Numerical Analysis of the Effects of Orthogonal Friction and Work Piece Misalignment during an AA5042 Cup Drawing Process

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Abstract

Wrinkle development during cup drawing operations is known to be highly dependent on many variables, including material anisotropy, tool geometry, process parameters, and tooling alignment. Weight reduction efforts in packaging industries have resulted in decreasing metal gauges, which exacerbates the formation of wrinkles.

In this study, the Numisheet 2014 Benchmark 4 cup drawing process is used to investigate the effects of orthogonal friction on wrinkle formation during drawing of an AA5042 aluminum cup. The anisotropic material properties of rolled AA5042 aluminum alloy sheet are implemented as specified in Numisheet Benchmark 4 for accuracy. The coefficient of friction of the rolled sheet blank is examined orthogonally. The effects of work piece misalignment are investigated and compared to ideal results. Furthermore, the effect of orthogonal friction on the punch force is examined.

Background

The development of wrinkles during drawing operations is a common occurrence in metal forming industries. Although the wrinkling phenomenon is well understood, the development of wrinkles has been shown to depend on many factors. For this study, numerical analysis effects of orthogonal friction and work piece alignment on wrinkle development are examined using LS-DYNA®.

The NUMISHEET 2014 Benchmark #4 [1] was chosen for this study as an established geometry. Units selected for all models were g/mm/ms/MPa.

Material anisotropy and uniform coefficients of friction in the range of μ=0.0 to 0.07 were examined by Neto et al. [2]. Wrinkle amplitude was shown to decrease in the transverse direction (90˚/270˚ from rolling direction) due to non-uniform circumferential thickening of the blank, resulting in increased contact pressure. Therefore, synergies between the material anisotropy and orthogonal friction are expected to compound or counteract the amplitude and shape of the wrinkles.

Material Characterization

The AA5042 material from the Numisheet 2014 benchmark was chosen for this study. The material properties are summarized in Table 1.

The anisotropic Yld2000 material model was employed to simulate the properties of the rolled aluminum sheet. To simulate isotropic properties, a linear plasticity model was used in place of Yld2000. Material flow stress was simulated using the Voce equation for both material models.

In Cartesian coordinates, the X axis was selected as the rolling direction of the material model. The X axis corresponds to the 0º/180º rolling direction shown in Figure 2.

Table 1: Material Characterization	
Material	AA5042
Density	0.00272 g/mm^3
Young's Modulus	68900 MPa
PR	0.33
Yld2000-2d Parameters (a=8.0)	
a_1	0.5891
a_2	1.4024
a_3	1.0892
a_4	0.994
a_5	1.065
a_6	0.7757
a_7	1.084
a_8	1.2064
Voce Constants	
a	404.16 MPa
b	107.17 MPa
c	18.416

Model Development

The 3D axisymmetric finite element model was developed using LS-INGRID® in addition to LS-PrePost®.

The contact card *CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE was used in conjunction with *DEFINE_FRICTION_ORIENTATION to impart orthogonal friction. The mesh was structured to give reasonable accuracy with minimal calculation time.

Machine and Tooling Specifications

The geometry considered during this study is that of "Tool Condition A" from the NUMISHEET 2014 Benchmark #4 description. The tooling dimensions (given in millimeters) are presented in Table 1.

Pressure pad force was held at 8.9 kN for all models. The draw die was held stationary, while the punch moved in the positive Z direction to a total displacement of 20mm. The AA5042 blank was input at a thickness of 0.2083 mm. Wrinkle amplitude was measured at z = -4.5mm form the origin of the radial model coordinate system shown in Figure 2.

It is noted that a radial coordinate system is used to examine the wrinkle amplitude and position (in degrees from rolling direction). In the Cartesian system of LS-PrePost, the X axis corresponds to the rolling direction, while the Y axis corresponds to the transverse direction.

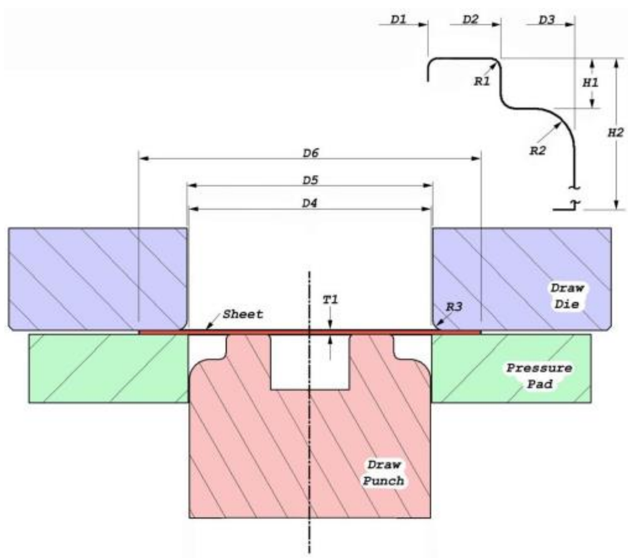

Figure 1: Cup Draw Tooling

Table 2: Tool Parameters (mm)											
D1	D2	D3	D4	D5	D6	R1	R2	R3	T1	H1	H2
15.24	31.75	45.72	45.72	46.74	64.77	1.016	3.81	1.905	0.2083	5.207	34.29

