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Research Paper

Ring Compression Test Analysis on Lead and Plasticine Materials

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Abstract
In this study, the coefficient of friction in bulk metal forming processes was investigated using the ring compression test for two different materials: lead and plasticine. The main objective was to determine the friction coefficients under various lubrication conditions by employing both theoretical calibration curves and numerical simulations using ANSYS software. The experimental data, including dimensional changes during the ring test, were compared to simulation results to extract accurate values for the coefficient of friction. The discrepancies between theoretical and numerical outcomes were primarily attributed to strain hardening and other modeling considerations not accounted for in analytical methods. The study showed that numerical simulations provided more realistic estimates of frictional behavior, making them better suited for industrial applications. Furthermore, the results confirmed that using a combined lubricant of talc powder and vegetable oil significantly reduced the coefficient of friction compared to using talc powder alone. This research highlights the importance of selecting appropriate lubricants and modeling methods for accurate prediction and optimization of metal and polymer forming processes. Overall, combining experimental testing and finite element analysis presents a comprehensive and effective approach to evaluating tribological conditions in forming operations.

Keywords
Bulk Metal Forming, Friction, Ring Compression Test, Numerical Analysis, Finite Element Modeling

1. Introduction
Friction is a critical factor in plastic forming processes, especially those involving large deformations such as forging. It significantly influences material flow, surface quality, internal structure, and the required forming forces and energy. Generally, friction has detrimental effects, causing material flow disturbances, tool wear, increased loads, surface and internal defects, and non-uniform distributions of strain and temperature [1]. Nonetheless, friction is essential for enabling many forming operations. Accurate friction modeling, therefore, requires a comprehensive understanding of influencing factors and mechanisms [2].
Despite various theoretical models, a complete and universal description of friction in metal forming remains unavailable [3]. Friction in forming differs fundamentally from that in mechanical components, particularly in the applied pressure range, which may reach 2500 MPa—far exceeding

the 10–50 MPa typical in mechanical contacts. Additionally, contact surfaces in forming experience highly variable particle displacements, unlike the more uniform displacements in mechanical parts. The presence of friction increases the forces and energy needed for deformation and contributes to inhomogeneous strain distributions [4].

The analysis of friction and lubrication—central to tribological conditions—is complex, involving many material and tooling-related factors, some of which remain poorly understood [5]. As a result, extensive research has been dedicated to characterizing these influences and defining friction coefficients. In plastic forming, real contact areas differ from nominal surfaces, consisting of microscopic asperity contacts that grow with increasing pressure. These create non-uniform pressure and frictional forces at the tool–material interface during deformation [6].

Friction types are typically classified by motion type, contact condition, material characteristics, and lubrication regime. The three main types encountered are dry friction, boundary friction, and fluid friction. In fluid friction, a continuous lubricant film fully separates the surfaces, and friction arises from internal fluid resistance [7-9].

In forming operations, especially forging, boundary friction predominates. It is influenced by strain rate, initial stress, forming temperature, surface finish, lubricant type and application, tooling material, and the material being formed [11-12]. Its complexity arises from the interplay of mechanical, physical, and chemical processes at the contact interface. Therefore, extensive research has focused on defining tribological conditions and developing simple, accurate methods to measure friction under realistic forming conditions [13-16].

Although tribometers like pin-on-disk devices are commonly used, their low-pressure operating conditions do not match those in real forming processes, which limits result applicability [17-18]. Therefore, test methods must replicate the geometry and pressures of actual forming operations, and results should be validated against industrial-scale conditions.

Recent studies have also shown that microscale parameters, such as contact surface topography, can significantly influence frictional behavior. For instance, investigations have demonstrated that surface microstructure can lead to considerable changes in stress distribution and, consequently, the coefficient of friction. These findings emphasize the importance of accounting for microscale effects in experimental design and numerical simulations [19].

Overall, although various analytical, experimental, and numerical methods have been developed to estimate the coefficient of friction, each has limitations due to indirect measurement methods and sensitivity to input parameters [20-22]. Therefore, selecting an appropriate friction evaluation method should be based on the specific process conditions and modeling requirements. The development of precise laboratory methods and accurate simulations—combined with validation under real-world conditions—is essential for achieving a reliable understanding of friction behavior.

