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MATHEMATICAL CALIBRATION OF THE RING TEST WITH BULDGE FORMATION

Vincent De Pierre, et al

Westinghouse Electric Corporation

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VINCENT DE PIERRE
AIR FORCE MATERIALS LABORATORY

FRED GURNEY
ALAN T. MALE
WESTINGHOUSE ELECTRIC CORPORATION

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An available mathematical solution of ring compression with bulge formation was utilized to calibrate ring test specimens on the basis of constant interface friction factor, m. Calibration curves for the 6:3:2 (Outside Diameter: Inside Diameter: Thickness) and other ring geometries were obtained by mathematical computation and a method was established for calibrating all ring geometries with bulge formation. Calculated calibration curves of the 6:3:2 ring showed very good correlation with experimentally determined interface friction factors, m.

The investigation demonstrated that a valid mathematical solution of ring compression can be utilized for more accurate and less laborious calibration than experimental calibration of ring test specimens.

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I-C

FOREWORD

This report was prepared by the Westinghouse Electric Corporation, Astronuclear Laboratory, Pittsburgh, Pennsylvania, under U.S.A.F. Contract F33615-71-C-1163. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735108, "Processing of Metals", and administered under the direction of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio with Mr. Vincent De Pierre as Air Force Project Engineer.

The research work was conducted by Mr. Fred Gurney and Dr. Alan T. Male of Westinghouse Electric Corporation and Mr. Vincent De Pierre of the Air Force Materials Laboratory.

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This technical report has been reviewed and is approved.

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ABSTRACT

An available mathematical solution of ring compression with bulge formation was utilized to calibrate ring test specimens on the basis of constant interface friction factor, m. Calibration curves for the 6:3:2 (Outside Diameter: Inside Diameter: Thickness) and other ring geometries were obtained by mathematical computation and a method was established for calibrating all ring geometries with bulge formation. Calculated calibration curves of the 6:3:2 ring showed very good correlation with experimentally determined interface friction factors, m.

The investigation demonstrated that a valid mathematical solution of ring compression can be utilized for more accurate and less laborious calibration than experimental calibration of ring test specimens.

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MATHEMATICAL CALIBRATION OF THE RING TEST WITH BULGE FORMATION

I INTRODUCTION

The first quantitative calibration of the ring test for friction studies in metalworking operations was made experimentally by Male and Cockcroft[1-2] on the assumption of constant coefficient of friction (μ) for a ring geometry of 6:3:2 (outside diameter: inside diameter: thickness) dimensions. Subsequent mathematical analyses[3-5] provided a possible means for more accurate calibration of the 6:3:2 and other ring geometries for friction evaluation. The analyses by Avitzur[3] and by Hawkyard and Johnson[4] were based on the assumption of a constant interface friction factor (m); the analysis by Burgdorf[5] was based on the assumption of constant coefficient of friction (μ). However these analyses[3-5] assume that there is no nonuniform distortion of cylindrical elements in the ring due to frictional constraints, i.e. no bulging or barrelling. Considerable barrelling after compression was observed by Male and De Pierre[6] on specimens of most ring geometries, especially with high interface friction conditions. As a result of barrelling during ring compression tests, Male and De Pierre showed a general lack of correlation between theoretical and experimental calibration curves under these conditions. Their investigation showed the mathematical solution for the compression of a flat ring made by Avitzur[3] can be applied to obtain realistic values of the interface friction factor (m) by the analyses of experimentally determined shape changes, provided that the initial ring is small in thickness when compared with the internal and external diameters. An initial ring geometry (outside diameter: inside diameter: thickness) of 6:3.0:5 was found to be adequate for this purpose. It thus appears that the theoretical assumptions made in the above analyses[3-5] are not justified experimentally over all conditions of interfacial friction until the initial specimen geometry approaches 6:3.0:5. Under conditions of low interface friction, the theoretical assumptions are met when using an initial geometry of 6:3:1. Experimentally, neither of these geometries is particularly satisfactory with which to work, especially at high temperatures, principally because the large ratio of surface area contacting the dies to the workpiece thickness gives a quenching effect, and also because relatively high loads are necessary to affect a particular increment of deformation.

In terms of general sensitivity of measurement and ease of experimentation, the ring geometry 6:3:2 has much to commend it. This was the initial geometry used by Male and Cockcroft[1-2] and seems to have been adopted as an unofficial standard geometry for friction studies. Therefore a method for mathematical calibration of this 6:3:2 ring geometry would provide an accurate means for calibrating this standard and other ring geometries. Other attempts[7-8] have been made to calibrate mathematically the 6:3:2 geometry but these are not considered satisfactory. This paper describes a mathematical method for calibration of ring geometries with bulge or barrelling and the correlation of mathematical calibration with experimental test results.

II THEORY

Both the coefficient of friction and interface friction factor have been used for evaluation of friction conditions in metalworking operations. The relative validity of the two concepts for use in metal deformation studies was investigated[9] by using ring test specimens of 6:3:0.5 and 6:3:1 (Outside Diameter: Inside Diameter: Height) geometries. It was proven that the use of the concept of interface friction factor as a quantitative index for defining friction stresses in upset forging operations is more realistic than use of the concept of coefficient of friction. Therefore analyses of ring compression tests should employ the concept of interface friction factor for the most accurate quantitative evaluation of friction.

The first satisfactory analysis of the compression of a flat ring with bulge formation was made by Avitzur[10] through an optimum upper bound mathematical solution. The solution was based on the following assumptions:

(a) the ring material obeys von Mises' stress-strain rate laws, implying no strain hardening effects, no elastic deformation and no volumetric change.

(b) a constant friction factor, m, for a given die and material under constant surface and temperature conditions such that the interface shear stress, γ, is given by:

$$\gamma = \frac{m\sigma_o}{\sqrt{3}} \tag{1}$$

where σ_o = basic yield stress of the ring material.

(c) the velocity field for ring compression is expressed by the following equations:

$$\dot{U}_R = \frac{b}{4}\,\frac{\dot{U}}{T}\,R\left[1-\left(\frac{R_n}{R}\right)^2\right]\left[\frac{e^{-by/T}}{1-e^{-b/2}}\right] \tag{2}$$

$$\dot{U}_y = -\frac{\dot{U}}{2}\left[\frac{1-e^{-by/T}}{1-e^{-b/2}}\right] \tag{3}$$

$$\dot{U}_\theta = 0 \tag{4}$$

where θ, R and y are coordinates of a cylindrical coordinate system, $\dot{U}_R$ is the radial velocity, $\dot{U}_y$ is the axial velocity, $\dot{U}_\theta$ is the circumferential velocity, $\dot{U}$ is the velocity of the moving platen, R_n is the neutral radius, T is the ring thickness and b is a parameter determining the amount of bulge.

