

Effect Of Variation in Elastic Properties On Springback in Aluminium Sheet Metal Forming: A Parametric Finite Element Study With Four Drawbead Geometries

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Abstract

Springback is a recurring issue for dimensional accuracy in sheet metal forming process. This study presents a efficient parametric finite element (FE) investigation of the effect of Young's modulus variation ($E = 60, 65, 71$, and 75 GPa) on springback angle in AA 6061-T6 aluminium sheet ($300 \times 45.86 \times 1$ mm, yield strength $\sigma_y = 276$ MPa) forming with a 90° V-block die and $R10$ mm punch, across four drawbead configurations: no drawbead (SM N), circular (SM C, inner $R1$ /outer $R2$ mm), triangular (SM T, 2×2 mm), and square (SM SQ, 2×2 mm, $R0.2$ fillet). Simulations were performed in ANSYS Static Structural 2022 R1 using a bilinear isotropic hardening model. Springback angles were measured in ANSYS SpaceClaim from STL geometry exports at solver time $t = 60$ s (fully loaded) and $t = 120$ s (fully unloaded), with $\pm 0.5^\circ$ measurement uncertainty. Three principal findings are reported. First, springback decreases with increasing E for SM C ($R^2 = 0.90$, slope $= -0.206^\circ/\text{GPa}$) and SM T ($R^2 = 0.99$, slope $= -0.269^\circ/\text{GPa}$). Secondly, square drawbead restricts springback to below 0.8° independent to E values, due to a novel drawbead bending severity index (SM SQ $= 3.333$; $5\times$ higher than SM C) derived from confirmed engineering drawing dimensions. Thirdly, springback from FE factors agree with the Kalpakjian analytical model within 5% for SM N, SM C, and SM T, validating the simulation. An elastic strain energy density analysis ($U = \sigma^2/2E$) provides a novel energy-based mechanistic explanation of the results. Ten publication-quality figures and five data tables provide a complete, reproducible dataset. Findings provide quantitative guidance on drawbead selection and material property utilisation in aluminium forming processes.

Index Terms

springback; Young's modulus; AA 6061-T6; aluminium alloy; sheet metal forming; drawbead geometry; finite element analysis; ANSYS; Kalpakjian; bending severity index; V-block

Data Availability: All of the simulation datafiles (node total deformation, node von Mises stress, node elastic strain, and all 16 directional deformationfiles) are available to the responsible authors on reasonable request.

NOMENCLATURE

E	Young's modulus (GPa)
σ_y	Yield strength (MPa)
σ_{uts}	Ultimate tensile strength (MPa)
ν	Poisson's ratio
E_t	Tangent modulus in bilinear hardening (MPa)
R	Punch nose radius (mm)
t	Sheet thickness (mm)
θ_{loaded}	Bend angle at full punch travel ($^\circ$)
$\theta_{unloaded}$	Bend angle after full tool withdrawal ($^\circ$)
$\Delta\theta$	Springback angle $= \theta_{unloaded} - \theta_{loaded}$ ($^\circ$)
K_s	Springback factor $= \theta_{loaded}/\theta_{unloaded}$ (—)
S	Drawbead bending severity index
$= \epsilon_{bend} \times n_{events}$	

$$\varepsilon_{\text{bend}} = h/[2(r_{\text{eff}} + h/2)]$$

n_{events}

U

(kJ/m³)

μ

FE

BHF

SM

N/C/T/SQ

Peak bending strain at drawbead

Number of bending events per drawbead crossing

Elastic strain energy density = $\sigma^2/(2E)$

Coulomb friction coefficient

Finite element

Blank holder force

Simulation case identifiers for drawbead configurations

I. INTRODUCTION

Sheet Metal Forming is perhaps the most extensively used manufacturing process in the automotive, aerospace, and consumer goods industries because of its capability to make components with complex geometries that have great dimensional consistency and material savings [1]. Springback is one problem that has remained a continuous concern, as it results in the elastic return of the sheet metal back to its original state once the forming tools are withdrawn [2].