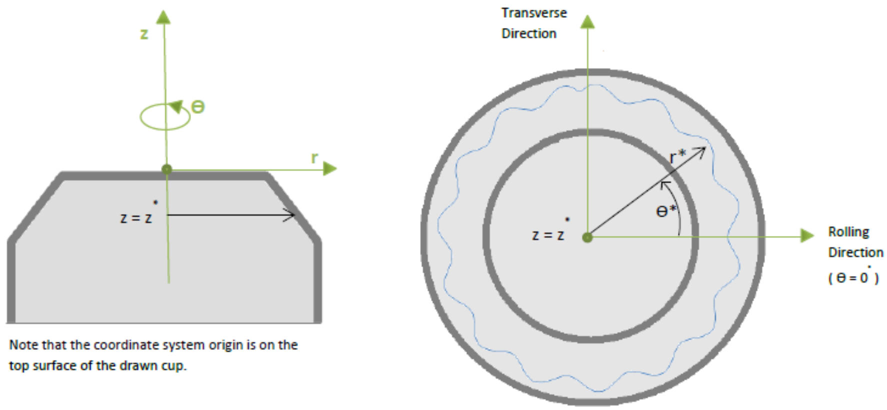

Figure 2: Model Coordinate System for Wrinkle Amplitude Examination

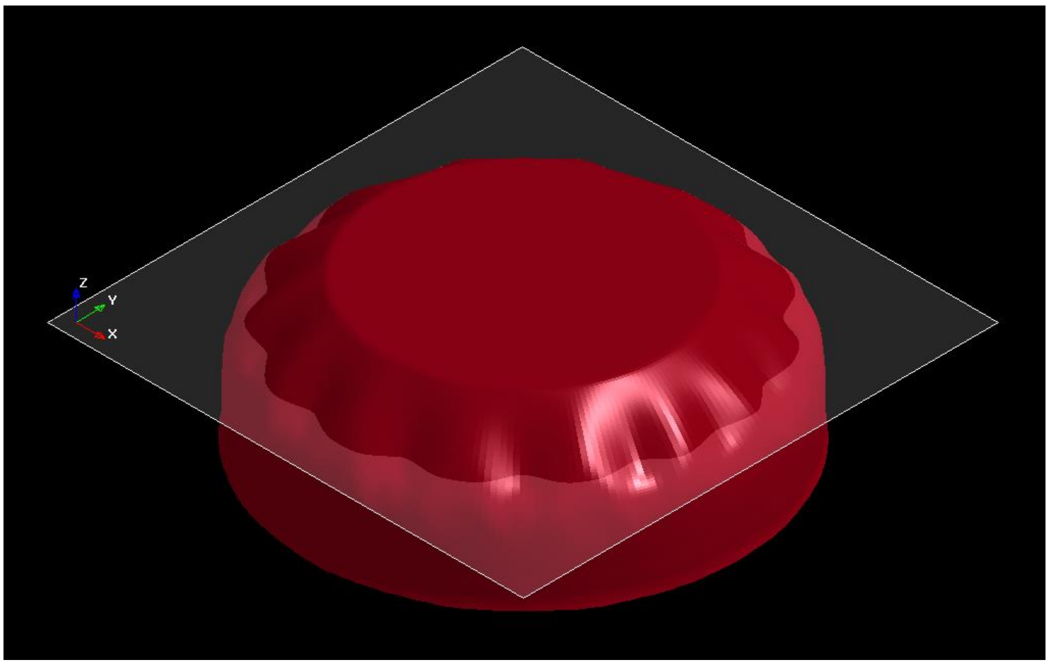

Figure 3: Representative Section Plane of Fully Drawn Cup

Examination of Friction Effects on Wrinkle Development

The coefficient of friction was varied orthogonally from the specified rolling direction of the material model (0º-90º from the global X axis, providing quarter symmetry). Coefficients of friction ranging from 0.03 to 0.06 were selected to represent realistic conditions possible with traditional rolled sheet surfaces and tool surface finishes. In addition, workpiece (blank) misalignment was considered in combinations of the x and y axes.