Avitzur's solution[10] is accurate only on the rate of formation of the bulge when a bulge still does not exist. Therefore, for this investigation, it was also assumed that the existing bulge in a ring would not influence the velocity field in the other parts of the ring and the shapes of the bulges were parabolas. Then only the non-bulged portion of the ring was considered in the following fashion for small increments of compression (1% or less):

(1) Equation 2 was converted to

$$\Delta R = \frac{b}{4} R \left[1 - \left(\frac{R_n}{R_o}\right)^2\right]\left[\frac{e^{-by/T}}{1 - e^{-b/2}}\right] \frac{\Delta T}{T} \qquad (5)$$

where ΔR and ΔT are small increments of R and T respectively

(2) Constant R_n was assumed for the small deformation.

(3) Contact radii were assumed to change in accordance with Equation 5.

From constant volume assumptions, the bulges were then calculated. A computer program, detailed in Appendix A, could be utilized for calculating dimensional changes in ring geometry for constant values of the interface friction factors.

III PROCEDURE

1. MATHEMATICAL CALIBRATION

Calibration curves relating the maximum change in internal diameter of the ring, expressed as a percentage of the original diameter, to the percent reduction in thickness on deformation for various values of the interface friction factor (m) were obtained for ring test specimens having the following starting geometries:

D_o	D_1	T
6	4.0	2
6	3.2	2
6	3.0	2
6	2.4	2
6	1.6	2
6	3.0	1

Mathematical solution of the relevant equations for this calibration was performed by writing the program outlined in the Appendix in Fortran IV and using a Control Data Corporation 6600 Digital Computer to perform the calculations.

2. COMPARISON WITH CALIBRATION CURVES FROM MATHEMATICAL ANALYSES WITH NO BULGE CONSIDERATION.

The calibration curves computed with bulge formation in this investigation were compared with the calibration curves with no bulge formation for the same ring geometries reported in Reference 9.

3. CORRELATION WITH EXPERIMENTAL RESULTS

Both published[1,11] and unpublished[2] experimental results obtained by Male on rings of various geometries were used for comparison with the calibration curves obtained from the mathematical computations for rings without bulges[6] and rings with bulge formation in this paper.

IV RESULTS

1. MATHEMATICAL CALIBRATION

For each of the five different starting ring geometries, the computer solution provided values for the internal and external radii at the contact surfaces and bulged surfaces and the neutral radii at each increment of deformation. The values are defined in Figure 1, where A_1 is the bulged internal radius, B_1 is the contact internal radius, A_o is the bulged external radius, B_o is the contact external radius and R_n is the neutral radius. The changes in internal diameters (A_1 and B_1) for each increment of deformation at set values of the interfacial friction factor, m, were also determined by the computer. These values are available separately in the U.S. Air Force Materials Laboratory and are therefore not presented here in detail with the exception of the curves given in Figure 2 for the standard initial geometry of 6:3:2. The shape of this family of curves is typical of the curves determined for other ring geometries. For these other geometries, only the relevant theoretical curves are given in particular figures for comparison with the experimental results.

2. COMPARISON WITH CALIBRATION CURVES FROM MATHEMATICAL ANALYSES WITH NO BULGE FORMATION

For 6:3:2 ring geometries, excellent correlation was shown between the shapes of the calibration curves with and without bulge formation. Up to m values equal to 0.30, practically identical quantitative values were noted for rings with and without bulge. Over m values of 0.30, the curves for rings with bulge were increasingly higher than the curves for rings with no bulge; the difference increased with increase in values of the interface friction factor.

For mathematical solutions with no bulge formation, the calibration curves for rings of different heights but same $D_o:D_1$ ratio could be adjusted simply by multiplying the values of the interface friction by the ratio of the heights to obtain the new m value. For mathematical solutions with bulge formation, the calibration curves of different heights but same $D_o:D_1$ could only be adjusted in this manner for values of interface friction factor below ≈0.3. For greater values, the calibration curves for rings of the same $D_o:D_1$ but different heights could not be adjusted in this manner.

3. CORRELATION OF MATHEMATICAL CALIBRATION WITH EXPERIMENTAL RESULTS

3(a) Maximum or Sticking Friction (m = 1) for Standard Ring (6:3:2)

In the early experimental calibration studies[1-2], conditions which gave sticking friction were identified by looking for the presence or absence of minute scratches on the specimen surface which has been in contact with the die. Male and Cockcroft standard geometry ring specimens of aluminum deformed at 600°C were completely devoid of these scratches on either the original

surface or new surface created by the deformation, thus showing that the friction must have been high ($m \geq 1.0$) so that at no stage was there any relative movement of the aluminum/die interface. Surface scratches were observed on all specimens deformed at temperatures below 600°C.

The experimental values obtained for aluminum rings deformed at 600°C for this sticking friction condition are compared with a mathematical derived curve for maximum friction ($m = 1$) in Figure 3. The following additional metals were compressed without lubricant at the elevated temperatures indicated and the results correlate well the results obtained on aluminum: copper at 400°C, magnesium at 400°C, titanium at 500°C, mild steel at 750°C, and zinc at 350°C. It can be seen that the experimentally derived curve for maximum friction is somewhat higher than the theoretical maximum curve for computations without bulge but correlates very well with the maximum curve ($m = 1$) for computations with bulge consideration.

3(b) Minimum or Zero Friction ($m = 0$) for Standard Ring 6:3:2)

Experimentally, conditions approaching zero friction have been achieved in the following manner[1]. Wax ring specimens of the standard geometry were warmed to within 2°C of the melting point and were compressed between polished steel dies which were a few degrees hotter. Melting of an extremely thin surface layer of the wax specimens provided almost perfect interfacial lubrication. The calculated curve for zero friction ($m = 0$) and some of these experimental results are also given in Figure 3. These results indicate that perfectly frictionless conditions were not achieved with this technique, but that variable friction conditions ($m = 0.02$ to $m = 0.14$) were experienced during testing. The theoretical curve tended to form a lower envelope for the experimental results.