2. Ring Compression Test Method

The ring compression test is a widely adopted method for evaluating friction in bulk forming, especially forging. A ring-shaped specimen with dimensions in the ratio Do:Di: H = 6:3:2 (outer diameter, inner diameter, and height) is compressed between two rigid parallel platens.

With zero surface friction, both inner and outer diameters increase during compression. As friction increases, the inner diameter expands less or may even shrink. This behavior makes the ring test a valuable tool for comparing different lubrication or tooling conditions. If precise friction values are unnecessary, changes in inner diameter alone can provide relative comparisons. An increase in the inner diameter after compression generally indicates lower friction.

Theoretical calibration curves predict changes in inner diameter as a function of height reduction under various friction levels. By comparing experimental data with these curves, one can estimate the friction coefficient quantitatively.

Among empirical friction evaluation methods, the ring test is considered the most reliable. It is simple, fast, cost-effective, and replicates industrial conditions well. Furthermore, using advanced tools such as 3D scanning and finite element modeling improves accuracy and test relevance.

Given the complex stress states and material flow behavior in forging, traditional analytical methods are often inadequate. Hence, numerical simulation, particularly finite element analysis (FEA), is essential for detailed process modeling and cost-effective experimentation.

This study aims to derive calibration curves for friction coefficients through ANSYS simulations of the ring compression test and to compare them with experimental results on different materials and lubrication conditions. ANSYS has previously demonstrated success in simulating sheet and bulk metal forming processes.

Using both ring compression testing and ANSYS simulations, this study estimates and compares friction coefficients for lead and plasticine under different lubrication scenarios.

3. Experimental Method

3.1 Materials and Test Conditions

Two materials, lead and plasticine, were tested to study the effects of material type and lubrication on deformation behavior and friction coefficient estimation. Lead samples were tested using talc powder and a 1:1 mass ratio of talc powder and vegetable oil. For plasticine, only talc powder was applied.

Ring specimens were machined to standard dimensions and tested to collect stress–strain and frictional data.

3.2. Compression Test Results

Compression tests on cylindrical specimens were conducted to determine mechanical properties. Stress–strain curves were recorded for lead under both lubrication conditions and for plasticine with talc powder. These curves were analyzed in Excel and fitted using the Hollomon model, yielding stress–strain Equation (1) for lead and Equation (2) for plasticine (Figure 1).

$$\sigma = 42.9\varepsilon^{0.23} \quad \text{(MPa)} \tag{1}$$

$$\sigma = 135.6\varepsilon^{0.25} \quad \text{(kPa)} \tag{2}$$

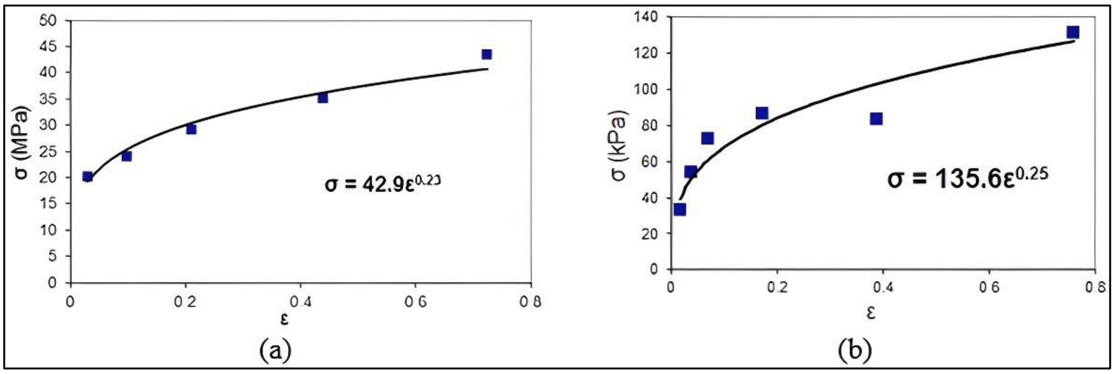


Figure 1. The stress–strain curve of materials: a) Lead, b) Plasticine

3.3. Ring Compression Test Results

Ring tests were conducted at 25°C with punch speeds of 0.01 mm/s (lead) and 0.05 mm/s (plasticine). Post-test inner diameter and height measurements were recorded. Data and percentage changes are summarized in Tables 1 and 2 for analysis.

