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An Iterative Numerical Approach to Evaluate the Variable Friction Coefficient of Steel AMS5643 Using Ring Compression Tests

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ABSTRACT

The coefficient of friction is an important variable that must be defined to allow the accurate prediction of the forming geometry and stresses involved in metal forming processes. Literature reports have shown that the coefficient of friction does not remain constant with respect to variables including but not limited to contact pressure, sliding speed, surface roughness, and surface morphology. Ring compression tests provide a simple and efficient process by which to measure the variable coefficient of friction present in the bulk-metal process; however, the conventional interpolating method can result in a poor evaluation of the evolution of friction, especially if the coefficient of friction changes significantly during a test. In this article, a novel approach to evaluate the relationship between the coefficient of friction and contact pressure is outlined using friction calibration charts generated via iterative computation models and ring compression tests. This relationship can be programmed into a computational model to allow for the coefficient of friction to behave as a dynamic variable. This approach improves on the prediction of the computational model when compared to conventional interpolation methods.

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KEYWORDS
Friction; cold forming; ring compression test; computation modeling

Introduction

The coefficient of friction between the workpiece and tooling must be correctly defined to be able to accurately predict the stresses, forming load, energy consumption, and final part geometry in a metal forming process. However, it is inherently difficult to precisely quantify even within a simple static problem due to the number of factors that can influence the coefficient of friction (*1*, *2*). Some of these influencing factors include, but are not limited to, surface roughness and morphology (*3–7*), contact pressure (*8–10*), lubricants (*11*), workpiece and die material combinations, and temperature (*12*, *14*).

While many of these parameters can be considered constant during a given metal forming process, parameters such as surface roughness dynamically change throughout the process due to both the high contact pressures and plastic deformation present, which can result in a variable coefficient of friction. The current state of the art for computational modelling is not able to capture or model the behavior of many of these dynamic parameters. Therefore, it is not possible to define a variable coefficient of friction within a computation modeling environment as a function of a parameter such as surface roughness or morphology. One of the few parameters that can be used to define a variable coefficient of friction within a computational model is the contact pressure between two mating surfaces, which can be obtained from a ring compression test.

Building off the work of Kunogi (*15*), Male and Cockcroft (*16*) published a standard methodology for determining the coefficient of friction through the use of a ring compression test (Fig. 1). The test consists of a ring compressed axially between two flat and parallel compression platens, such that the material undergoes plastic deformation. If the interface between the specimen and dies is of sufficiently low friction (assuming isotropic material properties, perfect-plastic behavior, and homogeneous deformation), then the inner diameter of the ring will expand together with the outer diameter. As the friction increases, sticking will occur at the interface, which resists the outward flow of material, causing the specimen to bulge at the midplane (barreling). Once the friction coefficient reaches a critical value it becomes favorable for material to flow inward and results in the reduction of the inner diameter. The coefficient of friction is evaluated by interpolating between the relationship of the inner diameter and height of the specimen against analytically derived friction calibration curves (FCCs) at constant coefficients of friction. This results in all the potential influencing factors on the coefficient of friction being reduced to a single parameter that is the contact pressure between the workpiece and dies.

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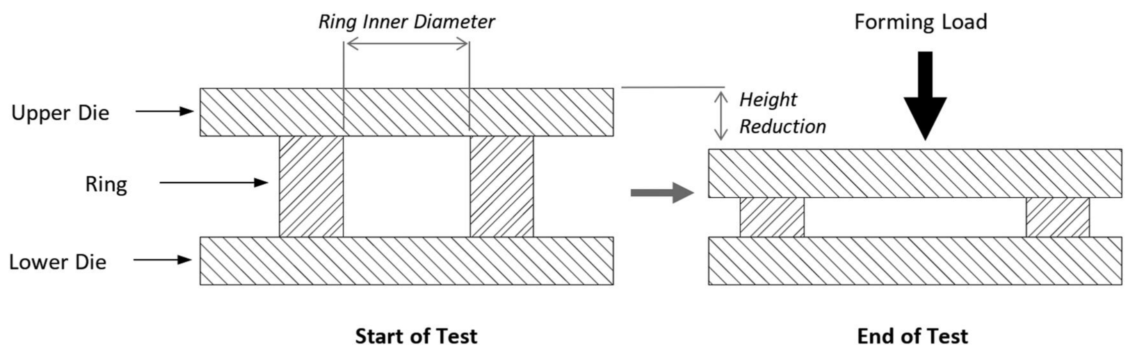

Figure 1. Ring compression test schematic.

