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WRINKLING PREDICTION IN METAL SPINNING THROUGH NUMERICAL SIMULATION: IMPACT OF LOADING RATE AND MASS SCALING

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Abstract

Metal spinning is an incremental sheet metal forming technique used to manufacture axisymmetric, thin-walled parts, ranging from rocket nose cones and jet engine components to automotive connecting rods and everyday items like ventilation ducts and kitchenware. A primary challenge in this process is the occurrence of wrinkling, especially when forming complex geometries. Although manufacturers often mitigate this defect through methods such as flanging or constraint spinning, determining the optimal spinning conditions typically relies on trial and error. This study aims to predict wrinkling in metal spinning using numerical simulations that are validated by experimental trials. Two common computational acceleration techniques, such as increasing the loading rate and applying mass scaling, are examined for their impact on material behavior and defect formation. A comprehensive analysis shows that when both the mass scaling factor and loading rate are kept below a threshold of 10, the simulation results closely mirror experimental observations. This correlation is attributed to the simulations' effective capture of the dynamic and inertial behaviors inherent in the spinning process. Overall, these findings emphasize the need for careful control of loading rate and mass scaling to preserve simulation accuracy, as excessive increases in these parameters lead to notable deviations from real world behavior.

Keywords: mandrel free spinning, toolpath, mass scaling, loading rate.

I. INTRODUCTION

Metal spinning is an incremental sheet metal forming technique renowned for producing axisymmetric, thin-walled parts with minimal waste, low forming forces, and excellent surface finishes. Its applications span critical aerospace components like rocket nose cones and jet engine casings to everyday items like kitchenware. Unlike traditional methods such as deep drawing or stamping, metal spinning incrementally shapes a rotating metal blank over a mandrel using a roller, offering flexibility and efficiency. However, wrinkling remains a persistent challenge, especially in complex geometries, where compressive stresses in unsupported regions (e.g., the flange) lead to buckling and compromise part quality [1, 2]. This defect not only affects aesthetics but also weakens structural integrity, making its prevention a priority for manufacturers.

Historically, wrinkling has been managed through empirical approaches, such as adjusting roller paths, adding constraining tools, or pre-forming the blank (e.g., flanging) [4]. These methods, while effective, depend on trial-and-error, driving up costs and hindering repeatability, particularly as industries demand lightweight, intricate designs [5]. To address this, finite element (FE) simulations have emerged as a powerful tool, offering insights into stress distributions, plastic strain, and defect formation [6, 7]. By simulating the spinning process, engineers can optimize parameters virtually, reducing the need for physical prototypes.

Explicit finite element simulations are highly effective at capturing the localized deformations in metal spinning, though they demand substantial computational resources because of the need for very fine meshes and small-time increments [6]. To enhance efficiency, two common acceleration methods are employed. Mass scaling increases the density of the elements, which permits larger time steps while preserving solver stability [10]. In contrast, loading rate scaling accelerates the movement of the tool, thereby reducing the overall simulation duration [8, 11]. However, when applied excessively, both techniques can introduce artificial inertial effects that cause deviations from actual physical behavior [9].

This study develops a predictive framework for wrinkling in metal spinning by combining FE simulations with experimental validation. We systematically analyze how mass scaling (using Abaqus Explicit) and loading rate scaling (using LS-DYNA) affect simulation accuracy, aiming to balance computational speed with physical fidelity. Our findings offer actionable guidelines for engineers to enhance part quality, reduce costs, and streamline production in metal spinning applications.

II. METHODOLOGY

This research integrates computational simulations and experimental trials to study wrinkling during the first pass of metal spinning. The goal is to correlate FE predictions with experimental outcomes, focusing on wrinkling onset and force-displacement behavior, while evaluating the impact of scaling techniques. Simulations were conducted using LS-DYNA (for loading rate scaling) and Abaqus Explicit (for mass scaling), with scaling factors outlined in Table 1. These values span from near-quasi-static (close to real-world conditions) to highly accelerated scenarios, identifying a critical threshold of 10 for accuracy.

TABLE 1. SIMULATION CONDITIONS FOR LOADING RATE (LR) AND MASS SCALING (MS) FACTORS.