A reference summary of analyses performed is given in Table 3.

Table 3: Run Summary

		Friction		
Run	**Material Model**	**0˚**	**90˚**	**Notes**
1	Isotropic	0.03	0.03	Linear Plasticity
2	Isotropic	0.06	0.06	Linear Plasticity
3	Anisotropic	0.03	0.03	Yld2000
4	Anisotropic	0.06	0.06	Yld2000
5	Isotropic	0.03	0.06	Linear Plasticity
6	Isotropic	0.06	0.03	Linear Plasticity
7	Anisotropic	0.03	0.06	Yld2000
8	Anisotropic	0.06	0.03	Yld2000
9	Anisotropic	0.03	0.03	Blank shifted x = -0.2 mm
10	Anisotropic	0.03	0.03	Blank shifted y = -0.2 mm

Isotropic Material Model/Uniform Friction Wrinkle Results

Baseline conditions of uniform friction and isotropic material models were simulated. Wrinkle amplitude for Runs 1 and 2 (corresponding to μ=0.03 and 0.06, respectively), as well as punch force, are shown in Figures 4 and 5. As expected, wrinkle amplitude decreases with increasing friction due to the increased resistance to metal flow between the draw die and pressure pad. Increased friction is also shown to discourage the development of minor wrinkles as exhibited at the peaks of the major wrinkles in Run 1.

Table 4: Reference Definition of Runs			
Run	**Material Model**	**Friction at 0°**	**Friction at 90°**
1	Linear Plasticity	0.03	0.03
2	Linear Plasticity	0.06	0.06