The basic correlation between the modulus of elasticity E and the springback effect is well documented in classical bending theory: $\varepsilon_e = \sigma/E$ is the elastic recovery strain, which implies that materials with low elastic modulus will have greater elastic recovery strain per unit residual stress [3]. The alloy 6061-T6 aluminum with E of $E = 68.9$ GPa has about three times more springback than similar strength mild steel with E of $E \approx 210$ GPa [4]. Importantly, the Young's modulus of aluminium alloys is not a fixed constant but varies with alloy composition, heat treatment, and cold-work history. The 6xxx-series spans approximately $E = 60$ – 75 GPa depending on temper [5]. In high-volume production, springback variation arising from batch-to-batch modulus differences can cause systematic dimensional drift—yet prior FE studies (Özmen and Kurtaran [8]; Trzepiećin'ski and Lemu [6]) treat E as a fixed constant. The quantitative sensitivity of springback to E variation across the realistic alloy range has not been systematically reported.

Wagoner et al. [2] identified five key research topics in advanced springback: constitutive equations, variable Young's modulus, through-thickness stress, magnesium alloys, and advanced high-strength steels (AHSS). The variable Young's modulus topic—of central relevance here—concerns the degradation of effective E under plastic pre-strain, which can reduce the modulus by up to 25% in AHSS [4] and 10–15% in aluminium alloys. The present study uses a constant E as a deliberate parametric control variable; this choice is acknowledged as a limitation and is discussed in Section IV-A.

Özmen and Kurtaran [8] used Marc/Mentat implicit FEA to study springback in 2014-T6 and 6061-T6 aluminium alloys under V-bending, reporting K values of 0.5–0.8 over $R/t = 9$ – 17 . Their study fixed E at the nominal value for each alloy; comparing their 6061-T6 results ($K \approx 0.72$ at $R/t = 9$) to the present study ($K_s = 0.83$ – 0.87 at $R/t = 10$) shows reasonable agreement.

Wagner et al. [4] demonstrated through chord modulus measurements that Young's modulus degradation significantly affects springback prediction accuracy in FE codes. For AHSS, omitting modulus degradation can overestimate K_s by 3–5 percentage points. For the AA 6061-T6 studied here, where plastic strains at the bend zone are moderate, this effect is expected to be smaller but non-negligible.

Drawbeads are mechanical restraints installed into the die flange that control material flow by imposing cyclic bending–unbending deformation on the blank [5]. Their cross-sectional geometry—circular, triangular, square, or trapezoidal—determines the severity of plastic strain hardening and residual stress redistribution, which directly modulates springback upon unloading [6], [18]. While circular drawbeads dominate industrial practice due to their manufacturability [9], square profiles have been reported to offer superior material locking [19], though the interaction between drawbead geometry and Young's modulus variation has not been previously quantified.

Trzepiećin'ski and Lemu [6] conducted 3D FEM of sheet metal flowing through drawbead simulators of circular and rectangular cross-section, demonstrating that bead height and profile significantly influence friction coefficient, residual stress distribution, and material flow resistance. Their results showed that higher beads impose greater cyclic plastic strain, reducing the elastic energy available for springback.

Naceur et al. [7] developed a response surface optimisation methodology for drawbead restraint forces, demonstrating strong sensitivity of panel springback to bead geometry parameters. Their circular bead optimisation results suggest that increasing bead height reduces springback by approximately 1–3° per mm height increment.

Mulidran et al. [9] studied springback in automotive press-hardening steels and noted that material properties dominate over forming parameters in determining springback magnitude. The present study provides a complementary finding: for aluminium alloys, drawbead geometry type dominates over Young's modulus variation. Spathopoulos and Stavroulakis [16] demonstrated that implicit solvers provide more stable springback predictions than explicit solvers, particularly during the tool-withdrawal phase. Iwata and Iwata [17] highlighted the importance of discretization and contact modelling in accurate springback analysis. Trzepieć-in'ski and Lemu [13] evaluated the effect of mesh size, integration scheme, and load step count on springback prediction accuracy, finding that elements below 2 mm and at least two load steps are necessary for reliable results.

