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FORECASTING THE QUALITY OF DRAWING OF THIN-WALLED SQUARE PARTS FROM MATERIALS WITH TRANSVERSE ANISOTROPY PROPERTIES

Abstract: *In this article, based on numerical modeling of the dynamics of the drawing process of thin-walled square parts from materials with transverse anisotropy properties, an analysis of the plastic deformation of materials was performed using the forming limit diagram. For each material studied, calculated values of the parameters are presented, according to which the risk of sheet metal failure under drawing conditions was assessed.*
Key words: *drawing, part, forming limit diagram, material, strain, stress.*
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1. Introduction

The drawing process inherently subjects sheet metal parts to strong biaxial and uniaxial deformations. For thin-walled geometries such as square sections, the deformation state varies significantly across the surface of the part, leading to potential localized failure mechanisms. The main difficulty lies in quantifying the fracture resistance of a material under these diverse high strain conditions. When materials exhibit transverse anisotropy - that is, their mechanical properties differ significantly when measured along the rolling direction compared to the transverse direction - the assumption of isotropic material behavior, which underlies many simplified forming models, becomes fundamentally invalid.

Forming limit diagrams are empirical charts that define the safe range of operating conditions for a material under plane strain conditions. They are constructed by testing materials until local contraction or failure occurs, thus determining the combination of primary and secondary principal strains (ε_1 and ε_2) beyond which failure is expected. In the context of predicting the quality of drawn parts, the forming limit diagram serves as the main predictive tool. It allows engineers to display the actual deformation path experienced by a material during a forming operation and compare it to established failure limits. If the calculated deformation path crosses the failure limit defined by the forming limit diagram, the component is predicted to undergo unacceptable strain or failure.

By systematically drawing and testing materials exhibiting varying degrees of transverse anisotropy, the study aims to clarify the relationship between the microstructural orientation of the material, the applied strain tensor during drawing, and the resulting strain state. Additionally, by analyzing the safe area deviation, secondary quality indicators such as excessive thinning or localized plastic strain can be predicted, thereby optimizing tooling parameters, drawing blank size, or process speed to ensure the final component meets stringent engineering requirements.

A key component of this research direction is the use of advanced modeling techniques, in particular finite element analysis in combination with the use of forming limit diagram. Studies such as those conducted by Stoughton et al. [1] have significantly advanced the understanding of the parameters that determine the structural integrity of these materials during the forming process. This paper addresses the need for robust and comprehensive methodologies to predict the limits beyond which sheet metal deformation will result in unacceptable material failure or dimensional inaccuracy. Several studies have been devoted to improving the prediction accuracy of forming limit diagrams using different and comprehensive methodologies [4]. In addition, the application of the finite element method to the analysis of deep drawing processes has made it possible to obtain detailed information on the behavior of the material under complex loading conditions [2]. These analyses are critical for assessing the deformation state of sheet metal, allowing researchers to accurately identify areas susceptible to failure before physical prototyping is required [3].

The research also goes deep into optimizing the process parameters themselves. Studies have shown that operational variables such as workpiece holding force have a significant influence on the resulting deformation paths during deep drawing, requiring careful consideration of these factors to control the process [7]. Similarly, it has been shown that precise alignment of tooling elements, such as die and punch alignment, determines the thinning behavior in certain geometries, such as deep drawing of square aluminum parts [9]. In addition to primary forming processes, secondary processes such as hot stamping require special attention, with studies determining the interaction between process parameters and the resulting residual stress profiles, including local sheet thickening [5].

The formability assessment was adapted for different metal substrates. Research has specifically focused on the deep drawing behavior of specialized materials including stainless steel sheet using integral approaches [8], and commercially pure titanium where finite element analysis provided an accurate assessment of formability [10]. In addition, comparative analyses were conducted to evaluate the influence of tooling design by comparing the results of different punch configurations on deep drawn aluminum sheets, allowing empirical recommendations to be proposed for process selection [6].

Accurately predicting material behavior and structural integrity during complex sheet metal forming operations remains a critical challenge in modern manufacturing engineering. This paper addresses the challenging problem of predicting the quality of thin-walled square parts subjected to the drawing process using an analytical model based on forming limit diagrams. Central to this research is the careful characterization and subsequent modeling of various materials that exhibit pronounced transverse anisotropy, which significantly complicates traditional forming prediction methods.

2. Materials and methods

To analyze the quality of the material after plastic deformation, forming limit diagrams were used. The process of drawing of a thin-walled box-shaped part was simulated using the LS-DYNA program in a three-dimensional setting. For this purpose, shell models of the square blank and the drawing die parts were constructed. The comparison of the formability effect and fracture prediction was performed for the following materials with transverse anisotropy properties: DC01 structural high-quality carbon steel, DC05 high-quality cold-rolled low-carbon steel, AISI 304 austenitic stainless steel, S355MC high strength low-alloy steel, 5754 deformable aluminum alloy, and Ti Grade 4 commercially pure titanium. The dimensions of the models, properties of the materials, and conditions for simulating the drawing process are presented in [11].