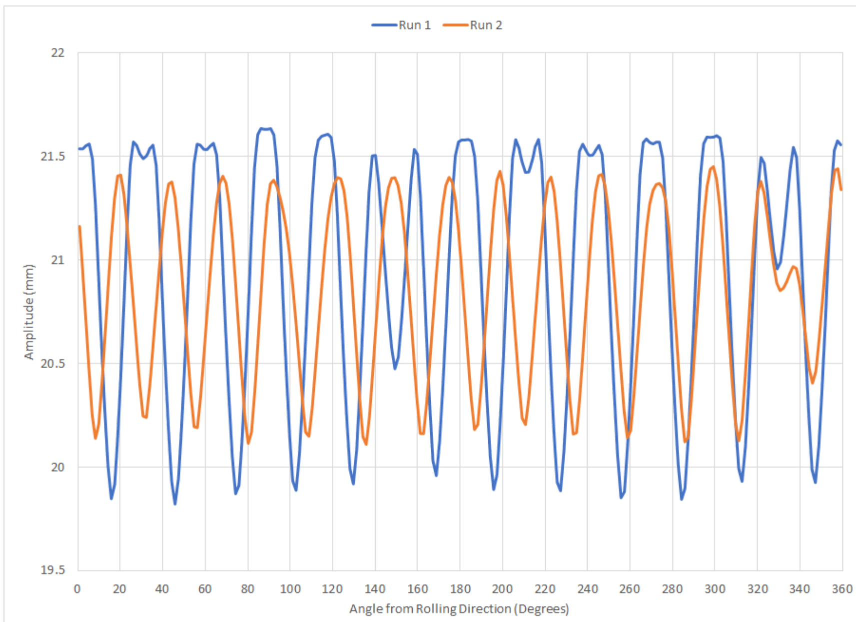

Figure 4: Wrinkle Amplitude for Runs 1 and 2

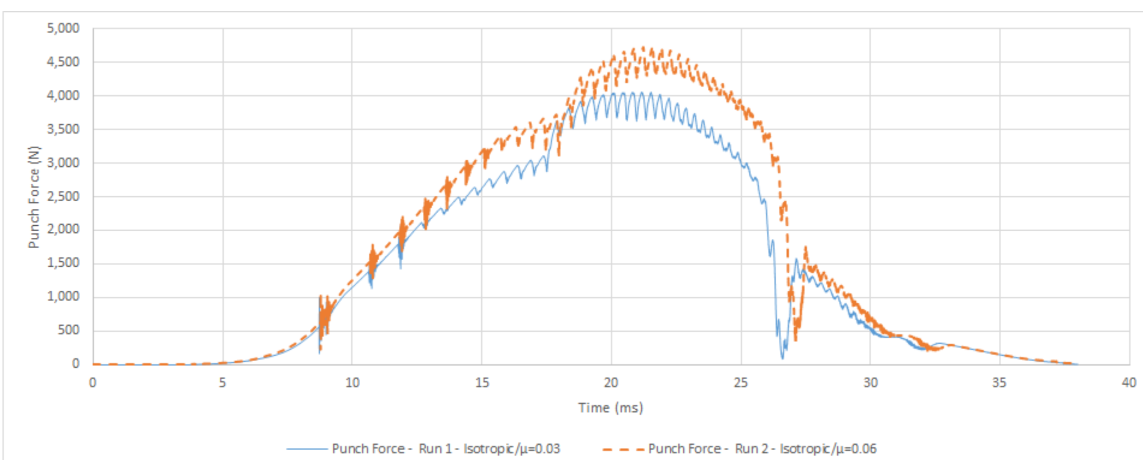

Figure 5: Punch Force Comparision for Runs 1 and 2

Anisotropic Material Model/Uniform Friction Wrinkle Results

Simulations with anisotropic material properties with uniform friction were conducted to understand the sensitivity of wrinkle formation to material anisotropy only. Wrinkle amplitude for Runs 3 and 4, as well as punch force, are shown in Figures 6 and 7. A synergistic effect between increasing friction and material anisotropy is observed via the decreasing wrinkle amplitude at 90˚ and 270˚ from the rolling direction. Wrinkle amplitude at 0˚ and 180˚ is essentially unchanged from μ=0.03 to 0.06, indicating an offsetting effect of higher contact pressure in the transverse direction due to anisotropic thickening as shown in Figure 8. As expected, the punch force increases with friction.

Table 5: Reference Definition of Runs

Run	Material Model	Friction at 0º	Friction at 90º
3	Yld2000	0.03	0.03
4	Yld2000	0.06	0.06