Table 1. Experimental results of the ring compression test for lead specimens with different lubricants.

Step	Lead (Talc)				Lead (Talc-oil)			
	$H(mm)$	$D_i(mm)$	$\Delta H(\%)$	$\Delta D_i(\%)$	$H(mm)$	$D_i(mm)$	$\Delta H(\%)$	$\Delta D_i(\%)$
1	7.9	12.0	0	0	8.1	12.0	0	0
2	7.3	11.8	7.60	1.67	7.3	11.75	9.88	2.08
3	6.15	11.0	22.15	8.33	6.4	11.2	20.99	6.68
4	4.9	9.8	37.98	18.33	4.7	10.9	41.98	9.17

Table 2. Experimental results of the ring compression test for plasticine specimens with talc powder as lubricant.

Step	Plasticine (Talc)			
	$H(mm)$	$D_i(mm)$	$\Delta H(\%)$	$\Delta D_i(\%)$
1	15.33	22.60	0	0
2	12.70	20.65	17.16	8.63
3	9.36	17.20	38.94	23.89
4	8.21	14.40	46.44	36.28

4. Numerical Simulation

The ring compression test was simulated in ANSYS using the MISO hardening model, which supports accurate elastic–plastic material characterization. Stress–strain curves (20 data points above yield stress) were used as input (Figure 2).

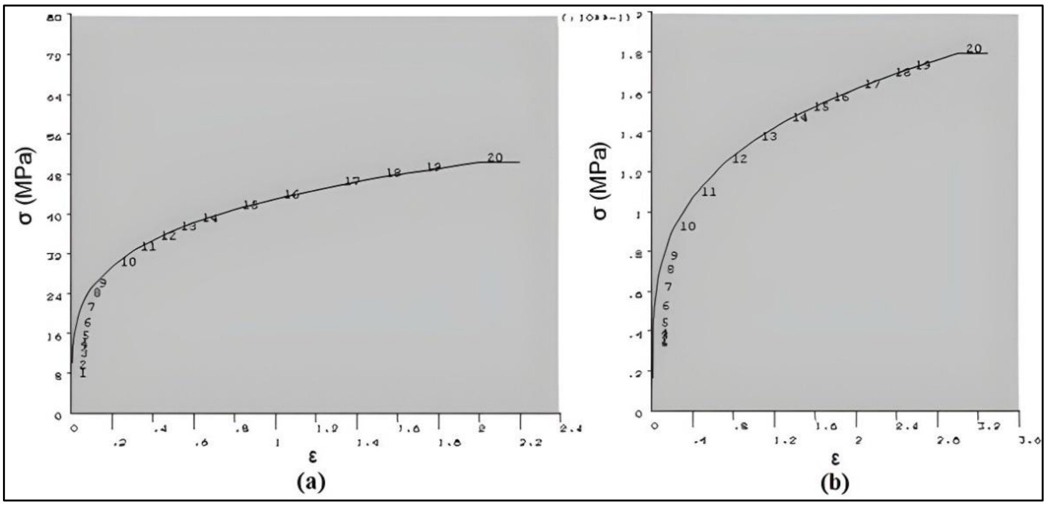


Figure 2. The stress–strain curves of the materials were defined in the ring test simulation: a) Lead, b) Plasticine

Key assumptions in the simulations included:

- Materials were assumed isotropic and homogeneous.
- The Bauschinger effect was neglected, assuming no directional change in properties post-deformation.