The use of computational modeling to numerically derive the FCCs (*10*, *11*, *14*, *17*, *19*) has allowed for the incorporation of material behaviors not possible via analytical methods, such as strain rate, strain hardening, and nonuniform contact pressures. While the interpolation method for determining the coefficient of friction from a ring compression test is an efficient process, as will be later investigated, interpolating the coefficient of friction between FCCs can result in a poor evaluation of the evolution of friction with respect to contact pressure, especially if the coefficient of friction is rapidly changing.

Despite evidence indicating that the coefficient of friction (under the correct conditions) can vary with respect to contact pressure (*10*, *21–23*), it is still common practice for the coefficient of friction to be quoted and modeled as a static value (*17*, *24–27*). The complex nature of friction and the comparably high cost required to investigate these phenomena give little incentive to conduct research or change industrial practices. However, with respect to bulk-metal forming, one of the largest factors leading to a loss in production is excessive die wear or failure whereby friction is the leading contributing factor (*28*), highlighting the importance of understanding this phenomenon. Recent research has begun to see the integration of a variable friction coefficient into computational models with the aim of improving the accuracy of both sheet (*26*) and bulk-metal forming (*10*, *19*, *30*). This is an active area of research and a continuing area of debate as to how to best implement variable friction coefficients into numerical and analytical models.

In this article, a new method for determining the pressure–friction relationship is presented where ring compression tests are analyzed with an iterative computational model. This is compared to the conventional approach of interpolating experimental data against FCCs. For this study, the two methods are referred to as the "iterative FCC" and "FCC interpolation." This research was in support of a wider study of work into the bulk-metal cold-forming process of staking, which is widely used in the aerospace sector for the manufacture and assembly of spherical-plain bearings and rod-end links (*31*). This manufacturing process is characterized as a single-strike operation, similar to wire crimping and sheet metal pressing. Therefore, the material investigated in this research was steel AMS5643, with all testing conducted at room temperature, to best replicate the conditions experienced in the manufacturing of spherical-plain bearings.

Table 1. Chemical composition of AMS5643.

Element	C	Mn	P	S	Si	Cr	Ni	Cu	Mo	Nb
Content (%)	0.07	1	0.04	0.03	1	17.5	5	5	0.5	0.45

Methodology

Test specimens

AMS5643 (H1150 condition) is a high-strength, corrosion-resistant steel used extensively within the aerospace industry. The chemical composition is given in Table 1.

There is no consensus on the most suitable specimen dimensions for a ring compression test; however, it has been shown that increasing the inner diameter can lead to an increase in measurement accuracy (*32*). If the inner diameter is increased too much, then the ring risks buckling during deformation due to the thinner wall thickness. This can be compensated for by increasing the outer diameter in kind, but this will have the undesired effect of increasing the required forming load. The most commonly used ratio of outer diameter to inner diameter to height (OD:ID:H) used is 6:3:2 (*10,18,19*) with an inner diameter of 9.53 mm; therefore, these dimensions were chosen for this study (Fig. 2). To maintain consistency between test specimens, the surface roughness (Ra) was machined to a finish of 1.6 μm and verified using a contact-type roughness meter.

Experiment setup

In total, 20 specimens were produced to ensure that an adequate number of data points could be acquired to ensure statistically valid results. Molybdenum disulfide lubricant (G-n Plus) was applied to each face of both the specimens and to the compression platens. Tests were conducted using a 640-kN, four-column press with tungsten carbide plates (Grade YG15) inserted into the compression platens to function as the upper and lower die surfaces.

