room temperature, drawability is curtailed by strain-induced martensite and planar anisotropy. Moderate heating can suppress martensite, lower flow stress, and improve formability. The present work evaluates warm deep drawing of 1 mm AISI 304 using experiments and finite-element simulation with an anisotropic yield law.

## 2. Background

Orthotropic yield criteria are essential for sheet metals. Hill's quadratic model and the Barlat family (Yld'89/Yld'91/Yld2000-2d) are widely used under plane stress. Forming limits are commonly assessed with forming-limit diagrams (FLDs). For austenitic stainless steels, several studies report better ductility and drawability between room temperature and about 150 °C, followed by degradation at higher temperatures associated with dynamic strain aging.

## 3. Materials and Methods

### 3.1 Material and Tests

Commercial AISI 304 sheet of 1 mm thickness was tested in uniaxial tension at a nominal strain rate of 0.01 $s^{-1}$. Specimens were cut along rolling, transverse, and diagonal directions. Tests were conducted from 50 to 350 °C in steps of 50 °C. Yield stresses and r-values were extracted for model identification.

### 3.2 Deep-Drawing Setup

Cylindrical cups were drawn with a flat-faced punch. Die radii, punch radii, blank diameters, and blank-holder force followed the experimental tooling set. A mineral-oil lubricant was used; the friction coefficient in simulation was set to 0.1. Blank, die, punch, and holder temperatures were controlled according to the target forming temperature.

### 3.3 Finite-Element Model

Numerical analyses were performed in Dynaform 5.6.1 with LS-DYNA 971. The blank was modeled using reduced-integration shell elements. Thermal contact, conduction through tooling, and convective/radiative losses were included. Tooling was treated as rigid for mechanics while retaining thermal properties.

### 3.4 Constitutive Description

A plane-stress Barlat yield function with three anisotropy parameters was adopted. Parameters were calibrated at each temperature using directional yield stresses and r-values. Isotropic hardening curves were taken from the corresponding tensile tests.

### 3.5 Validation Metrics

Validation used thickness profiles along the cup radius, the limiting drawing ratio (LDR), and distance to the FLD. Experimental thickness measurements were compared to simulated predictions at representative blank diameters.

## 4. Results

### 4.1 Thickness Distribution

Simulations reproduced the thicker flange, thinning in the wall, and the transition through the die-radius region. Increasing temperature from room temperature to 150 °C reduced wall thinning. Approaching 300 °C, a slight deterioration was observed, in line with the onset of serrated flow reported for this alloy.

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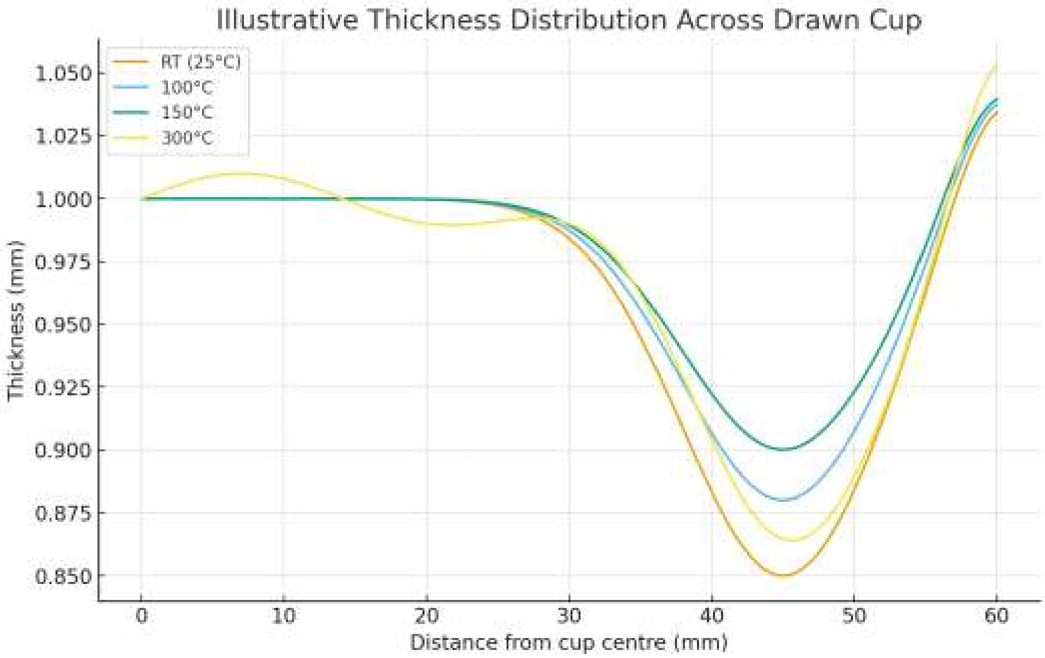


Figure 1. Thickness distribution across the drawn cup at several temperatures.

### 4.2 Limiting Drawing Ratio

The LDR showed a maximum near 150 °C. Lower values were obtained at room temperature and at temperatures close to 300 °C. This trend is consistent with the combined effects of martensite suppression at moderate temperatures and dynamic strain aging at higher temperatures.

