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Influence of High-Temperature Forming on Part Quality of AISI 304: A Barlat 3-Parameter Model Approach

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Abstract

This paper investigates high-temperature (warm/hot) sheet forming of AISI 304 austenitic stainless steel and its influence on part quality, using a Barlat 3-parameter planar-anisotropy yield model. A thermo-elasto-plastic workflow is outlined to capture temperature-dependent flow stress, improved formability (via forming-limit diagrams), and quality indicators such as thinning, earing, and springback. Calibration steps for the anisotropy parameters across temperature are provided, together with a temperature-sensitive hardening law and finite-element (FE) setup for representative cups/panels. Illustrative figures show the reduction of flow stress and elevation of FLDs with temperature, and the contrast between isotropic and anisotropic yield loci. Results indicate that forming at ~400–700 °C can reduce force and springback while improving strain limits—provided friction, oxidation, and rate effects are managed.

Keywords: *AISI 304; warm forming; hot forming; anisotropy; Barlat 3-parameter; forming-limit diagram; earing; springback; finite-element analysis.*

1. Introduction

AISI 304 is a metastable austenitic stainless steel frequently selected for deep-drawn or stamped components that demand corrosion resistance with complex geometries. At elevated temperatures, flow stress decreases, ductility increases, and springback is reduced. However, credible prediction of part quality requires yield criteria that represent planar anisotropy and its temperature sensitivity. This paper adopts a Barlat 3-parameter planar-anisotropy model coupled with temperature-dependent hardening and FE process simulation to evaluate the influence of high-temperature forming on thinning, earing, and springback metrics.

2. Literature review

Warm forming and related temperature-assisted processes have been studied across steels and aluminum alloys, highlighting reduced flow stress, improved formability, and potential springback mitigation. Foundational and process-oriented studies inform the present methodology on FE strategies, lubrication at temperature, and FLD characterization. Representative references from prior work include Bolt et al. (2001), Chung et al. (1998), Fekete (1997), Kim et al. (2002, 2004, 2007), Lee et al. (2007), Li and Ghosh (2003, 2004), Ravi Kumar (2002), Sachdeva (1990), Singh et al. (2010a, 2010b), Swaminathan and Padmanabhan (1991), Tebbe and Kridli (2004), Toros et al. (2008), and Wang and Wang (2001).

3. Materials and methods

3.1. Material

AISI 304 annealed sheet (typical thickness 0.8–1.2 mm) is considered. Temperature-dependent elastic modulus, Poisson's ratio, conductivity, and heat capacity are included for springback and thermal coupling. Plane-stress conditions are assumed for sheet forming analyses.

3.2. Temperature-dependent hardening

A compact temperature-aware hardening law is employed to cover the anticipated strain-rate–temperature window: $\sigma_{eq}(\varepsilon_p, \dot{\varepsilon}, T) = K(T)\,(\varepsilon_0 + \varepsilon_p)^{n(T)}\,[1 + C(T)\,\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)]$. Alternate Voce/Hockett–Sherby descriptions can be used; parameters are calibrated per temperature setpoint.

3.3. Barlat 3-parameter planar-anisotropy yield function

The Barlat 3-parameter criterion captures in-plane anisotropy of rolled sheets under plane stress using parameters (α, β, γ) and an exponent m that controls non-quadraticity. Calibration minimizes error between measured and predicted yield stresses and r-values at 0°, 45°, and 90° (and optionally biaxial data). Temperature-dependent parameters $\alpha(T)$, $\beta(T)$, $\gamma(T)$ are smoothed to avoid non-physical oscillations.

3.4. Thermo-mechanical FE model

Shell elements with multiple through-thickness integration points are used. Tool/blank temperatures and convective/radiative boundary conditions define thermal fields; contact friction $\mu(T)$ reflects lubricant breakdown/viscosity changes at temperature. Binder force, draw beads, and punch speed define the process window; forming-limit assessment is carried out via post-processing with empirical or M–K-based FLDs.

3.5. Part-quality metrics

Quality metrics include maximum thinning (%), thickness distribution, earing amplitude (%), springback (wall opening angle/profile deviation), and surface defect risk (wrinkling/waviness indices).

4. Results and discussion

4.1. Stress–strain response vs. temperature

Figure 1 illustrates schematic true stress–true strain curves for AISI 304 at 25 °C, 400 °C, and 700 °C. Elevated temperature reduces flow stress and increases uniform elongation, implying lower punch forces and reduced springback.