The load profile of the press was set to 15 kN and increased in increments of 5 kN to reduce the height of the specimens in even increments from approximately 10 to

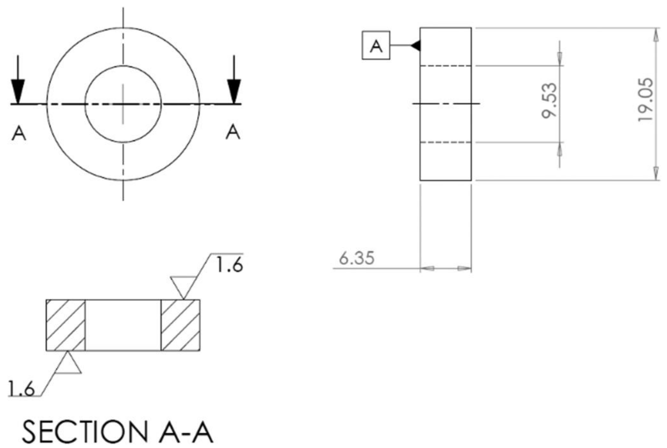

Figure 2. Ring compression test specimen drawing. All dimensions in mm and surface roughness (Ra) in µm.

50% (Fig. 1). Each load step was achieved at a constant velocity equivalent to a strain rate of $0.1\,s^{-1}$. While the actual strain rate will have deviated slightly during each load step (due to the changing height of the specimen), this approach was able to effectively eliminate strain rate as a variable across all of the test runs.

Variation in specimen diameter

The inner diameter of a specimen may take on a noncircular shape after deformation, especially if there is any degree of anisotropic frictional or material behavior, and therefore an averaged value for the inner diameter can be taken to account for this behavior (*10*). To measure for any anisotropic behavior, a sweep of the inner diameter was taken for each sample at every test load to obtain the maximum and minimum diameter. It was found across all load conditions that the variance of the average inner diameter was greater than the average variance between the maximum and minimum diameter typically by a factor no less than three. An example of the ovality of the test specimens at a load of 50 kN is shown in Fig. 3. It was therefore deemed appropriate to take an average of the maximum and minimum inner diameter when calculating the change in inner diameter because of the small measure of anisotropic behavior relative to the variance between test specimens.

Barreling compensation

Friction at the interface between the die and test specimen will result in barreling and an inhomogeneous strain field as the specimen is compressed (*19*). This creates a condition where the uniaxial stress state principle no longer holds true. Similar to Bridgman's correction factor (*33*), a bulge correction factor (C_f) was used to calculate the true stress (σ) of the ring specimens (*34*) at each load increment:

$$\sigma = C_f \frac{4P}{\pi(D^2 - d^2)} \quad [1]$$

where P is the compressive load, D is the outer diameter, and d is the inner diameter.

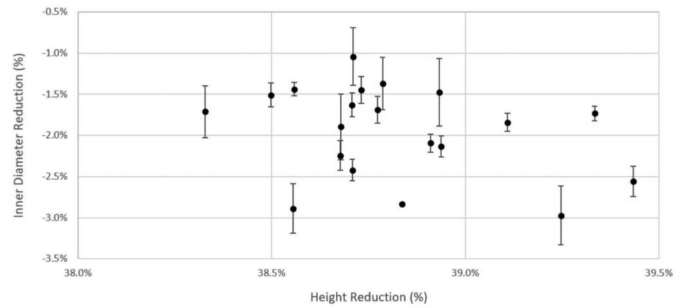

Figure 3. Variation of the inner diameter reduction percentage caused by the ovality of the test specimens for the 50 kN load condition. Larger error bars represent greater ovality.