Taking into account the high quality requirements of the part, the following criteria were adopted for the formability analysis:

1. Limit % FLC = 0%;
2. Safety margin % FLC = 20%;
3. Allowable thinning = 0.3 or 30%;
4. Essential thinning = 0.02 or 2%;
5. Allowable thickening = 0.01 or 1%.

The parameters set a strict, highly secure shaping mode. Modeling with such parameters strictly rejects any areas with a hint of folds (due to the 1% allowable thickening) and areas with a risk of cracking (due to the 20% FLC safety margin).

3. Results and discussion

The results of finite element modeling are presented in Figure 1 in the form of formability maps for assessing the quality of the drawing process of a 0.8 mm thick metal sheet to a depth of 20 mm.

Formability maps show areas of good formability (green) in the central drawing zone for all materials, with wrinkling tendencies (blue) and wrinkling (magenta) appearing primarily in the peripheral zones. Areas marked as inadequate stretch (gray) border these zones, indicating a risk of inadequate stretch.

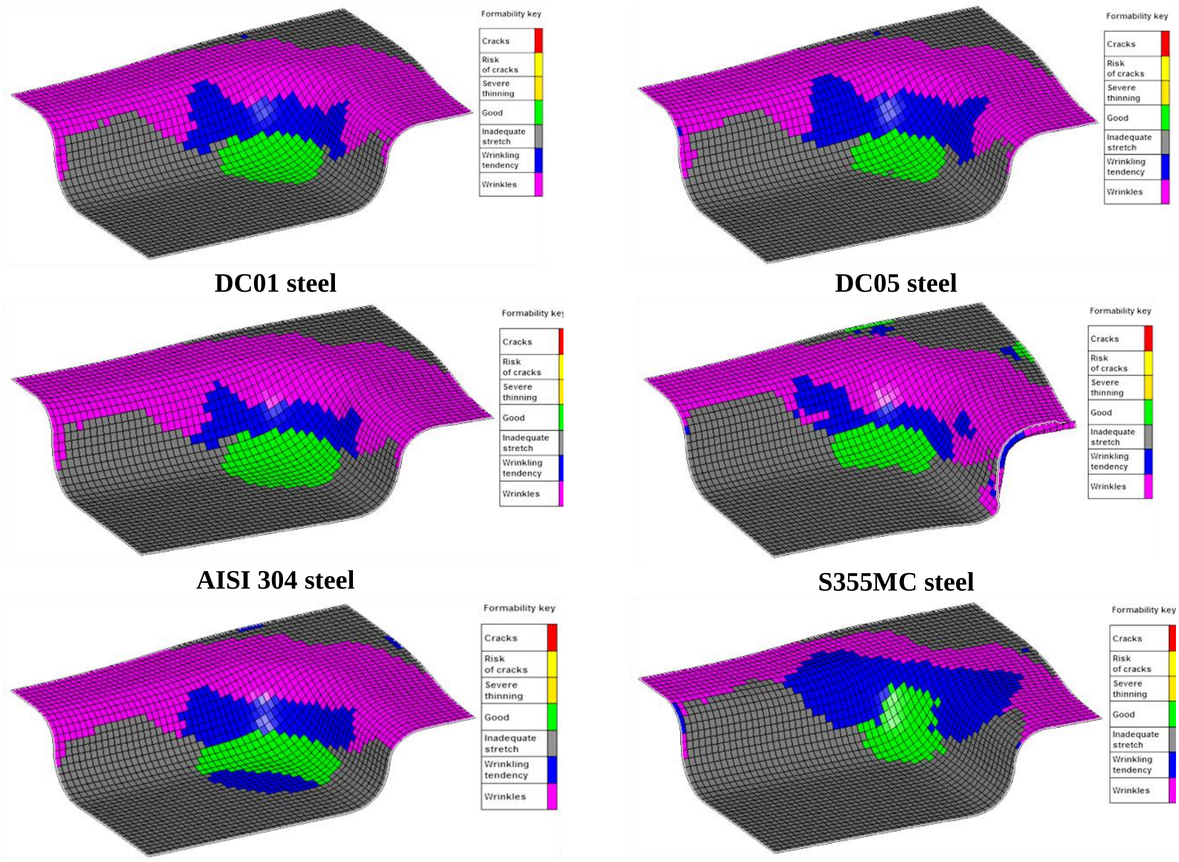

Figure 1. Formability maps of the studied materials after drawing.

DC01 structural high-quality carbon steel and DC05 high-quality cold-rolled low-carbon steel exhibit similar formability trends with strain hardening values *n* of 0.20 and 0.22, respectively, combining moderate tensile strength and controlled wrinkling.

AISI 304 austenitic stainless steel, with the highest strain hardening value (n = 0.45), exhibits better cracking resistance but more significant wrinkling, which is explained by lower tensile strengths and higher yield strength.

S355MC high strength low-alloy steel exhibits significant strain hardening (n = 0.15) but higher stress ranges resulting in more wrinkling and insufficient tensile zones, indicating problems in deep drawing.

5754 deformable aluminum alloy exhibits moderate strain hardening (n = 0.25) and relatively balanced formability with fewer cracks and wrinkles.