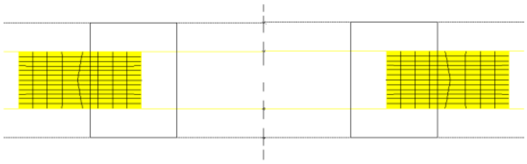
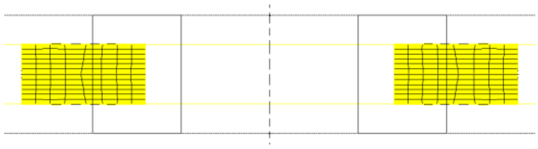
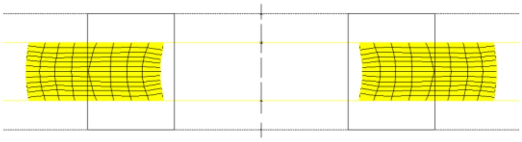
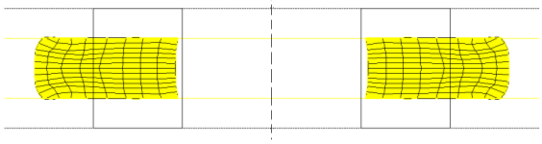
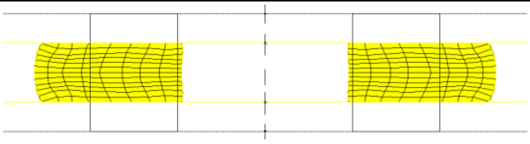
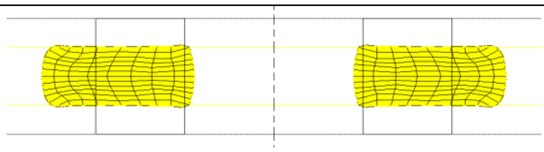
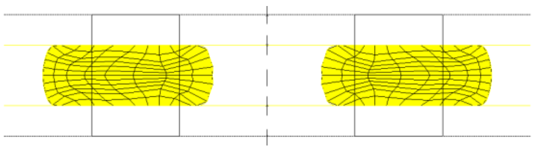
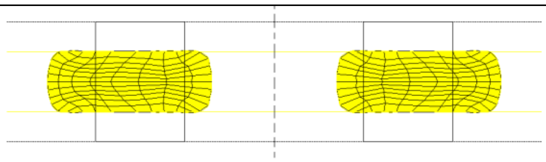
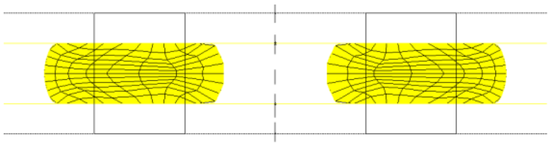
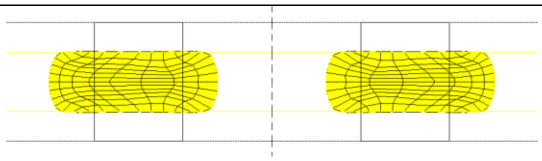
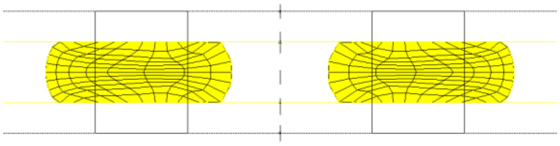
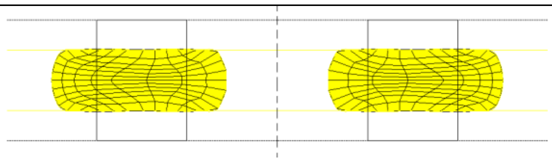
These assumptions simplify the model and are consistent with similar studies. The mechanical properties used for lead and plasticine in the simulation are listed in Table 3.

Table 3. Mechanical properties are defined in the ANSYS software

Properties	Lead	Plasticine
Young's modulus (MPa)	*17000*	100
Poisson’s ratio	*0.425*	0.3

Simulation results were used to generate calibration curves for each material under different friction conditions. These curves relate changes in inner diameter and height to the corresponding friction coefficients. Deformation outcomes are presented in Table 4, and calibration curves are shown in Figure 3.

Table 4. Ring deformation stages at different friction coefficients (simulation): a) Lead, b) Plasticine