The bulge correction factor is derived analytically from the analysis of the stress distribution at the midplane (*35*) and is given as

$$C_f = \left[\left(1 - \frac{2R}{a}\right)\ln\left(1 - \frac{a}{2R}\right)\right]^{-1} \quad [2]$$

where R is the outer bulge radius of the sample in the vertical plane and a is the outer radius at the horizontal midplane of the specimen. From geometric relations, the bulge radius was calculated as

$$R = \frac{h^2 + (D - d)}{4(D - d)} \quad [3]$$

were h is the actual height of the test specimen.

Finite-element simulation

Finite-element model

The computational model created to simulate the ring compression tests was made using the simulation software ANSYS. Due to the symmetric nature of the tests, an axisymmetric analysis was used to increase computational efficiency, with convergence achieved at 1734 nodes and 1579 elements. The flow stress model for AMS5643 followed a modified Hollomon profile and is given as

$$\sigma_{(MPa)} = 1526\dot{\varepsilon}^{-0.0198}\ \bar{\varepsilon}^{\ (0.0528\ \dot{\varepsilon}^{-0.1398})} \quad [4]$$

where $\dot{\varepsilon}$ is the true strain rate and $\bar{\varepsilon}$ is the true strain. The upper and lower platens were modeled as rigid bodies, as is typical for bulk-metal models (*10*, *20*).

Friction model

Friction is typically characterized by two models: either Coulomb's law or the Tresca friction model. For Coulomb's law, the tangential frictional stress is expressed as a function of the normal contract pressure and is given as

$$\tau_f = \mu\sigma_N \quad [5]$$

where τ_f is the tangential frictional stress, σ_N is the normal contact pressure, and μ is the coefficient of friction. A constant value for the coefficient of friction is only valid provided the ratio between the normal contact pressure and the yield stress remains below approximately 1.3–1.5 (*22*, *35*). Beyond this point, it is understood that the surface asperities at the contact interface will have deformed such that the real and apparent contact areas are equal. This leads to the frictional stress becoming constant and no longer proportional to the normal contact pressure, resulting in a decreasing coefficient of friction as the contact pressure increases. Under these conditions, the tangential frictional stress is better modeled by the Tresca friction model and is given as

$$\tau_f = mk \qquad [6]$$

where m is the friction factor and k the materials shear strength. However, it has been shown that neither friction model can accurately reflect the dynamic friction conditions present in bulk-metal forming and that a hybrid between the two models is required (*22*).

The reference friction model used within ANSYS follows Coulomb's law and was used to create the FCCs.

Analysis and discussion

FCC interpolation

The conventional approach to determining the coefficient of friction from ring compression tests is as follows. The ring compression test is simulated in a computational model across a range of friction coefficients (for this study the required range required was 0.05–0.1). From these simulations, the results history for the percentage reduction in inner diameter is plotted against the percentage reduction in height to create the FCCs. Finally, the experiment ring compression data are compared to the simulated results and the coefficient of friction is determined by interpolating between the constant friction curves. The results of the FCC interpolation approach are shown in Fig. 4. By interpolating between the FCCs and calculating the average forming pressure at each load step, the pressure–friction relationship was determined and plotted in Fig. 5.

By running a custom command within the ANSYS simulation environment, the friction coefficient determined in Fig. 5 could be programmed into the computational model. As shown in Fig. 6, this custom friction model was able to produce a good prediction for the ring compression experiment data up to approximately a 30% height reduction, after which the computational model begins to underpredict the reduction in inner diameter. At a height reduction of 33.5%, the friction coefficient is evaluated to be 0.08 but the gradient of the experiment data is significantly steeper than the 0.08 constant friction curve (Fig. 7). It is clear to see that the friction coefficient should be greater than 0.08 to maintain the gradient of the experiment data and reach the next data point at 38.8%.

Iterative FCC

To improve on the FCC interpolation method, an iterative approach to generating the FCCs was proposed (Fig. 8) and is described as follows. First, constant friction curves were created from the initial geometry up to the change in height recorded at the end of the first load step and the friction coefficient was evaluated similarly to the interpolation method. New constant friction curves were then generated starting from the geometry at the end of the first load to the end of the second load step and the friction coefficient was again evaluated for this second load step.