	LS Dyna	**Abaqus**
Case	***Loading rate (LR)***	***Mass scaling (MS)***
1	5	5
2	10	10
3	50	50

A. *Simulation model setup*

A robust three-dimensional FE model was developed to simulate the first pass of metal spinning process using shell elements to balance computational time and accuracy. It has been reported that continuum shell elements can accurately represent thin-walled structures in sheet metal forming. To reproduce the first pass in the numerical simulation, the spinning tool was programmed to follow the same experimentally predefined concave curve with a maximum axial stroke of h=30 mm. This profile is expected to impose a complex deformation condition that is critical for initiating wrinkling. The blank is modeled using an elastoplastic constitutive law with Hollomon hardening with the characteristic parameters of the AA5052-O aluminum alloy

$$\bar{\sigma} = 355\varepsilon^{0.29} \tag{1}$$

Material parameters were calibrated using standard tensile tests to ensure realistic behavior. Fig. 1 illustrates the detailed FE model configuration.

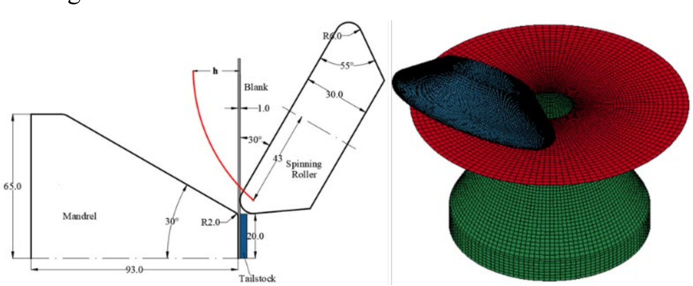

Fig. 1 Detail of FE model

B. *Numerical simulation framework*

To enhance computational efficiency, two acceleration strategies were independently examined in LS-DYNA and Abaqus Explicit.

- Loading Rate (LR) variation (LS-DYNA): An explicit time integration scheme was employed in LS-DYNA, scaling the rotational speed from 5 to 50 times the nominal rate. This approach maintains physical mass distribution and can achieve significant computational time reductions. However, higher speeds may introduce spurious inertial effects if the tool velocity exceeds realistic ranges.
- Mass Scaling (MS) variation (Abaqus explicit): In Abaqus explicit, mass scaling factors ranging from 5 to 50 were used to artificially increase element density. This approach allows larger stable time increments, thereby shortening total runtime. Although moderate mass scaling does not significantly distort physical results, excessive scaling can lead to unrealistic inertia that can overshadow actual forming behavior.

In both software environments, an identical mesh strategy was employed to facilitate direct comparison. Fig. 2 shows the meshing strategy, featuring a bias of 3.0 for the radial direction (38 elements) and 120 circumferential elements without bias. The smallest element dimension was further refined in the flange region, where wrinkling is most likely to occur. Additionally, a circular opening of 30 mm was included at the center to better capture deformations around the blank's boundary and reduce excessive element distortion.

All simulations were conducted under comparable boundary and loading conditions. In LS-DYNA, the rotational mandrel speed varied according to the chosen LR factor, while in Abaqus, the density scaling ensured a stable time step. Energy tests were performed to confirm that mesh refinement beyond the stated discretization yielded negligible changes in stress distribution and wrinkle amplitude for moderate scaling levels.

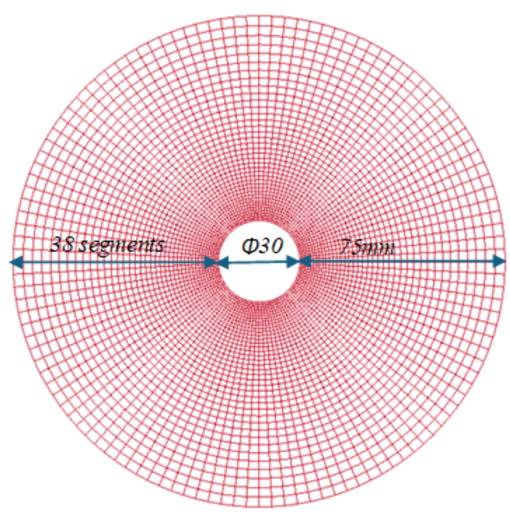

Fig. 2 Meshing strategy for FE model

III. RESULTS AND DISCUSSION

This section elaborates on the outcomes of numerical simulations and experimental trials conducted to investigate wrinkling in metal spinning, with a focus on the effects of mass scaling and loading rate scaling in finite element (FE) simulations. The analysis is divided into three key areas: (1) the influence of mass scaling versus loading rate scaling on simulation dynamics, (2) the comparison of simulated force-displacement curves with experimental measurements, and (3) the accuracy of wrinkling onset predictions. Each subsection includes a detailed examination of the corresponding figures, analyzing trends, identifying discrepancies, and discussing their significance for improving simulation fidelity and optimizing the spinning process.