3(c) Other Friction Values for Standard Rings (6:3:2)

The earlier experimental calibration of the ring test[1-2] at intermediate friction levels involved the determination of the loads necessary to deform solid disk specimens (0.5 in. dia. x 0.1 in. thick) by various amounts. These results were taken and values of the interface friction factor, m, were calculated using the analysis of Avitzur[3]. Yield stress values required for this analyses were obtained using the Polakowski technique[12] of compressing tall cylindrical specimens (height/diameter = 2), relubricating frequently during testing and remachining at intervals to remove any trace of barrelling. Values obtained in this way are shown in Figure 4.

Standard geometry ring test specimens were machined from the same materials used for the solid disks and were deformed under identical conditions. Data for the percentage change in internal diameter as a function of the amount of deformation in these tests are given in Figure 5 together with the most appropriate theoretical curves calculated with bulge formation considerations. The m values given by these curves are compared with the m values obtained from the solid disk tests (Figure 4) in Figure 6. This comparison shows very good correlation between the m values except for the following discrepancies between theoretical and experimental values.

values

	Theoretical (Rings)	Experimental (Disks)
α Brass Lubricated with Graphite	.27 - .39	.16
α Brass Lubricated with Lanolin	.14	.07

3(d) Nonstandard Geometry Ring Tests

Ring specimens having the same height (0.250 in.) and external diameter (0.750 in.) but of different internal diameters were machined from a single bar of commercially pure aluminum and annealed in vacuum for one hour at 450°C, followed by furnace cooling. The specimen geometries used were as follows:

Internal Diameter (in.)	Geometry Ratio (OD:ID:Height)
0.500	6.4:2
0.400	6:3.2:2
0.300	6:2.4:2
0.200	6:1.6:2

A series of rings of each geometry were then deformed over a range of deformation between the same pair of flat dies at a press speed of 2 in./sec. under the following frictional conditions:-

(a) 20°C No lubricant

(b) 600°C No lubricant

(c) 20°C Lanolin lubrication

The subsequent changes in shape on deformation were measured and the percentage changes in internal diameter as a function of amount of deformation are shown in Figures 7 to 10. Superimposed on these experimental results are the appropriate theoretical curves for the various initial specimen geometries. Summarizing these results, for the same test material and conditions, with different initial specimen geometry, the following interfacial friction factors were obtained:

Interface Friction Factor (m)

Ring Geometry	20°C No Lubricant	600°C No Lubricant	20°C Lanolin Lubricant
6:4.0:2	0.7 -0.8	0.7 -1.0	0.10 - 0.14
6:3.2:2	0.8 -1.0	1.0	0.08 - 0.10
6:2.4:2	0.8	1.0	0.08
6:1.6:2	0.8	1.0	0.06 - 0.12

In general terms, very good correlation is shown for the four initial ring geometries and the three interfacial friction conditions.

V DISCUSSION OF RESULTS

This investigation has demonstrated that the mathematical solutions of Avitzur[10] can be utilized for mathematical calibration of ring geometries with bulge or barrel formation for use in friction studies. The excellent correlation obtained between mathematical calibrations and experimental test results verifies the validity of the mathematical calibration. Concurrent investigations[14] recently completed, have furnished additional verification of Avitzur's solution which also provide a method for calculating both constant and varying friction factors, m, during ring compression tests. Both load and dimensional measurements made during the test furnish valid stress-strain curves for the ring materials.

By comparison with the two other published calibration methods[7-8] for ring testing with bulge formation, the method described in this paper furnishes calculated results which correlate most closely with experimental test results. Liu's[8] calibration curves have been developed without experimental verification and do not agree with the experimental results in this study. The other solution[7] fails to show good agreement between calculated and experimental results. The authors of that paper attribute the disagreement to the fact that their theoretical velocity field does not accurately express the metal flow conditions in the ring material during compression. In contrast, the method developed in this investigation has been verified by experimental tests. In addition visual observation of grid distortion resultant from metal flow during compression tests at the Air Force Materials Laboratory indicate the velocity field selected by Avitzur[10] accurately describes the metal flow during testing.

The experimental results (from Reference 1 and 2) used for this investigation demonstrate the difficulty in maintaining constant friction conditions during compression even under closely controlled laboratory tests. This is clearly illustrated in Figure 3. The scatter in correlation of m values from disks and rings, as well as the discrepancy between m values for disks and rings lubricated with graphite and lanolin, shown in Figure 5, may be attributed to failure to maintain experimentally constant friction conditions during tests. This indicated a need for taking experimental observations directly and calculating interface friction values. De Pierre and Gurney[13] have recently completed another investigation to provide a method for calculating both constant and varying interface friction factors (m) during ring compression tests with bulge formation.

VI CONCLUSION

This work has shown that the mathematical solution of Avitzur[10] for bulge in compression of hollow disks can be used for accurate calibration of ring specimens of various geometries for constant values of interface friction factor.

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CALCULATION OF THE RELATION BETWEEN ΔD AND THE AMOUNT OF DEFORMATION

Consider a cross-section of a ring subjected to compression in an axial direction (Figure 1). There exists a cylindrical boundary of neutral radius R_n such that on compression, the bulk of the material outside R_n will be displaced outward and that the bulk of the material inside R_n will be displaced inward. As a result two possible shapes of the ring may occur. When $R_n < B_1$, both the inner and outer free surfaces become axially convex as shown in Figure 1a: when $B_1 < R_n < R_o$, the inner free surface becomes axially concave and the free outer surface becomes axially convex as shown in Figure 1b.

The change in the shape of the ring upon deformation can be calculated if the following assumptions are made:

1. The volume of the ring material remains constant.
2. The shape of the free cylindrical surfaces of the ring in an axial cross-section are parabolic as shown in Figure 1.
3. The effects of the bulges developed in the ring as a result of compression are sufficiently small and do not influence the rate of formation of a new bulge.
4. For an incremental deformation from T_o to T_1, R_n remains constant.