This is repeated across all load steps to produce a relationship between the contact pressure and the coefficient of friction. Figure 9 shows the results of this method. Because the friction coefficient was modeled as a constant throughout each load step, a final "smoothed" pressure–friction relationship was obtained by using the average pressure for each load step as shown in Fig. 9.

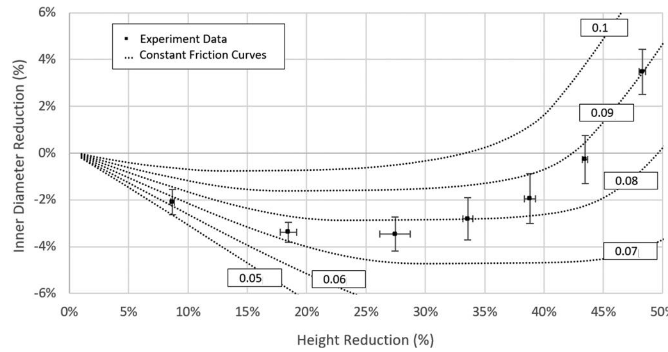

Figure 4. Ring compression test data for AMS5643 with a G-n Plus lubricant and FCCs ranging from a coefficient of friction of 0.05 to 0.1. Experiment error bars represent a 95% confidence interval.

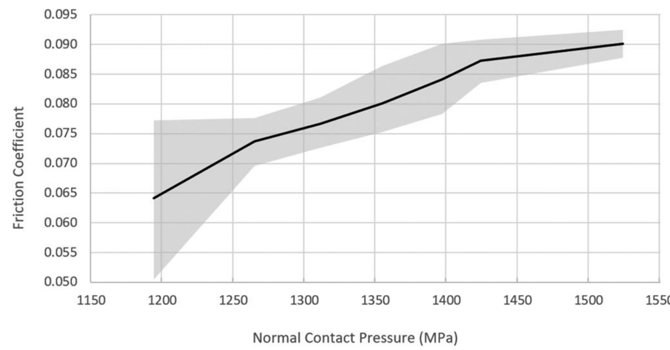

Figure 5. Variation in the coefficient of friction against contact pressure for steel AMS5643 with a G-n Plus lubricant. Shaded region, 95% confidence interval for the friction coefficient.

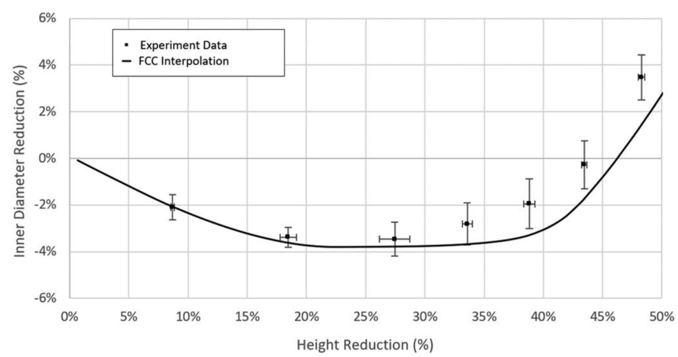

Figure 6. Comparison of the ring compression test data and the prediction using the FCC interpolation method.

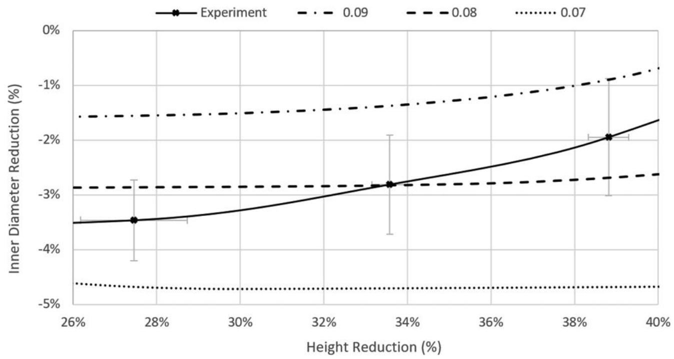

Figure 7. Detailed view from the FCCs in Fig. 3.