A. Influence of mass scaling and load rate scaling

Mass scaling and loading rate scaling are computational techniques employed to reduce the runtime of explicit FE simulations. However, their application alters the dynamic behavior of the system, affecting the accuracy of wrinkling predictions. This subsection compares their effects using energy ratios as a metric for simulation fidelity.

- Loading rate scaling (LS-DYNA): In this approach, the rotational speed of the mandrel is increased to accelerate the deformation process. For scaling factors up to 10, equivalent to an effective mandrel speed of approximately 2000 rpm, the simulation retains a quasi-static response, with inertial effects remaining minimal. Beyond this threshold, such as at a scaling factor of 5, the mandrel speed becomes unrealistically high, amplifying inertial forces. These forces distort the stress field, potentially masking or amplifying wrinkling tendencies.

- Mass scaling (Abaqus explicit): This method increases the density of the elements to allow larger time steps. At scaling factors up to 10, the additional inertia has a negligible impact, preserving the quasi-static nature of the process. However, at higher factors (e.g., 50), the increased density slows stress wave propagation, as dictated by the relation $\Delta t \sim \frac{\rho}{E}$ (where Δt is the time step, ρ is density, and E is Young's modulus). This delay alters deformation patterns, particularly in wrinkle-prone regions.

For scaling factors of 5 and 10, both software platforms produce ratios below 0.05, aligning with the quasi-static nature of metal spinning. However, at a scaling factor of 50, LS-DYNA exhibits a higher ratio (0.22) than Abaqus (0.16), suggesting that loading rate scaling introduces more pronounced dynamic artifacts than mass scaling.

The trends in Fig. 3 highlight a critical threshold where scaling factors up to 10 maintain a low kinetic-to-internal energy ratio, ensuring that the simulations accurately represent the physical process. Beyond this limit, inertial effects dominate, compromising reliability. In LS-DYNA, excessive loading rate scaling increases mandrel speed, introducing artificial dynamic forces that may suppress wrinkling by stabilizing the deformation through inertia. In Abaqus, high mass scaling delays stress wave propagation, potentially postponing wrinkle initiation. These distortions suggest that scaling factors should not exceed 10 to ensure dependable predictions for process optimization. The slight advantage of mass scaling over loading rate scaling at higher factors (lower energy ratio) indicates it may be a more robust choice for maintaining simulation accuracy when moderate acceleration is required.

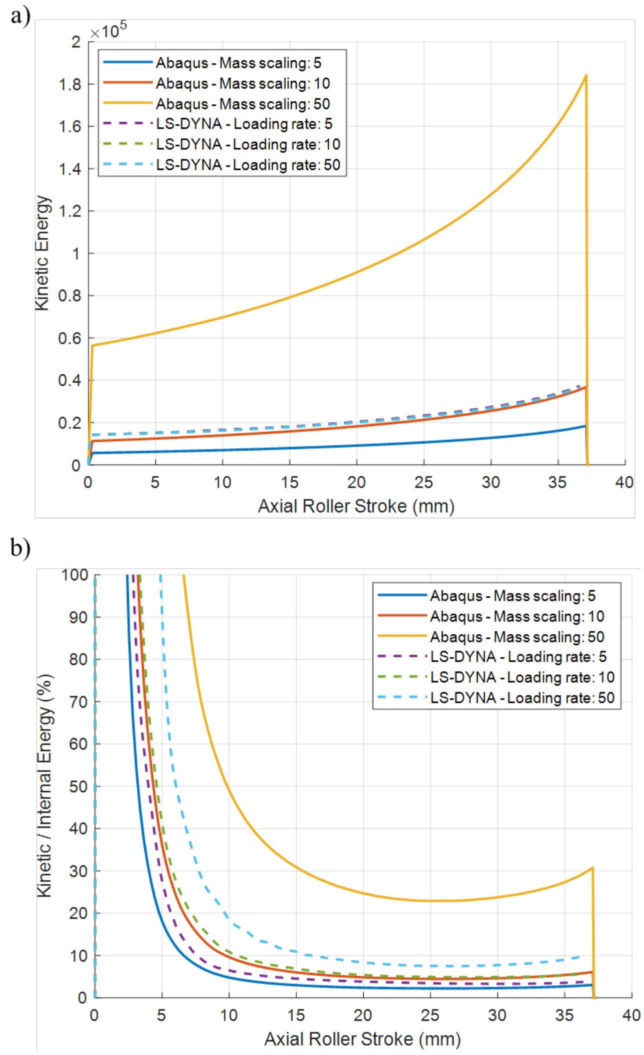

Fig. 3 a) Kinetic energy and b) ratio of kinetic energy and internal energy with mass scaling and loading rate in ABAQUS and LS DYNA