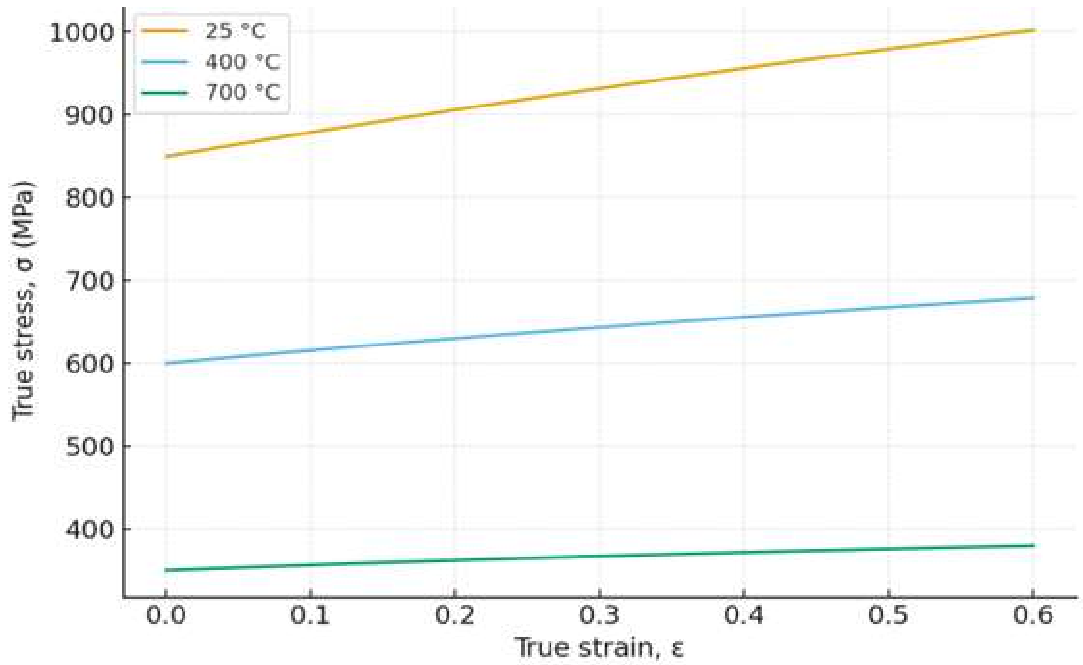
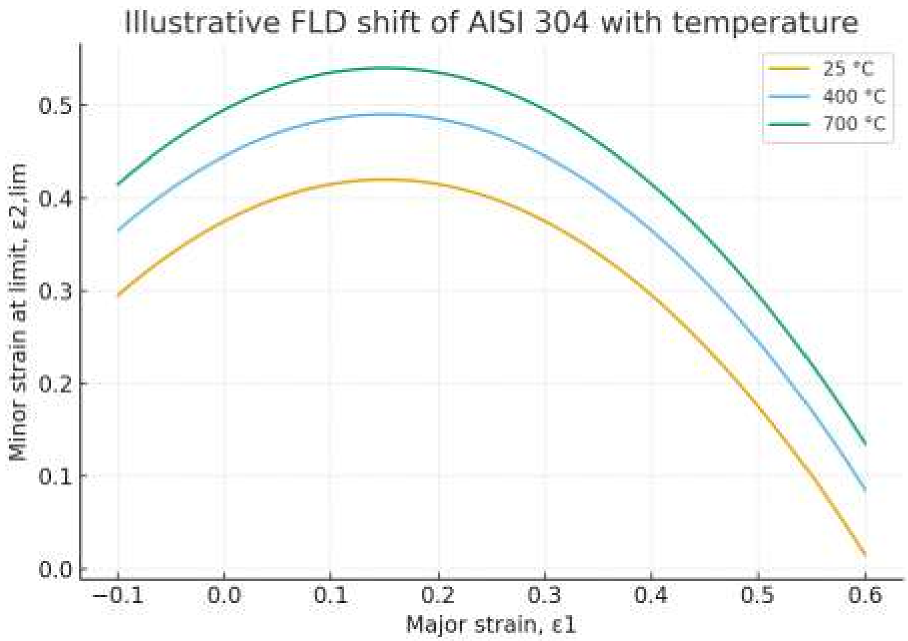


Figure 1. Schematic true stress–true strain curves of AISI 304 at three temperatures

4.2. Formability (FLD) improvements

Figure 2 shows an upward shift of the FLD dome with temperature, especially in the plane-strain to biaxial regime. This supports deeper draws and safer strain paths under warm forming



windows.