From the above considerations, the following steps were utilized to prepare a computer program for calibration of ring test specimens for friction studies on the basis of constant interface friction factor:

Given T_o, A_{oo}, B_{oo}, A_{10}, B_{10} H, C and D, (height, contact and equatorial inside radii respectively of starting ring geometry) for each m value (0.000 to 1.000) in steps of 0.010 perform the following operations:

(1) Calculate $R_{oo} = B_{oo}$

(2) Calculate R_{10} (a) When $A_{10} \geq B_{10}$, $R_{10} = A_{10}$

(b) When $B_{10} \geq A_{10}$, $R_{10} = B_{10}$

(3) Calculate R_{no}

(a) Calculate $A = \dfrac{mR_c}{T}$

(b) Calculate $B = \dfrac{1}{2\left[1 - \dfrac{R_{10}}{R_{oo}}\right]} \ln\left[\dfrac{3\left(\dfrac{R_{oo}}{R_{10}}\right)^2}{1 + \sqrt{1 + 3\left(\dfrac{R_{oo}}{R_{10}}\right)^4}}\right]$

(c) If A > B calculate $\frac{R_{no}}{R_{oo}}$ from

$$\frac{mR_{oo}}{T} = \frac{1}{2\left[1 + \frac{R_{10}}{R_{oo}} - \frac{2R_{no}}{R_{oo}}\right]} \ln\left[\left(\frac{R_{oo}}{R_{10}}\right)^2 \frac{1 + \sqrt{1 + 3\left(\frac{R_{10}}{R_{oo}}\right)^4 \left(\frac{R_{oo}}{R_{no}}\right)^4}}{1 + \sqrt{1 + 3\left(\frac{R_{oo}}{R_{no}}\right)^4}}\right]$$

(d) If A $\leq$ B, calculate $\frac{R_{no}}{R_{oo}}$ from

$$\left(\frac{R_{no}}{R_{oo}}\right)^2 = \frac{\sqrt{3}}{2} \frac{1 - \left(\frac{R_{10}}{R_{oo}}\right)^4 X^2}{\sqrt{X\left[X - 1\right]\left[1 - \left(\frac{R_{10}}{R_{oo}}\right)^4 X\right]}}$$

where

$$X = \frac{R_{oo}}{R_{10}} \exp\left\{-\frac{mR_{oo}}{T}\left[1 - \frac{R_{10}}{R_{oo}}\right]^2\right\}$$

(e) $R_{no} = \frac{R_{no}}{R_{oo}} \times R_{oo}$

(4) Calculate b_o

(a) If A > B

$$b_o = 6 + \frac{m\left\{\frac{1}{3}\left(\frac{R_{oo}}{R_{no}}\right)^2\left[1-\left(\frac{R_{1o}}{R_{oo}}\right)^3\right]-\left[1-\left(\frac{R_{1o}}{R_{oo}}\right)\right]\right\}}{\frac{R_{oo}/T}{\sqrt{1+3\left[R_{oo}/R_{no}\right]^4}}\left\{\frac{1}{4}\left(\frac{R_{oo}}{R_{no}}\right)^4\left[1-\left(\frac{R_{1o}}{R_{oo}}\right)^4\right]-\left(\frac{R_{oo}}{R_{no}}\right)^2\left[1-\left(\frac{R_{1o}}{R_{oo}}\right)^2\right]+\ln\left(\frac{R_{oo}}{R_{1o}}\right)\right\}}$$

(b) A < B

$$b_o = 6 + \frac{m\left(\frac{R_{no}}{R_{oo}}\right)\left\{\frac{4}{3}+\frac{1}{3}\left(\frac{R_{oo}}{R_{no}}\right)^3\left[1+\left(\frac{R_{1o}}{R_{oo}}\right)^3\right]-\left(\frac{R_{oo}}{R_{no}}\right)\left[1+\left(\frac{R_{1o}}{R_{oo}}\right)\right]\right\}}{\frac{R_{oo}/T}{\sqrt{1+3\left(\frac{R_{oo}}{R_{no}}\right)^4}}\left\{\frac{1}{4}\left(\frac{R_{oo}}{R_{no}}\right)^4\left[1-\left(\frac{R_{1o}}{R_{oo}}\right)^4\right]-\left(\frac{R_{oo}}{R_{no}}\right)^2\left[1-\left(\frac{R_{1o}}{R_{oo}}\right)^2\right]+\ln\left(\frac{R_{oo}}{R_{1o}}\right)\right\}}$$

(5) Calculate percent deformation $\Delta T = \left[\frac{H-T_o}{H}\right] 100$

(6) Calculate percent change in B_1, ΔB_1

$$\Delta B_1 = \left[\frac{C-B_{10}}{C}\right] 100$$

(7) Calculate percent change in A_1, ΔA_1

$$\Delta A_1 = \left[\frac{D-A_{10}}{D}\right] 100$$

(8) Calculate V_o (Volume outside neutral radius)

$$V_o = \pi T_o \left[B_{oo}^{\ 2} - R_{no}^{\ 2}\right] + \frac{4\pi T_o}{15} \left[3B_{oo} + 2A_{oo}\right]\left[A_{oo} - B_{oo}\right]$$

(9) Calculate V_1 (Volume inside neutral radius)

(a) When $R_{no} > R_{10}$

$$V_1 = \pi \left[R_{no}^{\ 2} - B_{10}^{\ 2}\right] T_o + \frac{4\pi T_o}{15} \left[3B_{10} + 2A_{10}\right]\left[B_{10} - A_{10}\right]$$

(b) When $R_{no} < R_{10}$

$$V_1 = \pi \left[B_{10}^{\ 2} - R_{no}^{\ 2}\right] T_o + \frac{4\pi T_o}{15} \left[3B_{10} + 2A_{10}\right]\left[A_{10} - B_{10}\right]$$

(10) Print out information

T_o A_{oo} B_{oo} A_{oo} B_{10} R_{no} b_o ΔT ΔB_1 ΔA_1 V_{o1} V_1

(11) Repeat with new values of T_o, A_{oo}, B_{oo}, A_{10} and B_{10} obtained as follows until $\Delta A_1 = 100$ or $\Delta T = 80$:

New Values

(a) $T_1 = T_o - .01H$ when $T_o > .4H$ $\quad T_1 = .975\ T_o$ when $T_o \leq .4H$

(b) $$B_{o1} = B_{oo} + \frac{b_o}{4}\left[1 - \left(\frac{R_{no}}{R_{oo}}\right)^2\right]\left[\frac{e^{-bo/2}}{1 - e^{-bo/2}}\right]\left[\frac{T_o - T_1}{T_o}\right] R_{oo}$$