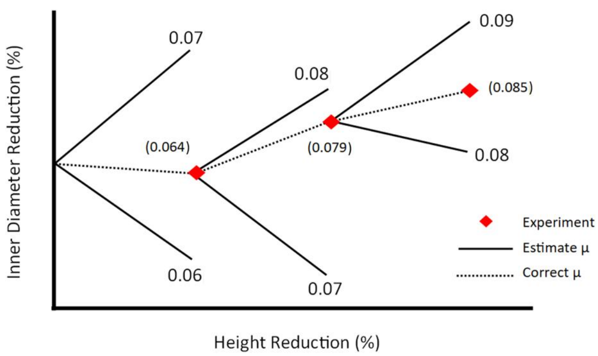

Figure 8. Schematic for the Iterative FCC methodology to evaluate the coefficient of friction (μ).

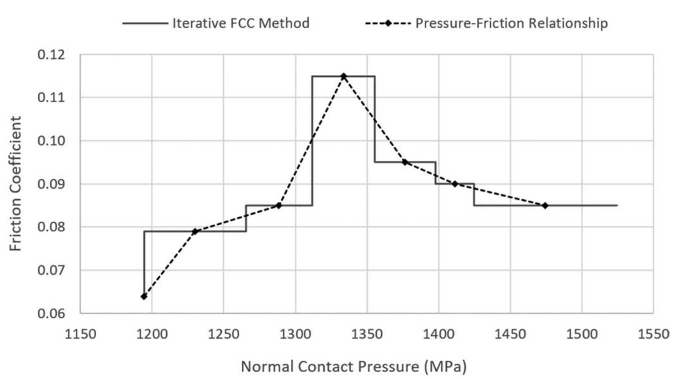

Figure 9. Pressure–friction relationship derived via the iterative FCC method.

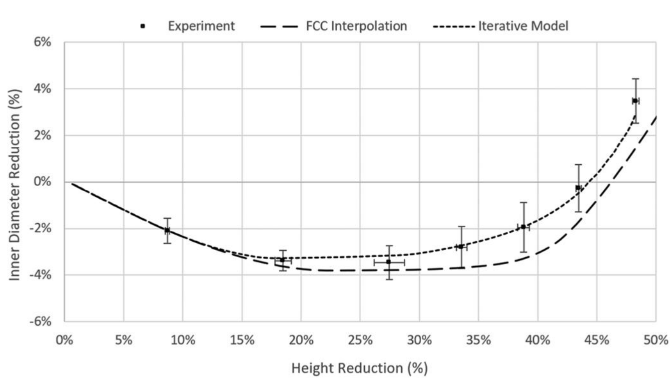

Figure 10. Comparison of the interpolation and iterative friction models to the ring compression experiment data.

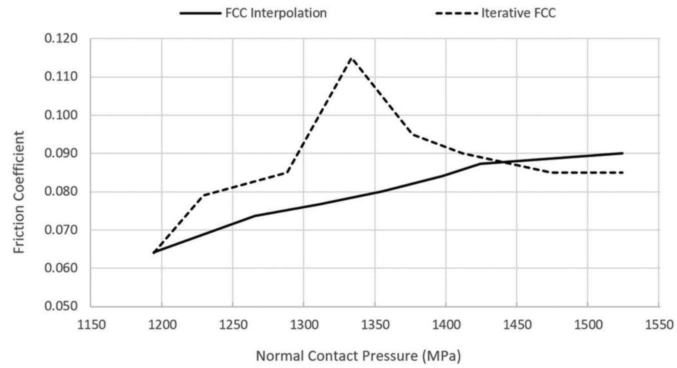

Figure 11. Friction–pressure relationship comparison.