Ti Grade 4 commercially pure titanium has the lowest strain hardening value (n = 0.12), but a high yield strength, causing significant wrinkling and limited formability during drawing.

Table 1 presents the calculated ranges of parameter values for a detailed analysis of the formability of the studied metal alloys. The following parameters were calculated:

1. $\varepsilon_{1,actual}/\varepsilon_{1,limit}$ is the safety factor for failure. If $\varepsilon_{1,actual}/\varepsilon_{1,limit} > 1.0$, the material is guaranteed to fail; if $\varepsilon_{1,actual}/\varepsilon_{1,limit}$ = 0.9 - 1.0, the material is at risk of failure; if $\varepsilon_{1,actual}/\varepsilon_{1,limit}$ = 0.7 - 0.9, the material is in the safe zone; if $\varepsilon_{1,actual}/\varepsilon_{1,limit} = 0$, the material is at risk of wrinkling.

2. $\varepsilon_{1,limit} - \varepsilon_{1,actual}$ is engineering safety margin of sheet metal during drawing. $\varepsilon_{1,limit} - \varepsilon_{1,actual} > 0$ is the safety factor of the material; $\varepsilon_{1,limit} - \varepsilon_{1,actual} < 0$ is rupture or local thinning.

3. $\varepsilon_{1,actual}$ is the current, actual value of the principal stretch in each specific element of the model grid.

4. ε_2 is the maximum minor strain in the material. $\varepsilon_2 > 0$ is biaxial tension, $\varepsilon_2 = 0$ is plane strain, and $\varepsilon_2 < 0$ is pure shear.

5. τ_{max} is maximum tangential (shear) stress.

6. σ_1 is the first (maximum) principal stress in the material. σ_1 shows the greatest tensile force acting at a particular point of the part.

7. σ_2 is the second principal stress in the material. σ_2 represents the normal stress that acts perpendicular to the first principal stress σ_1.

Table 1. Calculated ranges of parameter values based on the forming limit diagrams of the studied metal alloys.

Parameter	***DC01 steel***	***DC05 steel***	***AISI 304 steel***
$\varepsilon_{1,actual}/\varepsilon_{1,limit}$	0…0.3197	0…0.3168	0…0.1745
$\varepsilon_{1,limit} - \varepsilon_{1,actual}$	0…0.4756	0…0.4956	0…0.8977
$\varepsilon_{1,actual}$	-0.0004…0.1898	-0.0003…0.2023	-0.0006…0.1765
ε_2	-0.1354…0.0145	-0.1384…0.0141	-0.1319…0.02
τ_{max}	4.8689…358.078	2.4589…336.319	2.7596…365.083
σ_1	-157.848…490.503	-128.368…496.461	-167.923…475.995
σ_2	-461.356…448.601	-420.515…458.806	-478.473…410.056
Parameter	***S355MC steel***	***5754 aluminum alloy***	***Ti Grade 4***
$\varepsilon_{1,actual}/\varepsilon_{1,limit}$	0…1.1298	0…0.7662	0…0.6111
$\varepsilon_{1,limit} - \varepsilon_{1,actual}$	0…0.9452	0…0.372	0…0.3526
$\varepsilon_{1,actual}$	-0.0008…0.3291	-0.0013…0.2028	-7.8051×10^{-6}…0.3449
ε_2	-0.1251…0.061	-0.1654…0.0664	-0.2171…0.0105
τ_{max}	4.5069…687.827	10.3083…159.777	24.8777…515.83
σ_1	-290.678…1331.74	-39.7456…272.215	-223.934…1372.21
σ_2	-620.75…835.693	-188.692…206.019	-705.862…1180.43

DC01 structural high-quality carbon steel and DC05 high-quality cold-rolled low-carbon steel are in the safe zone with safety factors well below 1.0, indicating no risk of fracture or wrinkling. AISI 304 austenitic stainless steel also exhibits good strength with a safety factor, but has a smaller safety factor compared to the previous ones. High-strength low-alloy steel S355MC is distinguished by its maximum safety factor, which in some places exceeds 1.0, indicating a potential risk of fracture under given drawing conditions. This requires additional attention when choosing the processing mode. For 5754 deformable aluminum alloy and Ti Grade 4 commercially pure titanium, the safety factors are within the safe zone, but with a smaller safety factor than carbon steels.

4. Conclusion

The formability and quality of the drawing process of a square-shaped part are closely correlated with the strain hardening index, strain limits, and stress distribution. Materials such as AISI 304 austenitic stainless steel and 5754 deformable aluminum alloy provide higher quality drawing with fewer cracks and wrinkles due to higher strain hardening and a balanced stress state. In contrast, S355MC high strength low-alloy steel and Ti Grade 4 commercially pure titanium present formability issues, manifested by increased wrinkling and inadequate stretch area, limiting their suitability for deep drawing to a given depth and sheet thickness.

Comparison of the finite element analysis results with observed production results confirms the predictive ability of the model. The areas identified by the simulation as prone to wrinkling or inadequate stretch closely correspond to defects observed during physical drawing, confirming the feasibility of using finite element analysis to optimize the process for various materials.

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