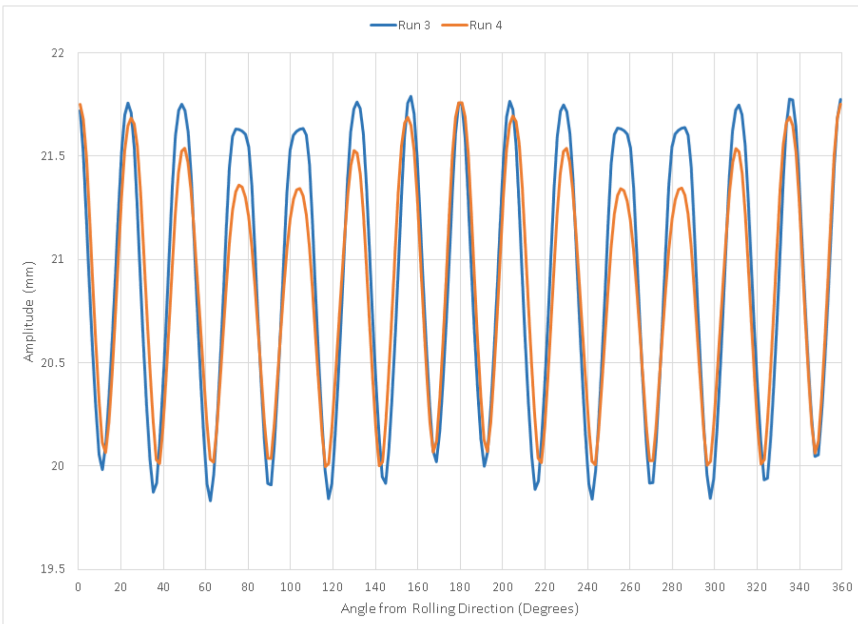

Figure 6: Wrinkle Amplitude for Runs 3 and 4

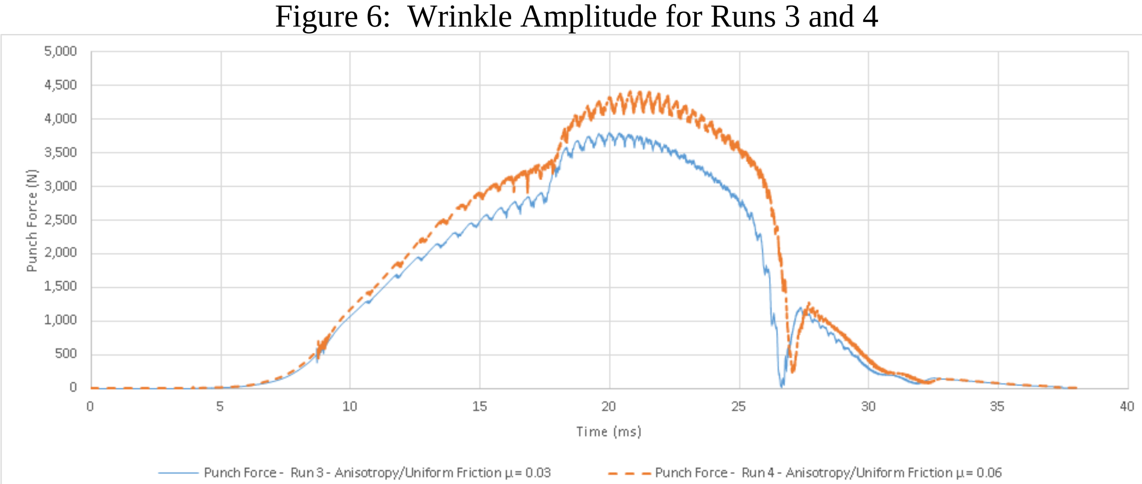

Figure 7: Punch Force Comparison for Runs 3 and 4

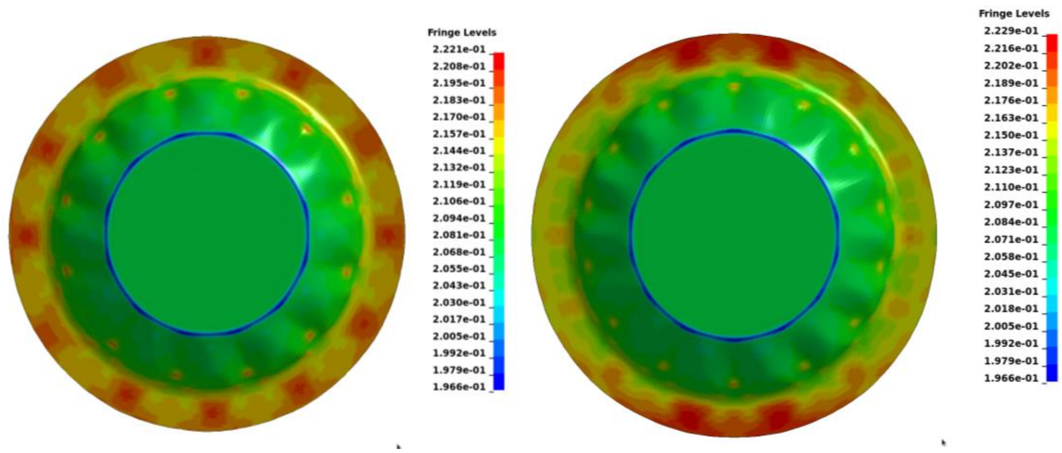

Figure 8: Flange shell thickness during draw with isotropic material model (left), flange shell thickness during draw with anisotropic material model (right)

Anisotropic Material Model/Orthogonal Friction Wrinkle Results

Simulations with orthogonal friction, utilizing isotropic and anisotropic material properties, were conducted to explore the compounding effects shown in Runs 3 and 4. Wrinkle amplitude for Runs 5 through 8 (corresponding orthogonal friction in the range of μ=0.03 and 0.06), as well as punch force, are shown in Figures 9 through 12. A synergistic effect between increasing friction and material anisotropy is observed via the decreasing wrinkle amplitude at 90˚ and 270˚ from the rolling direction. Also note the development of small amplitude minor wrinkles at the peaks of the major wrinkles.

Table 6: Reference Definition of Runs

Run	Material Model	Friction at 0º	Friction at 90º
5	Linear Plasticity	0.03	0.06
7	Yld2000	0.03	0.06

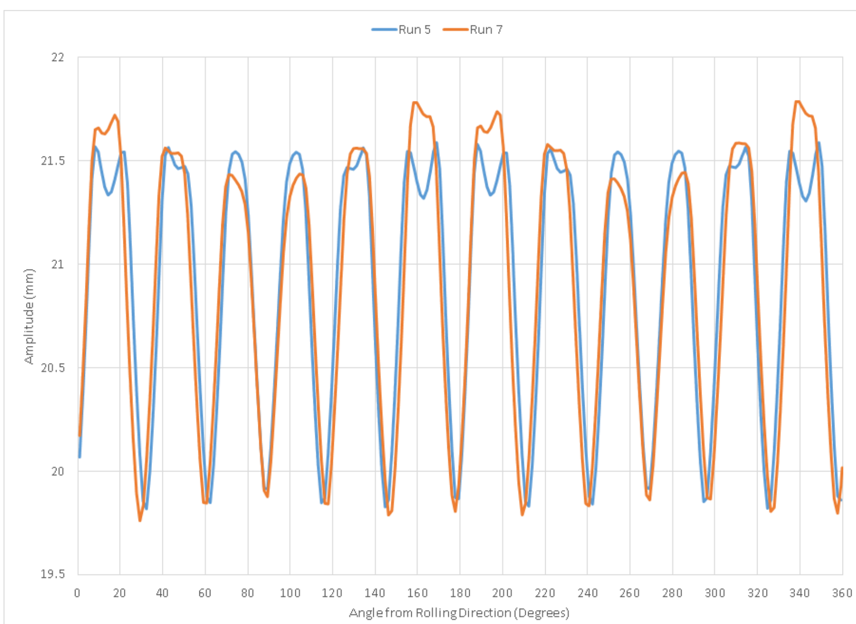

Figure 9: Wrinkle Amplitude for Runs 5 (Isotropic Material) and 7 (Anisotropic Material)