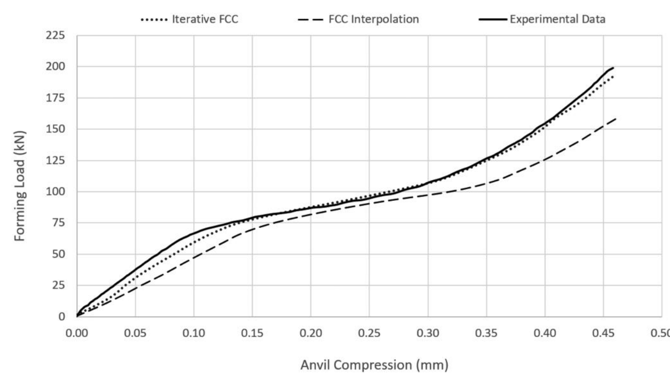

Figure 12. Performance of the two ring compression analysis methods compared to the forming loads experienced during the staking of a production spherical-plain bearing.

When compared to FCC interpolation, the iterative FCC method produces a better prediction for the ring compression test and remains within the 95% confidence interval of the experiment data across its entire test range (Fig. 10). A comparison of both contact pressure–coefficient of friction relationships is shown in Fig. 11.

The relationship generated by the iterative FCC method saw a rise in the friction coefficient from 0.064 to 0.115 at a contact pressure of 1334 MPa before decreasing to 0.085. The initial rise in the friction coefficient is likely attributed to the breakdown of the lubricant as the load-bearing capacity is exceeded and is spread thinner as the surface area of the test specimens increases with forming load. The peak friction coefficient at 1334 MPa was 1.35 times the yield strength of AMS5643 at 0.1 s^{-1} (985 MPa). This result agrees with the predicted decrease in friction coefficient expected at 1.3–1.5 times the yield strength (*22, 36*).

When viewed in a broader context, the significant improvements of the iterative-FCC method does not completely diminish the usefulness of the standard interpolation method if the coefficient of friction remains constant across the entire contact pressure range. Under these specific conditions the interpolation method can still produce accurate results without the need for further computational modeling. However, small changes in the evolution of the coefficient of friction can have a significant impact on the forming loads experienced during a forging process. To demonstrate this, a finite-element simulation was created to model the staking of a spherical-plain bearing (*31*) using the pressure–friction relationships derived from both analysis methods. As shown in Fig. 12, the iterative-FCC model was able to better predict the forming load across all ranges of anvil compression.

At a peak anvil compression of 0.46 mm, the error in the forming load of the interpolation method was ∼30%, compared to only ∼5% for the iterative-FCC method.

Conclusions

Friction is one of the most important properties in metal forming operations, yet it is often neglected or simplified to a single constant value. Presented in this research is the evaluation of two different methods for determining the relationship between the contact pressure and coefficient of friction for steel AMS5643 via ring compression testing. The conventional method (FCC interpolation) compares the deformation of the ring specimens against FCCs simulating the ring compression test at various constant friction coefficients. The new method proposed in this study (iterative FCC) generates new FCCs for each load step that begins at the geometry of the last load step. The results from this research are summarized as follows:

- The FCC interpolation method provides a good initial prediction of the experimental data but fails to follow the experiment data at height reductions greater than 30%. Interpolation between FCCs is not able to describe the changing friction coefficient at each load step and becomes less accurate as the coefficient of friction changes more.
- The iterative FCC method was able to produce an accurate prediction of the experiment data, remaining within the 95% confidence interval across the entire test range.
- The iterative FCC coefficient of friction decreased from its maximum value of 0.115 after exceeding a contact pressure of 1334 MPa. This matched the theoretical decrease in the coefficient of friction expected at 1.3 to 1.5 times the yield strength of AMS5643.

The iterative FCC analysis method developed in this research can be applied to any ring compression test condition and provides improvement over the conventional FCC interpolation method. This improvement is expected to increase in conditions with higher contact pressures or when the variability of the coefficient of friction increases.

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Conflicts of interest

The authors declare no conflicts of interest.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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