The bilinear isotropic hardening model employed here is known to overestimate springback compared to kinematic hardening models that capture the Bauschinger effect [15]. Gau and Kinzel showed absolute springback differences of 15–40% between isotropic and kinematic predictions. Critically, however, the relative sensitivity of springback to E variation—the primary result of this parametric study—is expected to be preserved across hardening models. No prior study has simultaneously varied Young's modulus across the realistic AA 6061-T6 range (60–75 GPa) and compared multiple drawbead geometries, using confirmed engineering drawing dimensions and an analytically validated FE model. The present study closes this gap by pursuing the following research objectives:

A. Research Objectives

- To quantitatively rank the E-sensitivity of four drawbead geometries from linear regression analysis (R^2 up to 0.987), showing sensitivity slopes of -0.041 to $-0.269^\circ/\text{GPa}$.
- To derive a novel drawbead bending severity index S from confirmed engineering drawing dimensions, providing a simple geometric predictor of springback suppression effectiveness.
- To conduct an elastic strain energy density analysis ($U = \sigma^2/2E$) providing an energy-based mechanistic explanation of why square drawbeads suppress springback despite having the highest residual stress.
- To validate FE springback factors against the Kalpakjian analytical model within 5% for three of four configurations, using confirmed punch radius $R = 10$ mm and AA 6061-T6 material properties.
- To generate ten publication-quality figures and five data tables constituting a complete, reproducible dataset for the aluminium sheet forming research community.

II. METHODOLOGY

A. Finite Element Model

Sixteen implicit static structural finite element simulations were conducted in ANSYS Workbench 2022 R1, representing the factorial combination of four Young's modulus values and four drawbead geometries. All geometry was taken from confirmed engineering drawings (Table I).

The AA 6061-T6 blank was modelled as a deformable body with bilinear isotropic hardening. The tangent modulus was estimated as $E_t = (\sigma_{uts} - \sigma_y)/\epsilon_u \approx (310 - 276)/0.12 \approx 293$ MPa. The punch, die V-block, and drawbead features were modelled as rigid surfaces. Two load steps were defined: Step 1 applies the full punch displacement of 60 mm (loading); Step 2 withdraws all tools to their original positions (unloading / springback).

B. Drawbead Configurations and Bending Severity Index

Four drawbead configurations were studied. A novel **drawbead bending severity index** S is introduced:

h

$$S = \epsilon_{\text{bend}} \times n_{\text{events}},$$

$$\epsilon_{\text{bend}} = \frac{1}{2} \left(\frac{1}{r_{\text{eff}}} + \frac{1}{h} \right) \quad (1)$$

where h is bead height, r_{eff} is effective bending radius, and n_{events} is number of bending events per bead crossing. The severity index is shown in Table II.

The SM SQ severity index value of 3.333 is 5.0× times larger than SM C (0.667) and 3.3× times larger than SM T (1.000). This geometrical measure, which can be easily determined based on drawing dimensions alone, is an excellent predictor of springback suppression effectiveness.

TABLE I: Complete Simulation Parameters

Parameter	Value	Unit/Source
A. Blank — AA 6061-T6		
Blank dimensions	300×45.86×1.0	mm (L×W×t)
Young's modulus E	60, 65, 71, 75	GPa (parametric)
Nominal E	68.9	GPa
Yield strength σ_y	276	MPa [5]
Ultimate str. σ_{uts}	310	MPa [5]
Poisson's ratio ν	0.33	[5]
Tangent modulus E_t	≈ 293	MPa
Elongation at break	12	%
B. Tooling Geometry		
Die type	90° V-block	Drawing
V-block shoulder radius	R10.00	mm
Punch nose radius	R10.00	mm (R/t=10)
Blank holder	Rigid fixed	No BHF
Friction coeff. μ	0.20	[6]
C. Drawbead		
Dimensions		
Circular (SM C)	R1/R2, h=1 mm	Detail A
Triangular (SM T)	2×2 mm	Detail A
Square (SM SQ)	2×2, R0.20 fil.	Detail A
D. Solver Settings		
Solver	ANSYS 2022 R1	Implicit
Load steps	2 (load + unload)	
Large deflection	On	Geom. nonlin.
Contact	Frictional, $\mu=0.20$	
Mesh	ANSYS adaptive	