μ	Lead	Plasticine
0		
0.05		
0.1		
0.2		
0.3		
0.4		

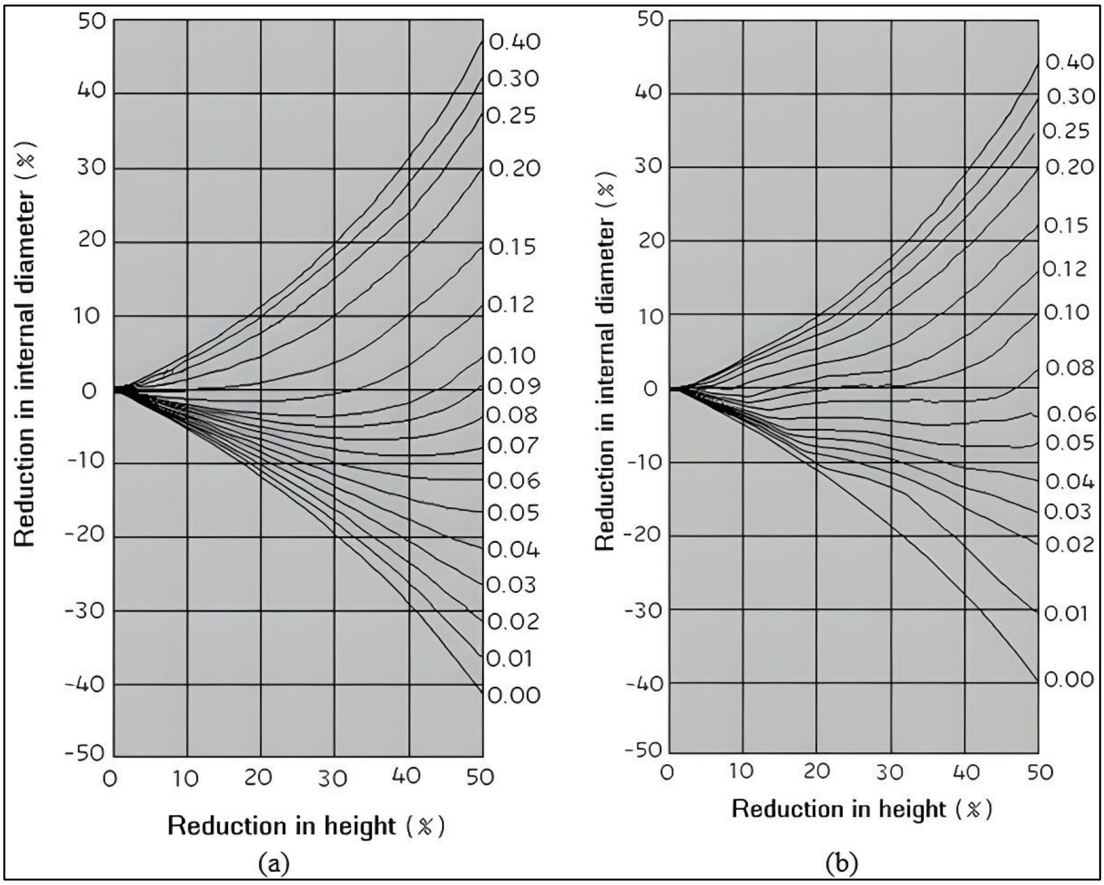


Figure 3. Calibration curves plotted using numerical simulation: a) Lead, b) Plasticine

5. Results and Discussion

To compare the theoretical and numerical outcomes, the experimental results from the ring compression test were correlated with the numerical simulation data to determine the final coefficient of friction for each material and lubrication condition.

5.1 Coefficient of Friction from Theoretical Calibration Curves

Using the inner diameter and final height values obtained from the experimental tests, the friction coefficients were extracted from the theoretical calibration curves (Figure 4, Table 5). The results confirm that both the type of lubricant and the material significantly influence the friction behavior during forming. This observation is in agreement with previous studies [23,24], which also emphasized that lubrication conditions and material properties jointly affect surface interaction and deformation uniformity.