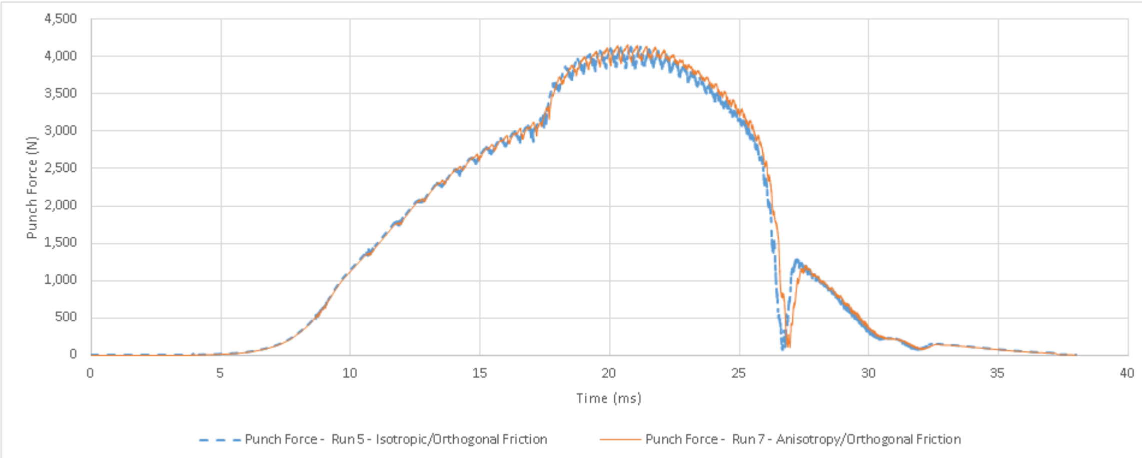

Figure 10: Punch Force Comparison for Runs 5 and 7

Table 7: Reference Definition of Runs			
Run	**Material Model**	**Friction at 0º**	**Friction at 90º**
6	Linear Plasticity	0.06	0.03
8	Yld2000	0.06	0.03

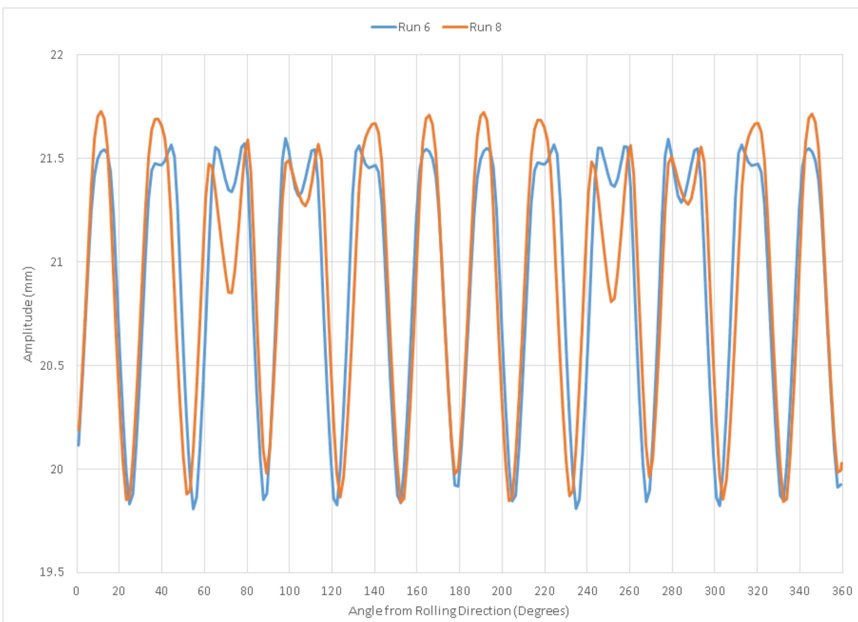

Figure 11: Wrinkle Amplitude for Runs 6 (Isotropic Material) and 8 (Anisotropic Material)