B. Force-displacement: Comparison with experimental data

When both mass scaling and loading rate scaling factors are maintained below the critical threshold of 10, the simulation reliably captures the onset of wrinkling. In these conditions, the formation of a plastic hinge at the blank edge, indicative of the transition to a wrinkled state, is observed. This behavior is consistent with the mechanisms reported by Watson and Long [12], wherein a reduction in bending moments signals an energetically favorable shift toward instability.

In metal spinning, the axial force reflects the material's resistance to deformation and provides insight into process stability. Fig. 4 plots the axial force as a function of roller stroke, offering a direct comparison between simulation and experiment. Initially, the axial force rises sharply as the roller begins deforming the blank, reflecting the effort required to overcome elastic resistance and initiate plastic deformation. As the roller stroke progresses, the force plateaus or slightly decreases, indicating that the material has yielded, and less force is needed to sustain deformation. The ABAQUS simulation, employing a mass scaling factor of 10, closely mirrors the experimental curve, especially during the initial loading phase. However, at higher roller strokes, the simulated force slightly exceeds the experimental values, suggesting an overestimation of the resistance to deformation. In contrast, the LS-DYNA simulation, using a loading rate scaling factor of 10, follows the experimental trend but consistently underestimates the force across the stroke range, indicating a lower predicted resistance.

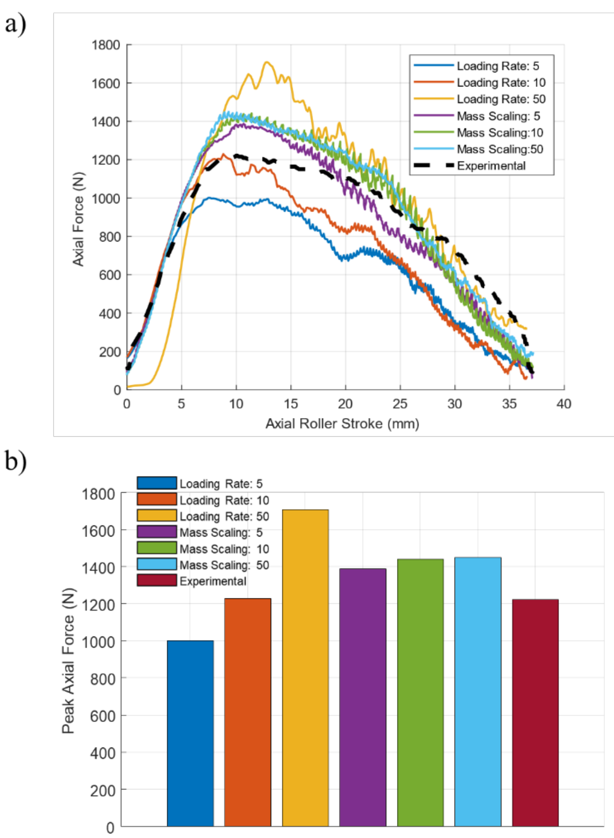

Fig. 4 Comparison of loading rate scaling, mass scaling, and experimental data: (a) axial force–displacement curves, and (b) the peak axial force during the spinning process.

The simulations capture the general force-displacement behavior but exhibit distinct deviations:

- Abaqus overestimation: The higher forces in Abaqus likely stem from the increased element density (mass scaling), which enhances inertial resistance and stiffens the material response. This effect becomes more pronounced at larger strokes, where cumulative inertia amplifies the discrepancy.
- LS-DYNA underestimation: The lower forces in LS-DYNA result from the accelerated deformation rate, which reduces the time available for strain rate-dependent material responses (e.g., hardening or relaxation), leading to a softer predicted behavior.