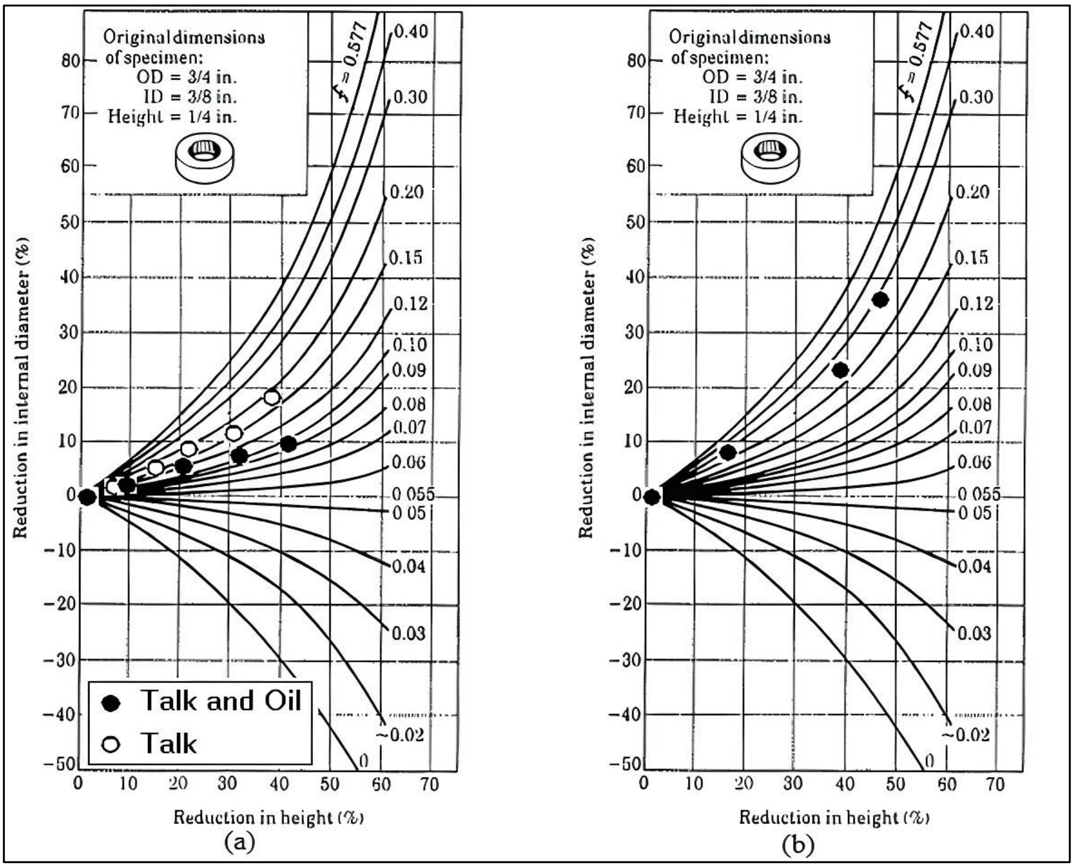


Figure 4. Friction coefficient determined using theoretical calibration curves: a) Lead, b) Plasticine

Table 5. Friction coefficients from theoretical calibration curves.

Material	Lubricant	Friction coefficient
Lead	Talc and Oil	0.10
	Talc	0.15
Plasticine	Talc	0.25

5.2 Coefficient of Friction from Numerical Simulation

Numerical simulations using ANSYS provided additional insights, as calibration curves derived from simulation data (Figure 5, Table 6) allowed for more detailed analysis. The friction coefficients obtained from simulation were generally higher than the theoretical ones, consistent with earlier reports by Kim et al. [25] and Roshandeh et al. [26], who observed that FEM-based models capture material hardening and contact pressure more accurately than upper-bound analytical methods.