(c) $$B_{11} = B_{10} + \frac{b_o}{4}\left[1 - \left(\frac{R_{no}}{R_{oo}}\right)^2\right]\left[\frac{e^{-b/2}}{1 - e^{-b/2}}\right]\left[\frac{T_o - T_1}{T_o}\right] R_{10}$$

(d) A_{o1} from equation for constant V_o

$$B_{o1}^2 + \frac{4}{3} A_{o1} B_{o1} + \frac{8}{3} A_{o1}^2 - \frac{5V_o}{\Pi T_1} - 5R_{no}^2 = 0$$

(e) A_{11} from equation for constant V_1

(1) When $R_{no} > R_{10}$

$$B_{11}^2 + \frac{4}{3} A_{11} B_{11} + \frac{8}{3} A_{11}^2 + \frac{5V_1}{\Pi T_1} - 5R_{no}^2 = 0$$

(2) When $R_{no} < R_{10}$

$$B_{11}^{2} + \frac{4}{3} A_{11} B_{11} + \frac{8}{3} A_{11}^{2} - \frac{5V_1}{\pi T_1} - 5R_{no}^{2} = 0$$

(f) New Values T_1 T_o, A_{o1} A_{oo}, B_{c1} B_{oo}, A_{11} A_{oo} and B_{11} B_{10}

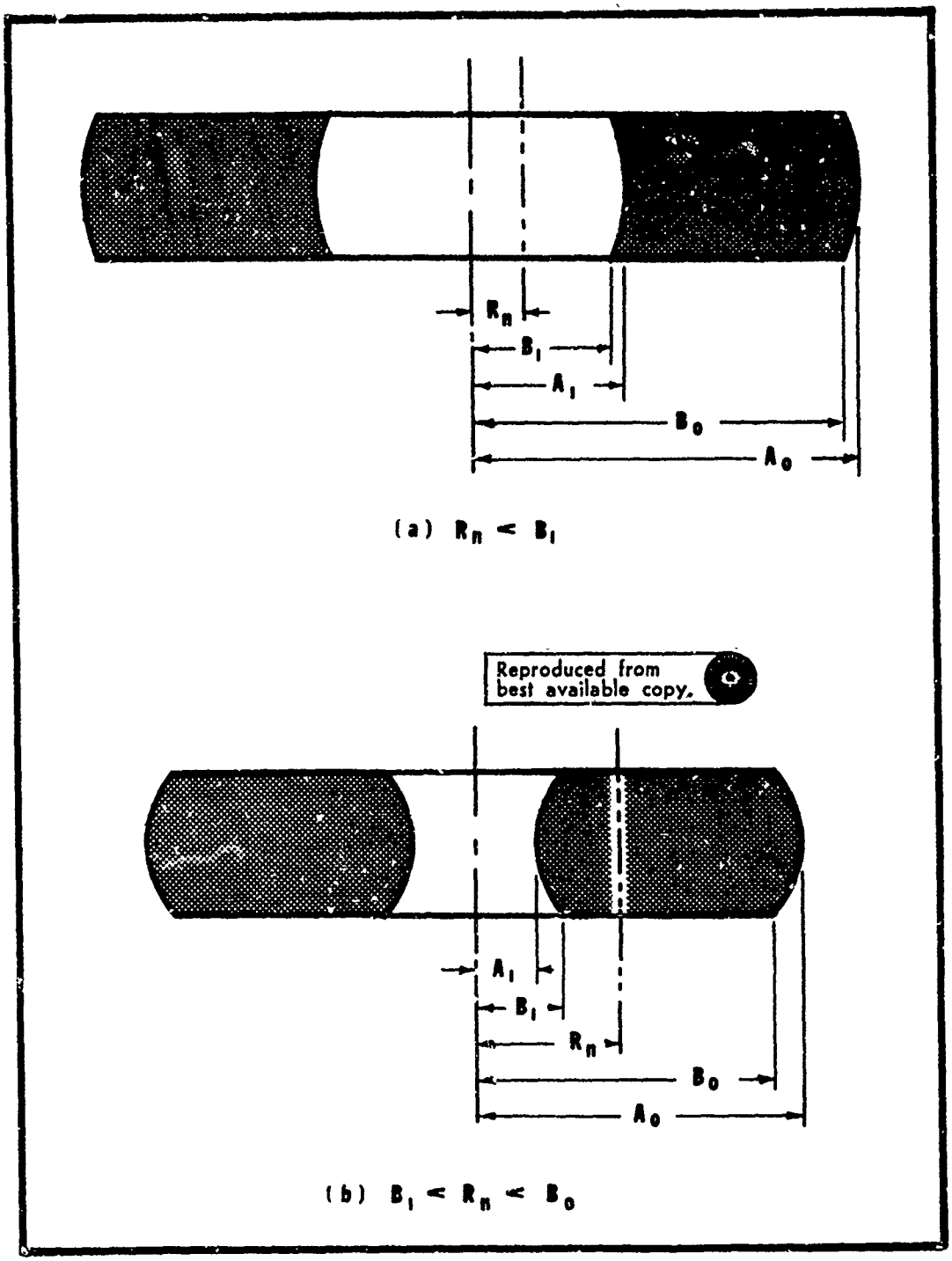

Figure 1. Schematic Representation of the Ring Geometry after Forging.