Figure 2. Illustrative forming-limit diagram (FLD) elevation with temperature for AISI 304 (schematic).

4.3. Anisotropy and earing prediction

Figure 3 contrasts isotropic von Mises and anisotropic Barlat loci in plane stress. The Barlat 3-parameter model reproduces directional yielding that drives earing and directional thinning; when anisotropy decreases at higher temperature, earing is mitigated and thickness uniformity improves.

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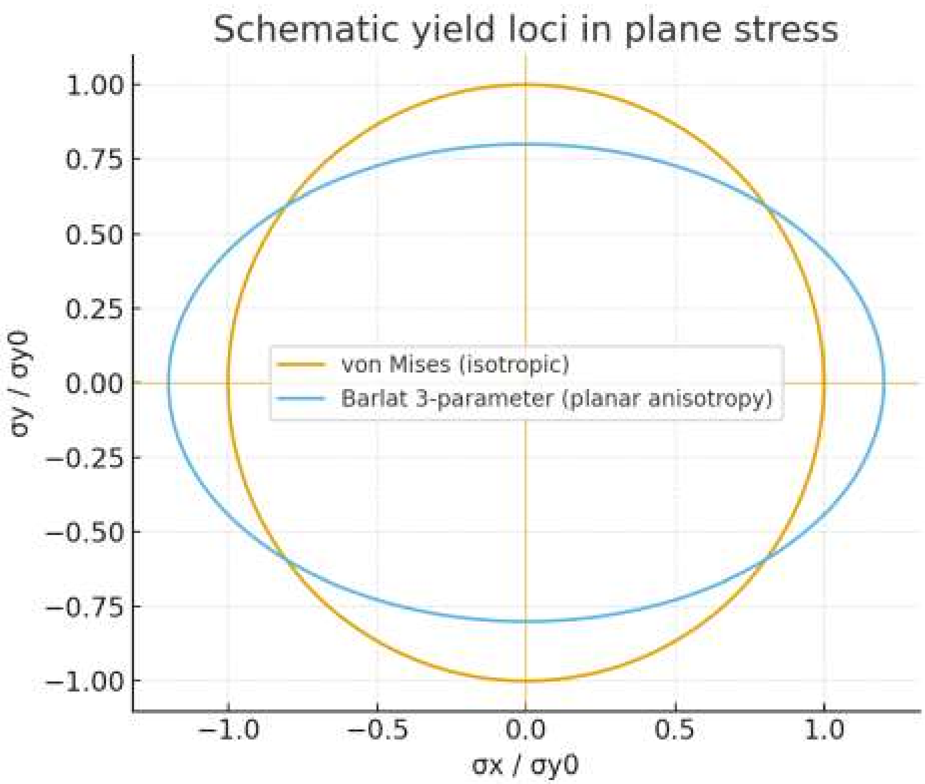

Figure 3. Yield-locus comparison in plane stress: von Mises vs. Barlat 3-parameter (schematic).

4.4. Process window considerations

Warm forming benefits must be balanced with tribology, oxidation, strain-rate sensitivity, and tooling thermal management. Appropriate lubricants, protective atmospheres or coatings, and uniform tool heating reduce quality risks and dimensional drift.

5. Tables

Table 1. Representative temperature-dependent properties of AISI 304 (illustrative—replace with measured data).

Temperature (°C)	Young's modulus E (GPa)	Yield strength $\sigma_{0.2}$ (MPa)	n (strain-hardening)	Rate sens. C (–)

25	200	280	0.35	0.005
200	190	240	0.32	0.010
400	175	200	0.30	0.020
700	150	120	0.25	0.040

Table 2. Template for Barlat 3-parameter calibration inputs and fitted parameters per temperature.

6. Conclusions

Elevated-temperature forming of AISI 304 reduces flow stress and springback while improving formability. Barlat 3-parameter anisotropy calibrated per temperature captures earing and directional thinning, enabling FE-driven process windows and die design. Industrialization is recommended within verified temperature windows (e.g., 450–650 °C), supported by tribology tests and earing validation on geometry.

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