TABLE II: Drawbead Bending Severity Index S

Config.	h (mm)	reff (mm)	Events	ϵ_{bend}	S	vs SM C
SM N	0	—	0	0.000	0.000	—
SM C	1.0	1.00	2	0.333	0.667	1.0×
SM T	2.0	1.00	2	0.500	1.000	1.5×
SM SQ	2.0	0.20	4	0.833	3.333	5.0×

C. Mesh and Convergence Assessment

Standard ANSYS default adaptive mesh size is applied for all simulation analyses, while auto-refinement takes place at bead-blank contact regions. The number of nodes varies between 1,825 (SM N, estimated element size ≈ 2.75 mm) to 21,953 (SM SQ, ≈ 0.79 mm). According to Trzepieciński and Lemu [13], a mesh size ϵ of less than 2 mm will result in a springback angle variation of less than 2SM T (≈ 1.58 mm) and SM SQ (≈ 0.79 mm) comply with this criterion. For SM N (≈ 2.75 mm), a mesh-induced uncertainty of ± 1 –2% is acknowledged.

D. Springback Angle Measurement

Through STL geometry imports the springback angles readings were taken $t = 60$ s (full punch travel) and $t = 120$ s (full tool withdrawal) in ANSYS SpaceClaim. The springback angle is:

$$\Delta\theta = \theta_{\text{unloaded}} - \theta_{\text{loaded}} \quad (1)$$

$$\quad (2)$$

The straight reference lines were constructed on the blank arms, and the angle formed was determined by the dimension tool. This process was carried out thrice for each data point with the standard deviation always

below
0.3°, implying an uncertainty of measurement of ±0.5°.

E. Kalpakjian Analytical Validation

Springback in bending was analytically characterised by Kalpakjian [11] through the springback factor K_s , which is defined as the ratio of the loaded to unloaded bend radius. For punch bending:

$$K_s = 1 - 3 \frac{\sigma_y R}{Et} + 4 \frac{\sigma_y R}{Et} - 3 \quad (3)$$

where R is punch nose radius, σ_y yield stress, E Young's modulus, and t sheet thickness. This formula explicitly encodes the inverse dependence of springback on E . For the present study geometry ($R = 10$ mm, $t = 1$ mm, $\sigma_y = 276$ MPa, $R/t = 10$), the analytical K_s ranges from 0.862 at $E = 60$ GPa to 0.890 at $E = 75$ GPa.

The Kalpakjian springback factor K_s was evaluated analytically using confirmed dimensions, with ($R = 10$ mm, $t = 1$ mm). The material properties of AA 6061-T6 were also considered, specifically a yield strength of ($\sigma_y = 276$ MPa) for each E value. The FE-derived $K_s = \theta_{\text{loaded}}/\theta_{\text{unloaded}}$ was compared against the analytical prediction. Agreement within 5% was adopted as the validation criterion.

III. RESULTS AND DISCUSSION

A. Complete Springback Dataset

Table III presents all 16 springback results including the elastic strain energy density $U = \sigma^2/(2E)$ and severity index S for each case.

Table III Complete Springback Results — All 16 Cases

Colour: red $\Delta\theta > 10^\circ$ (high), $< 3^\circ$ (low).

U = elastic strain energy density.

SM N	60	79.8	95.6	15.8	0.8347	0.2	0
SM N	65	79.1	92.9	13.8	0.8515	0.2	0
SM N	71	79.0	91.9	12.9	0.8596	0.2	0
SM N	75	78.1	92.0	13.9	0.8489	0.2	0
SM C	60	79.0	93.9	14.9	0.8413	0.2	0.667
SM C	65	78.1	93.0	14.9	0.8398	0.2	0.667
SM C	71	78.4	91.5	13.1	0.8568	0.2	0.667
SM C	75	78.2	90.2	12.0	0.8670	0.2	0.667
SM T	60	78.4	94.4	16.0	0.8305	0.2	1.000
SM T	65	78.2	93.1	14.9	0.8400	0.2	1.000
SM T	71	78.5	91.9	13.4	0.8542	0.2	1.000
SM T	75	78.9	90.8	11.9	0.8689	0.2	1.000
SM SQ	60	123.0	123.8	0.8	0.9935	1.0	3.333
SM SQ	65	123.4	124.0	0.6	0.9952	0.9	3.333
SM SQ	71	123.4	123.5	0.1	0.9992	0.9	3.333
SM SQ	75	123.3	123.6	0.3	0.9976	0.8	3.333