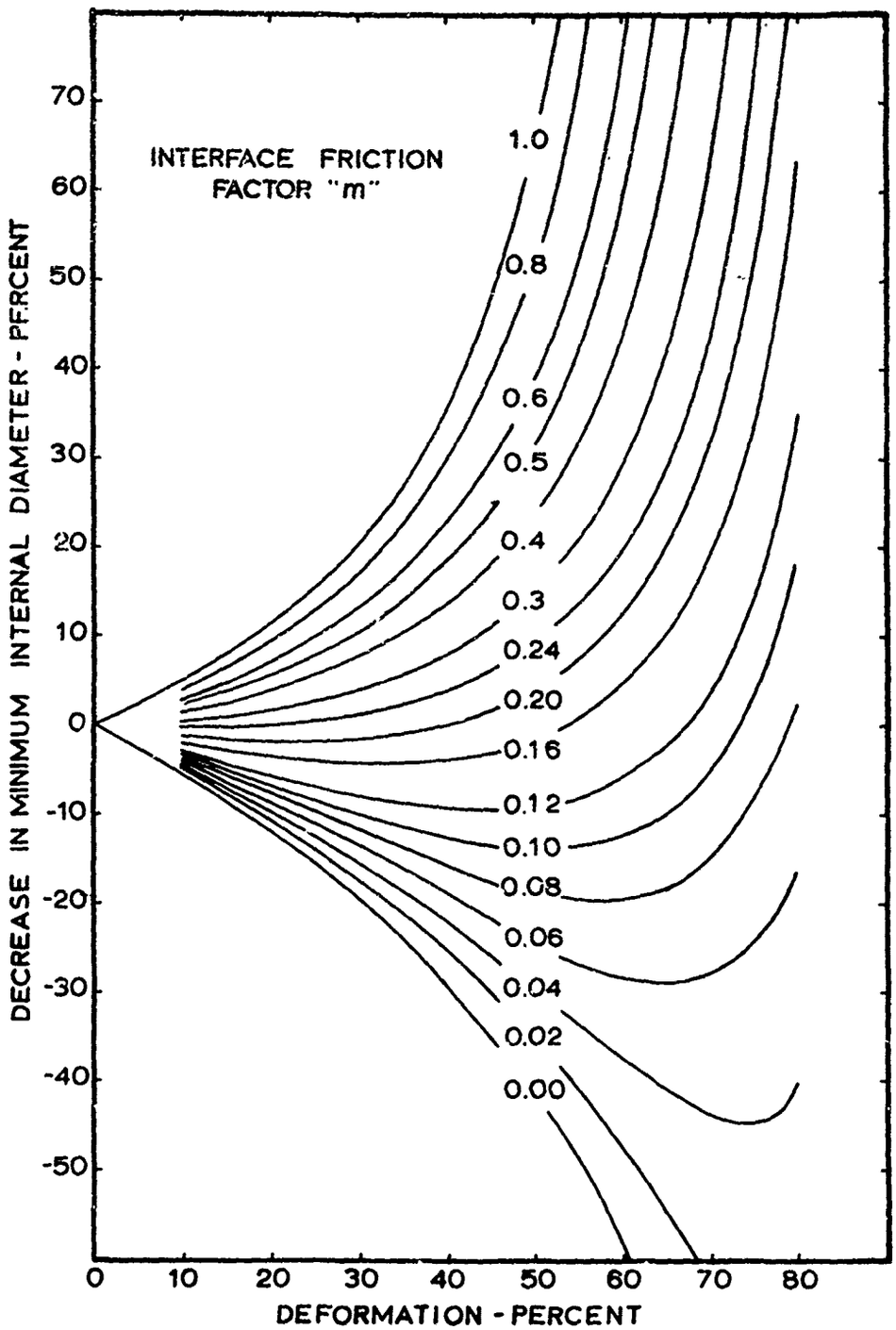

Figure 2. Theoretical Calibration Curve for Standard Ring 6:3:2 with Bulge Formation.

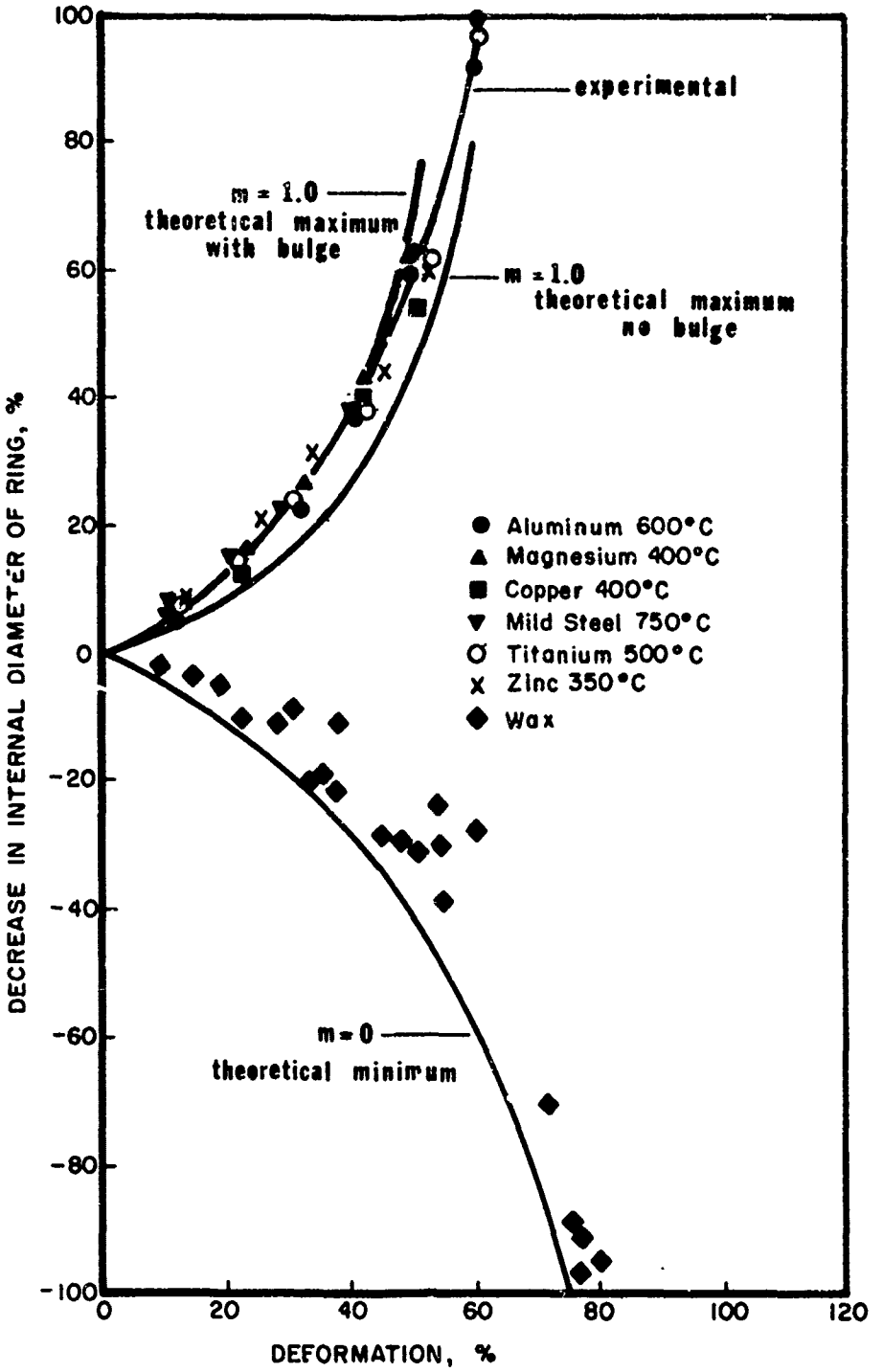

Figure 3. Comparison of Maximum and Minimum Theoretical and Experimental Curves for Standard Ring, 6:3:2.