Despite these differences, both simulations are sufficiently accurate for practical purposes, such as identifying stable process windows or optimizing roller feed rates. The errors (4–9%) are within acceptable tolerances for industrial applications focused on defect prevention rather than exact force matching. For greater precision, reducing the scaling factor (e.g., to 5) or incorporating material damping could align the curves more closely with experimental data. These results affirm the utility of scaled simulations as a cost-effective tool for process design.

C. *Wrinkling prediction*

Accurate prediction of wrinkling onset and its spatial distribution is essential for preventing defects in metal spinning. Fig. 5 compares axial displacement patterns, indicative of wrinkle formation, at a roller stroke of 30 mm across Abaqus (MS=10), LS-DYNA (LR=10), and experimental results. It illustrates the axial displacement along the flange circumference, highlighting wrinkle locations and amplitudes. These amplitudes are symmetrically arranged around the blank's circumference, consistent with the axisymmetric nature of the spinning operation. In contrast, the ABAQUS and LS-DYNA simulations aim to replicate this behavior under their respective scaling conditions, providing insight into the effectiveness of these computational approaches.

Both simulations successfully predict the wrinkling mode (number and location of wrinkles), demonstrating their effectiveness as predictive tools:

- Abaqus overprediction: The higher displacement in Abaqus may result from the added inertia of mass scaling, which exaggerates local buckling in the flange by amplifying deformation under compressive stress.
- LS-DYNA underprediction: The lower displacement in LS-DYNA could be due to the accelerated loading rate, which limits the time for wrinkles to fully develop, effectively damping their growth.

These minor amplitude discrepancies (8% error) do not undermine the simulations' ability to identify critical wrinkling regions, which is vital for process optimization. The consistent prediction of 12 wrinkles aligns with the axisymmetric mechanics of spinning and corroborates the plastic hinge mechanism proposed in prior studies where residual bending moments in the flange trigger buckling [12]. Manufacturers can leverage these insights to adjust parameters like roller path or blank thickness, minimizing wrinkling without extensive physical prototyping. Scaling factors of 10 thus strike a balance between computational efficiency and predictive accuracy for wrinkling analysis.

a)

b)

c)

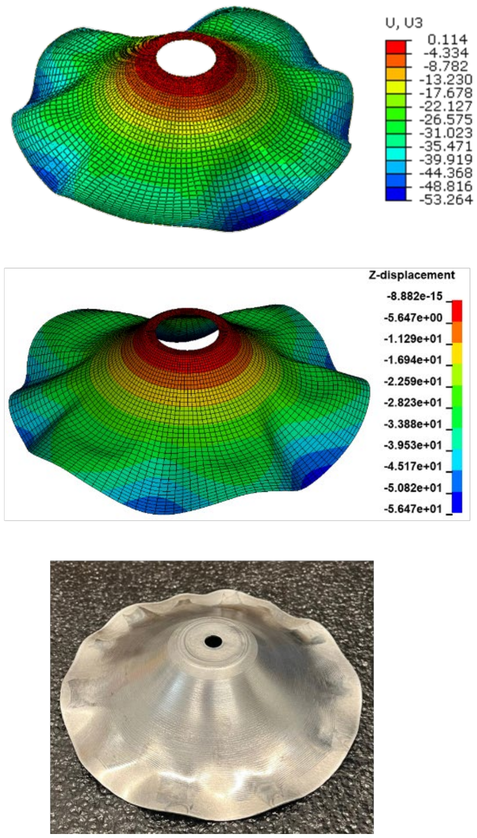

Fig. 5 Comparison of axial displacement pattern of a) ABAQUS simulation with mass scaling of 10; b) LS Dyna simulation with loading rate of 10 and c) experimental trial with a roller stroke of 30 mm

IV. Conclusion

The results validate the use of mass scaling and loading rate scaling in FE simulations for metal spinning, provided the scaling factor remains at or below 10:

- Dynamic fidelity: Low kinetic-to-internal energy ratios at scaling factors ≤10 ensure quasi-static conditions, critical for accurate stress and deformation predictions.
- Force trends: Simulations closely track experimental force-displacement behavior, with minor over- or underestimations that are acceptable for process design.
- Wrinkling insight: Both Abaqus and LS-DYNA accurately predict wrinkle locations and patterns, with slight amplitude variations that do not detract from their practical value.

These findings establish a reliable framework for using scaled simulations to predict and mitigate wrinkling, offering a time- and cost-efficient alternative to traditional trial-and-error approaches in metal spinning optimization.

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