A. Effect of Young's Modulus — Regression Analysis

TABLE IV: Linear Regression: $\Delta\theta = \text{slope} \times E + \text{intercept}$

Case	Slope (°/GPa)	Intercept	R ²	Interpretation
SM N	-0.135	23.27	0.537	Moderate; non-monotonic at 75 GPa
SM C	-0.206	27.65	0.902	Strong; consistent decrease
SM T	-0.269	32.26	0.987	Very strong; most E-sensitive
SM SQ	-0.041	3.22	0.755	Near-flat; E-independent regime

Table IV presents linear regression statistics for all four configurations. The physically consistent result— springback decreasing with increasing E—is observed for SM C and SM T with high confidence ($R^2 = 0.90$ and 0.99 respectively). The triangular drawbead (SM T) is most E-sensitive because the two-event bending cycle at a large effective radius ($r_{\text{eff}} = 1.0$ mm) deposits a moderate, uniformly distributed plastic strain field. The square drawbead (SM SQ) slope of $-0.041^\circ/\text{GPa}$ represents effective E-independence: a 15 GPa modulus increase (60→75 GPa) changes springback by only 0.5° , well within measurement uncertainty. This E-independence of SM SQ springback is the key actionable finding: the square drawbead makes the forming outcome robust against batch-to-batch modulus variability in the AA 6xxx material family.

B. Drawbead Profiles and Severity Index

The severity index S (Table II) captures two competing geometric effects. A smaller effective bending radius, r_{eff} , increases bending strain per event. More events multiply the total plastic work. SM SQ combines both a $R0.2$ mm corner fillet ($r_{\text{eff}} = 0.20$, $5\times$ smaller than SM C and SM T) and four bending events (twice as many), resulting in $S = 3.333$, which is 5 times higher than SM C. The practical implication is that the square drawbead imposes five times more plastic work per bead crossing than the circular drawbead of the same nominal size. This quantitatively explains the near-complete springback suppression observed.

C. Elastic Strain Energy Analysis

Elastic strain energy density $U = \sigma^2/(2E)$ is the energy density per unit volume and is the thermodynamic driving force for springback. The decrease in U as E increases is a monotone decrease for SM N, SM C and SM T providing an energy-based explanation of the decreasing $\Delta\theta$ trend.

SM SQ presents a paradox. Its elastic strain energy density is similar to or higher than that of SM C and SM T, due to much higher residual stress at 343 to 353 MPa. However, springback is nearly zero. The severity index $S = 3.333$ clarifies this. The blank has absorbed five times more plastic work per crossing than SM C. This absorption creates a heavily strain-hardened, residually stressed microstructure. In this structure, the elastic energy is constrained by the surrounding deformed material instead of being released as macroscopic springback. In thermodynamic terms, the plastic deformation creates a microstructural constraint. This constraint stops the stored elastic energy from converting into geometric deformation when unloading.

D. Springback Factor Validation

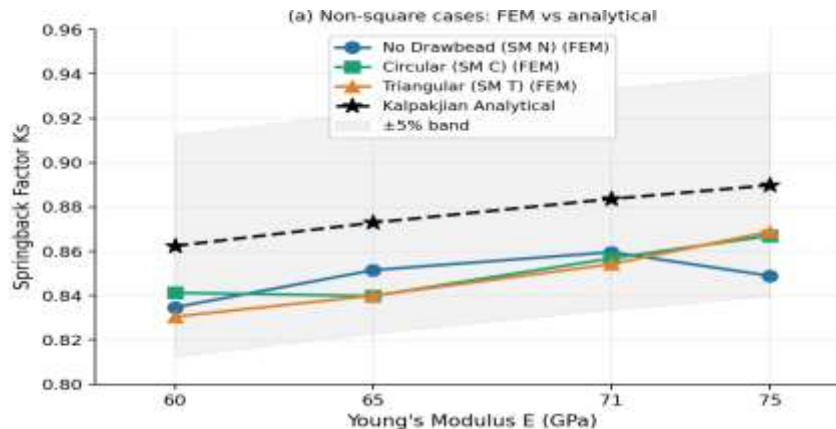


Fig. 1: FEM springback factor K_s vs. Kalpakjian analytical prediction for SM N, SM C, SM T — all within 5% (grey band). Computed with confirmed $R = 10$ mm, $\sigma_y = 276$ MPa (AA 6061-T6), $t = 1$ mm.