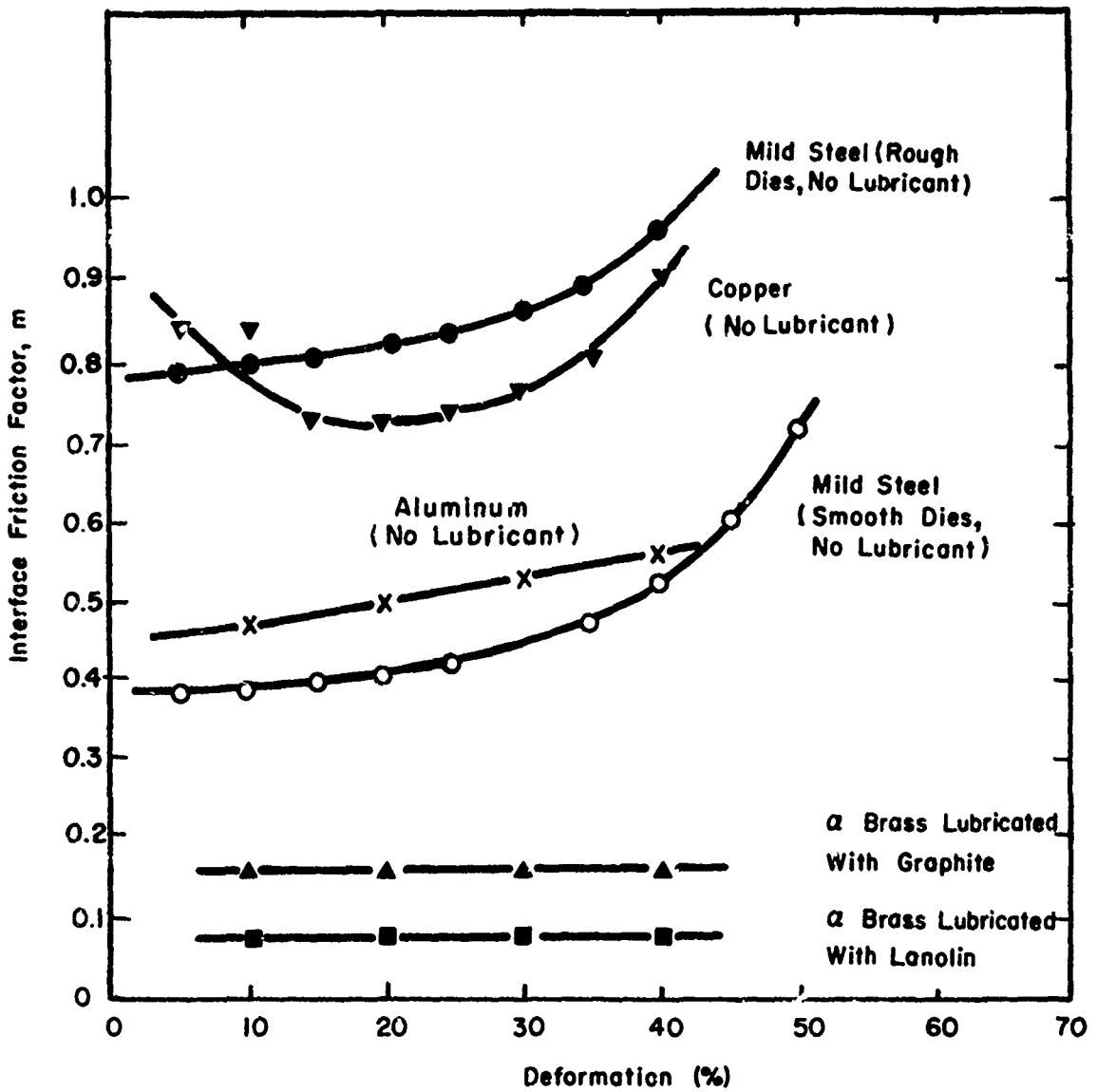

Figure 4. Interface Friction Factor of Several Metals for Various Lubrication Conditions at 20°C (Calculated from Experimental Data Using the Analyses of Avitzur Reference 3).