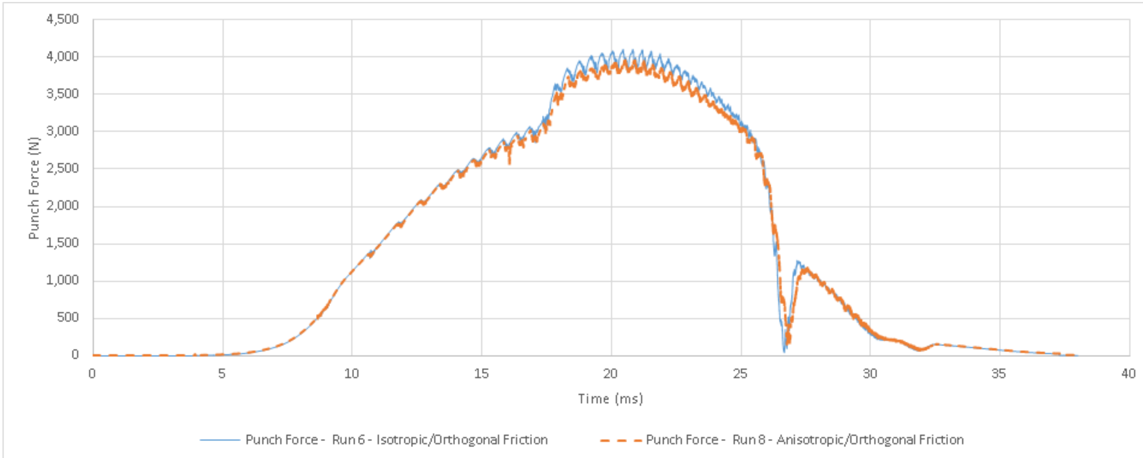

Figure 12: Punch Force Comparison for Runs 6 and 8

As the anisotropic material thickens less in the rolling direction during the draw, the orthogonal friction, combined with uneven thickening, can exacerbate the development and amplitude of wrinkles in the rolling direction, as shown in Figure 9. As can be seen in Figure 11, lower friction in the transverse direction results in higher-frequency partial wrinkle development at 90˚/270˚.

Effect of Off-Center Draw due to Blank Misalignment

The effect of off-center blank alignment was examined in the negative x and y in runs 9 and 10, respectively.

Figure 13 exhibits 180º wrinkle symmetry with the Run 3 results (Anisotropic Material /Uniform Friction μ = 0.03), while being 180º out of phase at 0º. The increase of draw force in the negative x direction resulted in the formation of one less wrinkle, reducing the peaks from 14 in Run 3 to 13 in Run 9.

As shown in Figure 14, the wrinkle formation followed a similar path when the blank was shifted in the negative y direction Similarly, Run 10 exhibited a decrease of the number of wrinkles from 14 to 13. The wrinkles are in phase at the 90º coordinate, while being out of phase at 270º. The increased resistance to flow as a result of the greater contact area in the negative y direction (270º) results in wrinkles with well-defined peaks when compared to the positive y direction (90º).

Table 8: Definition of Runs				Notes
Run	**Material Model**	**Friction at 0º**	**Friction at 90º**	
3	Yld2000 (Anisotropic)	0.03	0.03	Standard Alignment
9	Yld2000 (Anisotropic)	0.03	0.03	Blank shifted x = -0.2mm
10	Yld2000 (Anisotropic)	0.03	0.03	Blank shifted y = -0.2mm

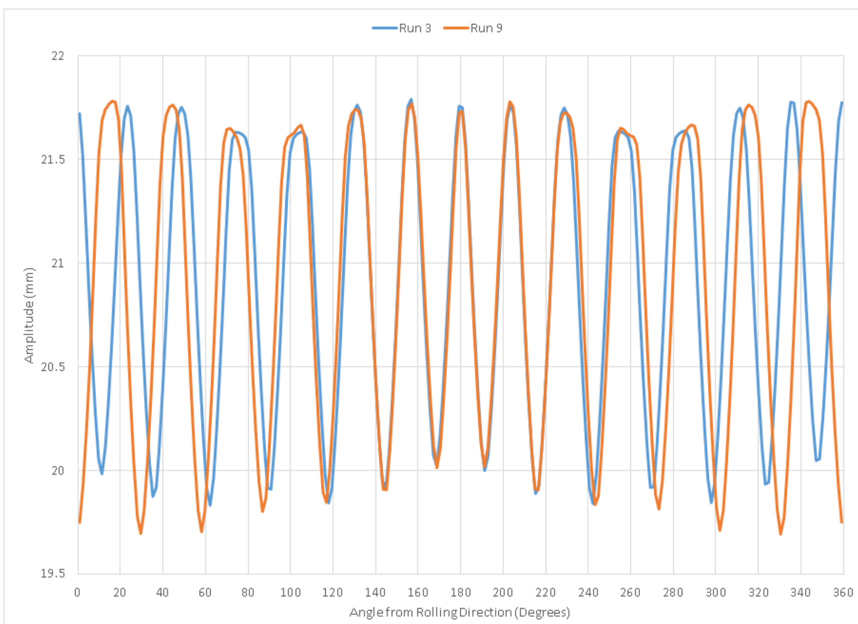

Figure 13: Wave Amplitude for Runs 3 and 9 (Blank shifted x = -0.2mm)