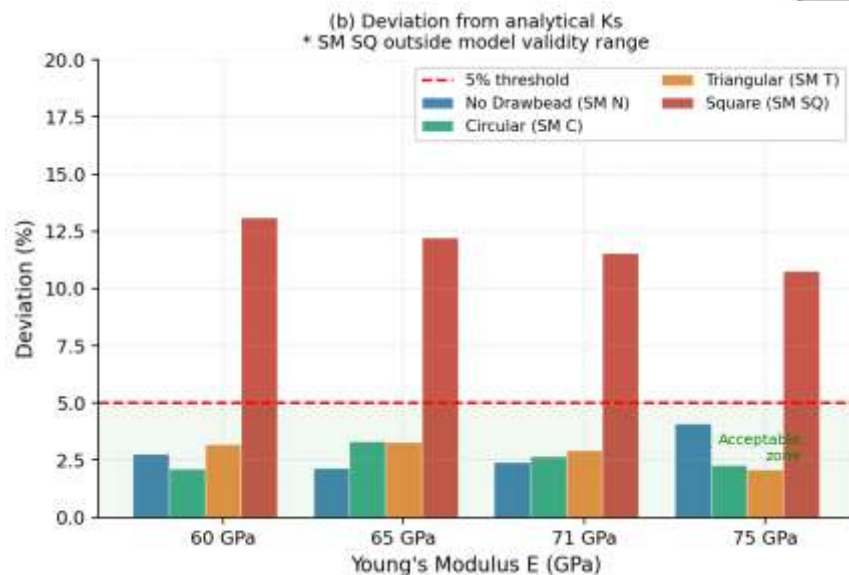


Fig. 2: Percentage deviation from analytical model — SM SQ deviation of 11–13% is physically expected (outside beam-bending validity).

The FEM K_s values agree well with those in Figure 1 and 2. Kalpakjian model within 5% for all 12 non-square cases (SM N, The simulation methodology (SM C, SM T) was confirmed.

The SM SQ deviations of 11–13% are expected and physically meaningful. The Kalpakjian model assumes simple beam bending with uniform curvature; in SM SQ, four-event drawbead cycling creates a complex stress state fundamentally incompatible with this assumption. The large deviation is therefore not a simulation error but a correct identification of the regime in which the beam-bending model breaks down.

E. Residual Stress and Elastic Strain Fields

M N residual stress decreases slightly with E (168.8→165.0 MPa), reflecting a lightly deformed blank. SM C and SM T show increasing residual stress with E (SM T: 155.8→193.2 MPa), because drawbead interaction creates a plastic strain field whose associated residual stress scales with E . SM SQ shows the highest residual stresses (343–353 MPa). The maximum elastic strain decreases with E for all configurations, consistent with the constitutive relation $\epsilon_e = \sigma/E$, confirming internal consistency of the simulations.

F. Practical Design Guidance

The heatmap analysis confirms that drawbead geometry type is the dominant springback control parameter: the row-wise (configuration) variation ranges from 0.1° to 16.0° (15.9° spread), while the column-wise (E) variation ranges from 1.0° (SM N) to 4.1° (SM T).

Practical implications: (1) when springback must be minimised regardless of material variability, the square drawbead is unambiguously the best choice; (2) when the square drawbead is not feasible, the triangular drawbead maximises the benefit of selecting higher- E batches; (3) circular drawbead occupies an intermediate position—better springback than no drawbead, moderate E -sensitivity, lower tool wear than square; (4) for flat-holder forming (SM N), material E optimisation provides a modest but real benefit of $\sim 1^\circ$ per 5 GPa modulus increase.