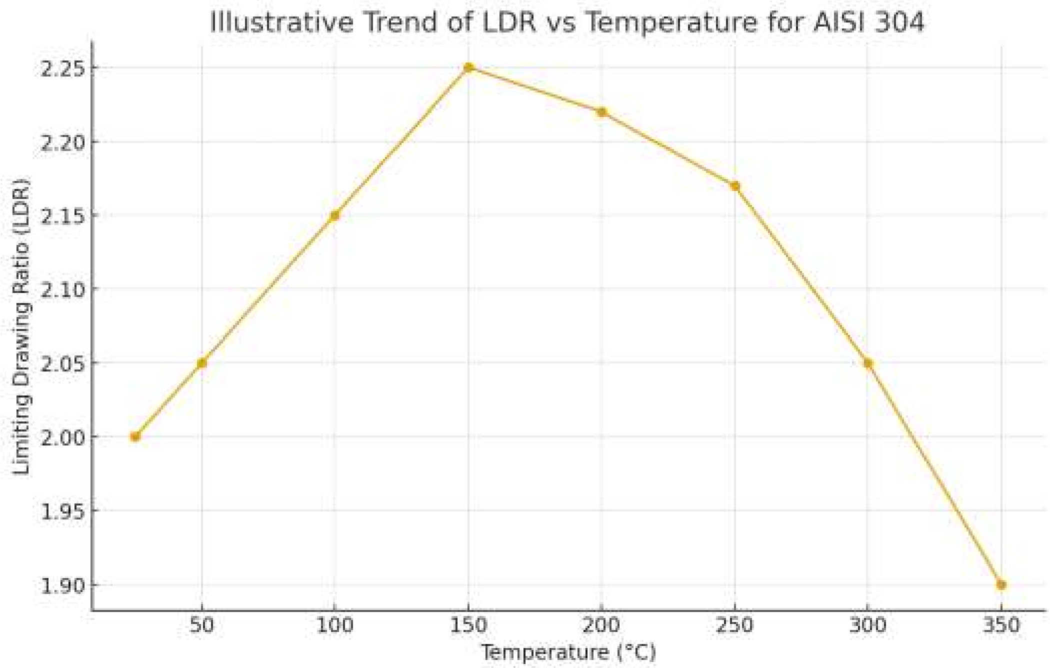


Figure 2. Limiting drawing ratio versus temperature for AISI 304.

### 4.3 Forming-Limit Diagrams

An upward shift of the forming-limit curve was observed at 150 °C relative to room temperature, particularly under biaxial stretching. This provides additional margin against localized necking during drawing.

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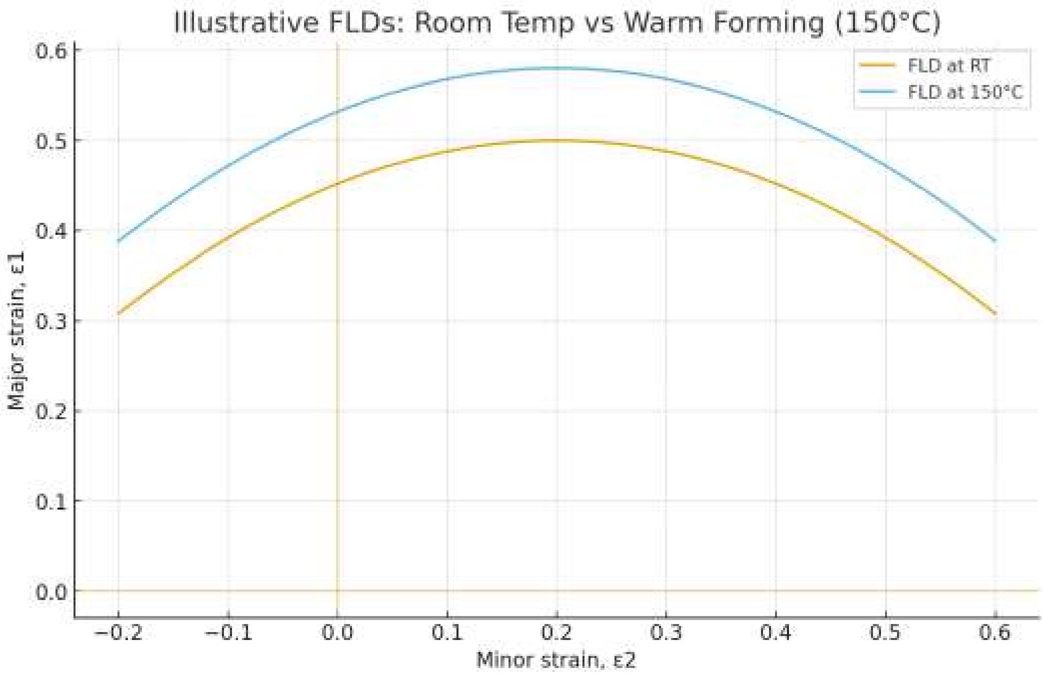


Figure 3. Schematic FLDs at room temperature and 150 °C.

## 5. Discussion

The temperature-dependent Barlat model captured planar anisotropy with a limited number of parameters that can be identified from standard tests. The predicted improvements near 150 °C and the degradation toward 300 °C agree with published observations on austenitic stainless steels. For industrial application, the recommended window for 1 mm AISI 304 under the present tooling is approximately 50–200 °C, with attention to tool heating, lubricant selection, and ram speed.

## 6. Conclusions

1) Warm forming improves drawability of AISI 304 up to about 150 °C; higher temperatures reduce performance.

2) A temperature-dependent Barlat yield law, calibrated at each temperature, reproduces measured thickness profiles and LDR trends.

3) Process windows should avoid the DSA-influenced regime and include thermal management for consistency.

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