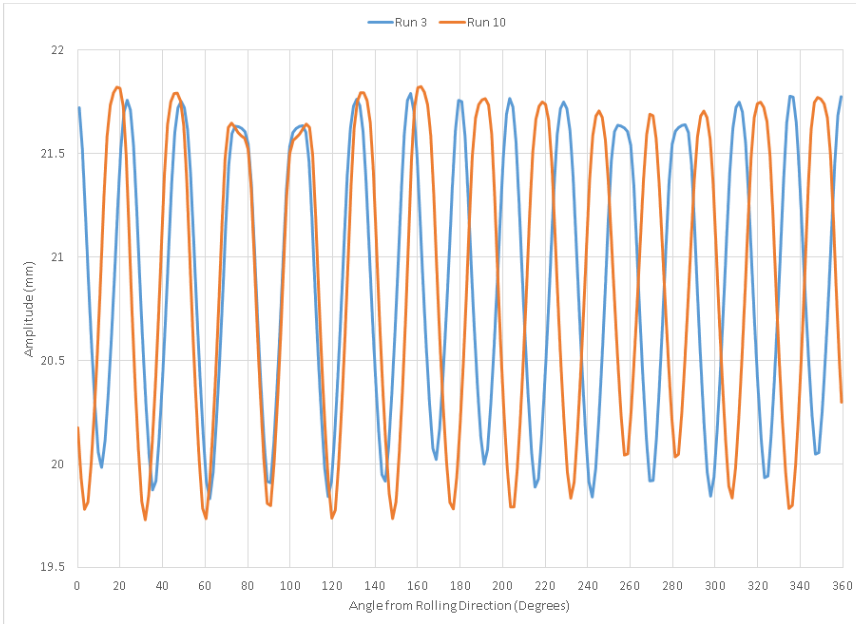

Figure 14: Wrinkle Amplitudes for Runs 3 and 10 (Blank shifted y = -0.2mm)

Summary

In this study, numerical analysis tools within LS-DYNA have been used to predict cup wrinkling during sheet metal drawing operations. As shown in previous studies of the Numisheet Benchmark [1][2], the frequency, amplitude and position of the wrinkles on the fully drawn cup have been shown to be highly dependent on the material anisotropy, friction, and alignment.

The coupling effects of anisotropic material properties and friction are shown to be an important factor in wrinkle formation. When increased friction is coupled with uneven thickening of the blank in the transverse direction, as shown in Figure 9, wrinkle amplitude is shown to decrease at 90˚/270˚, with simultaneously increasing amplitude in the 0˚/180˚ direction due to lower friction and blank thickness. When friction is increased in the rolling direction, it is shown in Figure 11 that the wrinkle amplitude is not as greatly affected; the increased friction is partially offset by the decreasing contact force as a result of the uneven thickening of the blank in the 0˚/180˚ direction.

The evolution of punch force while forming isotropic and anisotropic materials with orthogonal friction is shown to be influenced by the non-uniform thickening of the anisotropic material. While an isotropic material requires the same forming loads regardless of orthogonal friction orientation, the anisotropic material forming loads will increase or decrease based on the friction orientation in relation to the non-uniform thickening of the material.

It is shown that orthogonal friction characteristics of rolled sheet products have the potential to change drawing and forming characteristics, however, it is recognized that proper lubrication used in practice may limit the orthogonal friction to magnitudes that are too low to be a measurable factor. This is further supported by the capability of LS-DYNA to predict wrinkle formation with a uniform friction that is very representative of test conditions.

References

1. Dick RE, Cardoso R, Paulino M, Yoon JW (2013) Benchmark 4 – wrinkling during cup drawing. AIP Conf Proc 1567:262-327. Doi:10.1063/1.4849984

2. Neto DM, Oliveira MC, Dick RE, Barros PD, Alves JL, Menezes LF, (2015), Numerical and experimental analysis of wrinkling during the cup drawing of an AA5042 aluminum alloy. DOI 10.1007/s12289-015-1265-4

3. LSDYNA Keyword User's Manual version 971. Livermore Software Technology Corporation, California, May 2007.