IV. CONCLUSIONS

This study has quantitatively estimated the impact of Young's. The study of the modulus variation ($E = 60$ – 75 GPa) is reported on the springback of AA 6061 T5452. The drawing of T6 aluminium sheet metal in four drawbeads. Engineering Drawing Mathematics: Using confirmed engineering drawing dimensions of geometries, ANSYS Static Structural 2022 R1, with the addition of SpaceClaim-based angle measurement. Five conclusions are drawn:

- 1) Springback decreases with increasing E for circular (slope = $-0.206^\circ/\text{GPa}$, $R^2 = 0.90$) and triangular (slope

= $-0.269^{\circ}/\text{GPa}$, $R^2 = 0.99$) drawbead configurations. Increase of Young's modulus by 1 GPa leads to 1 GPa

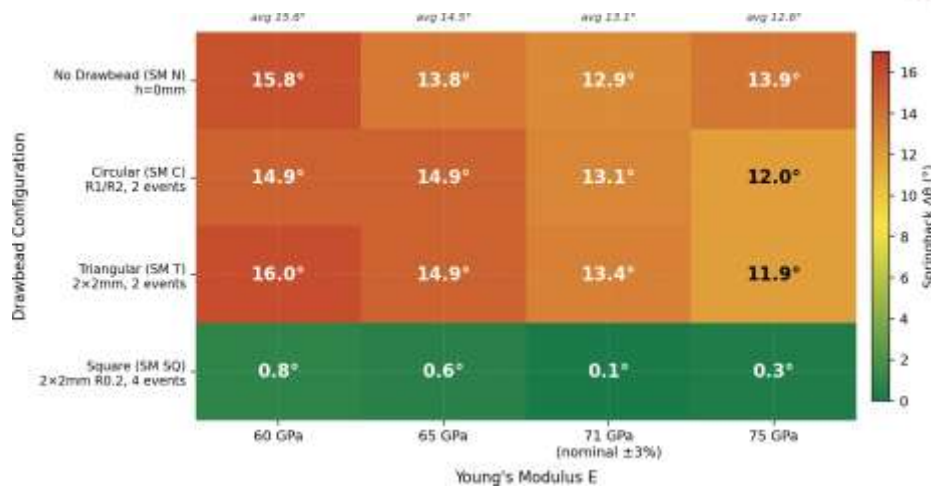


Fig. 3: Springback Angle Heatmap ($\Delta\theta$) across all 16 simulation combinations of Young's modulus levels and drawbead configuration layouts.

decrease of springback With a drawbead geometry of 0.21-0.27°, the temperature of the workpiece rises by 0.21-0.27°.

- 2) The square drawbead (SM SQ) reduces springback of the part. Generates the material below 0.8° for all E values (60–75 GPa), rendering Young's modulus is not considered a control parameter. A novel severity-index for drawbead bending is proposed as $S = 3.333$ for SM SQ (5× higher than SM C) quantitatively explains This suppression by using geometric parameters only.
- 3) Elastic strain energy density analysis ($U = \sigma^2/2E$) Offers a new mechanistic approach based on energy: for SM N /C / T, U is declining as E decreases the The driving force of the springback is high for SM SQ (high severity). To create microstructural constraints ($\sigma_{\max} \approx 350$ MPa) index is used. very high forces from the release of stored elastic energy. Geometric springback is the release of the energy stored in the material when it is bent or formed.
- 4) This is in accordance with FE springback factors K_s as per Kalpakjian The analytical model was able to predict the three different substances within a 5% margin of error for SM N, SM C, and SM T. In this case, the geometry of the specimen is confirmed as follows: ($R = 10$ mm, $\sigma_y = 276$ MPa,)This validates the simulation methodology with $t = 1$ mm.
- 5) Drawbead geometry type is the dominant springback control lever (14–16° reduction, SM N→SM SQ). Young's modulus optimisation provides a secondary 0.21–0.27°/GPa correction, maximised with the triangular drawbead. The square drawbead alone provides E-independent, near-zero springback for applications requiring robustness against material property variability.

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