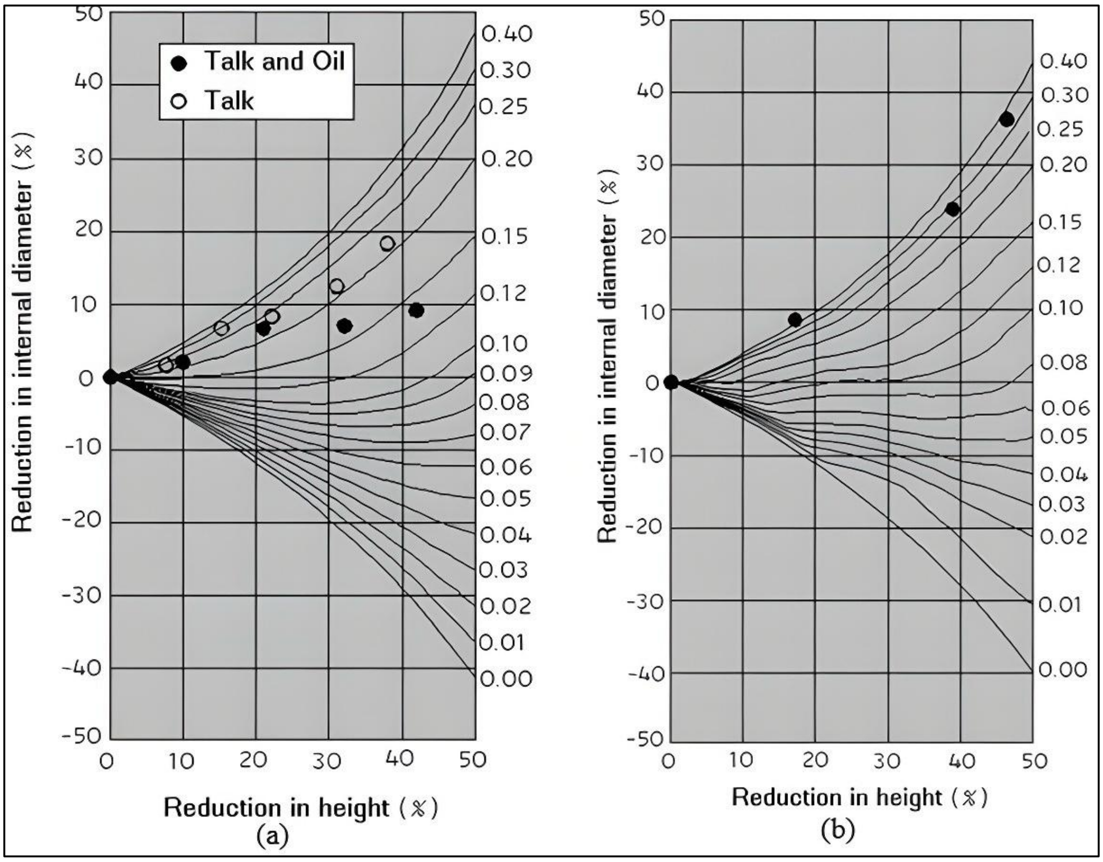


Figure 5. Friction coefficient determined using numerical calibration curves: a) Lead, b) Plasticine

Table 6. Friction coefficients from numerical calibration curves.

Material	Lubricant	Friction coefficient
Lead	Talc and Oil	0.15
	Talc	0.20
Plasticine	Talc	0.30

The comparison between plastiline and lead showed that plastiline had a consistently higher coefficient of friction, which may be attributed to its higher viscosity and adhesive behavior. Similar trends were reported by Fang et al. [27], who studied plasticine-based forming analogs and found elevated friction coefficients due to material softness and interface stickiness.

Moreover, the combined use of talc powder and vegetable oil was found to significantly reduce the coefficient of friction compared to talc powder alone. This supports the findings of Ebrahimi et al. [28], who demonstrated that multi-phase lubricants create a more stable film at the interface, leading to reduced metal-to-die adhesion and lower forming forces.

In general, the deviation between experimental and simulated results can be attributed to modeling simplifications in the theoretical method, particularly the neglect of strain hardening and non-uniform stress distribution. These limitations have been widely discussed in previous literature [29-30], which suggests that simulation-based calibration is a more reliable method for complex forming processes.

6. Conclusion

This study focused on determining the coefficient of friction in metal forming processes through a combination of ring compression testing and numerical simulation. The findings lead to several key conclusions:

1. Numerical simulations consistently yielded higher friction coefficients than theoretical methods. This outcome underscores the enhanced predictive capabilities of simulation-based approaches, which account for material strain hardening and complex deformation behavior—factors often simplified or neglected in analytical models.

2. A comparative analysis of lead and plasticine revealed that plasticine exhibited higher friction coefficients under similar conditions. This can be attributed to its greater viscosity and stronger adhesion to tooling surfaces, confirming its effectiveness as a representative material for studying friction in high-adhesion forming environments.

3. Moreover, the use of a combined lubricant—talc powder mixed with vegetable oil—proved more effective in reducing friction than talc powder alone. This suggests that multi-phase lubrication systems can significantly enhance lubrication performance by forming more stable interfacial films and reducing die–material interaction.

4. Finally, the integration of experimental measurements with simulation-based calibration curves demonstrated the potential of the ring compression test as a quantitative and reliable method for evaluating friction. This approach advances the test beyond its traditional qualitative application, providing a robust framework for friction analysis in practical forming processes.

In conclusion, this research offers a comprehensive methodology for friction evaluation in bulk metal forming, combining experimental accuracy with the analytical depth of numerical modeling.

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