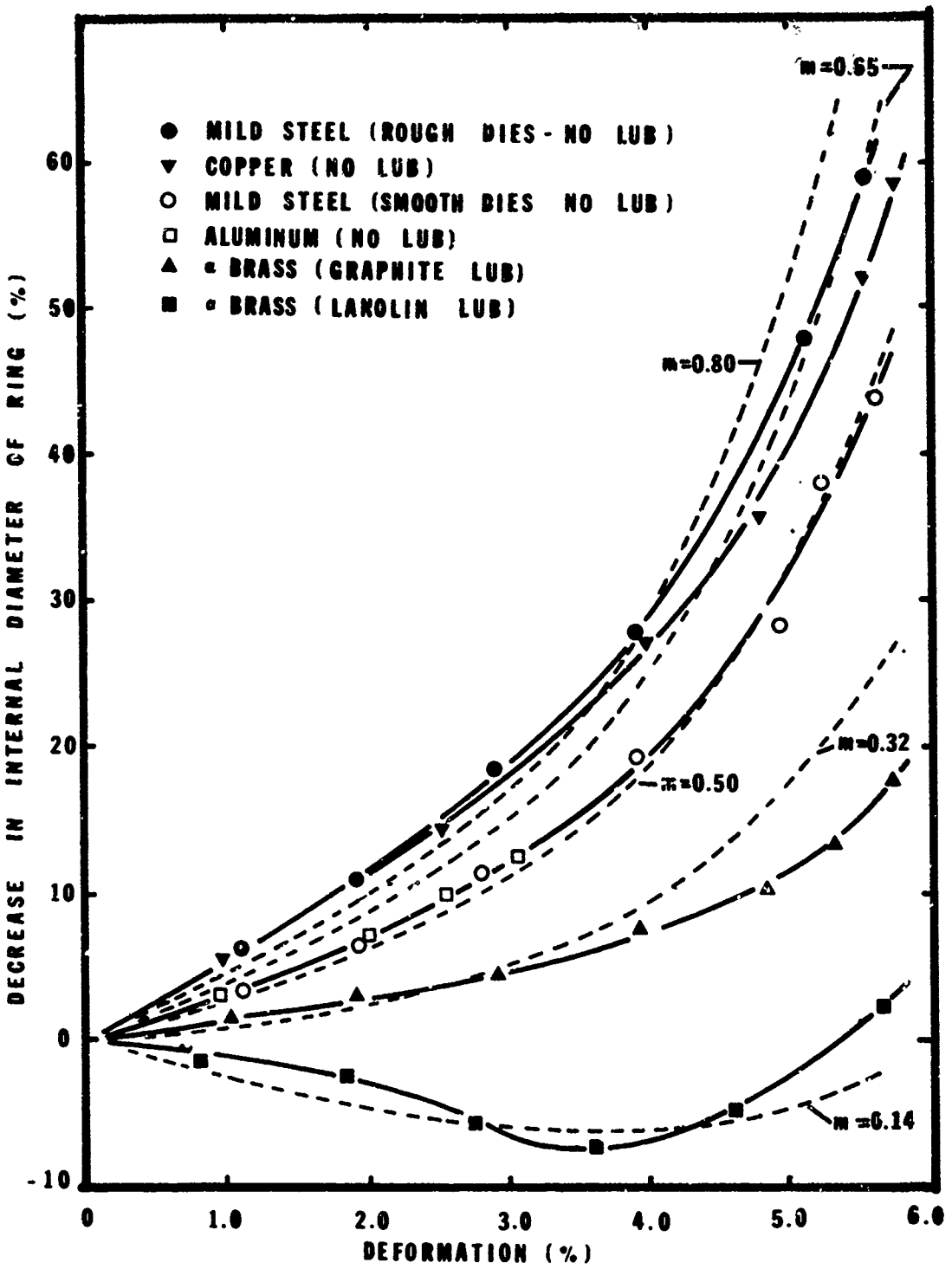

Figure 5. Comparison of Experimental and Theoretical Curves for Materials and Lubrication of Figure 4.

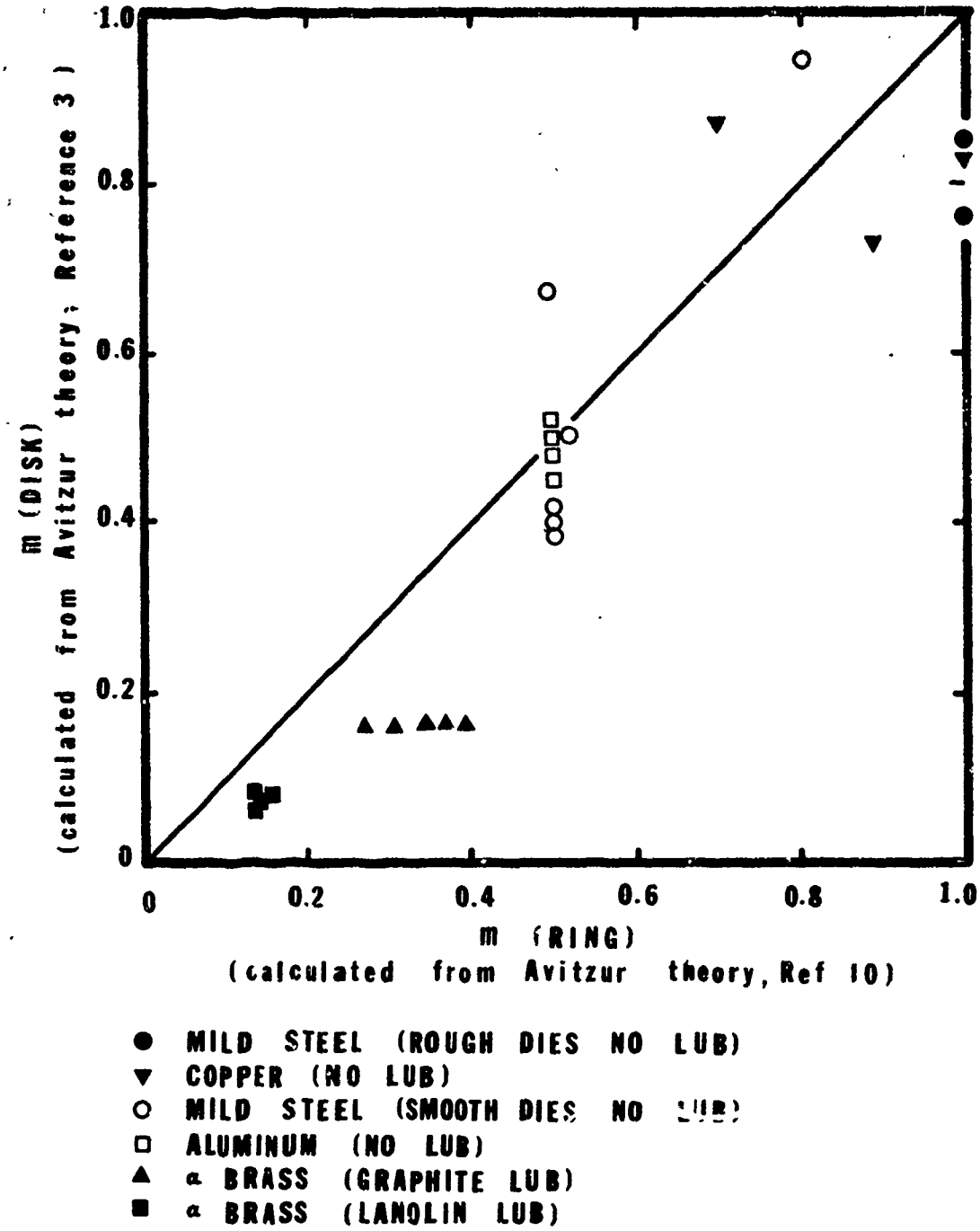

Figure 6. Comparison of m Values Obtained from Disk (Figure 4) and Ring (Figure 5) Compression Tests Carried Out under Identical Test Conditions.

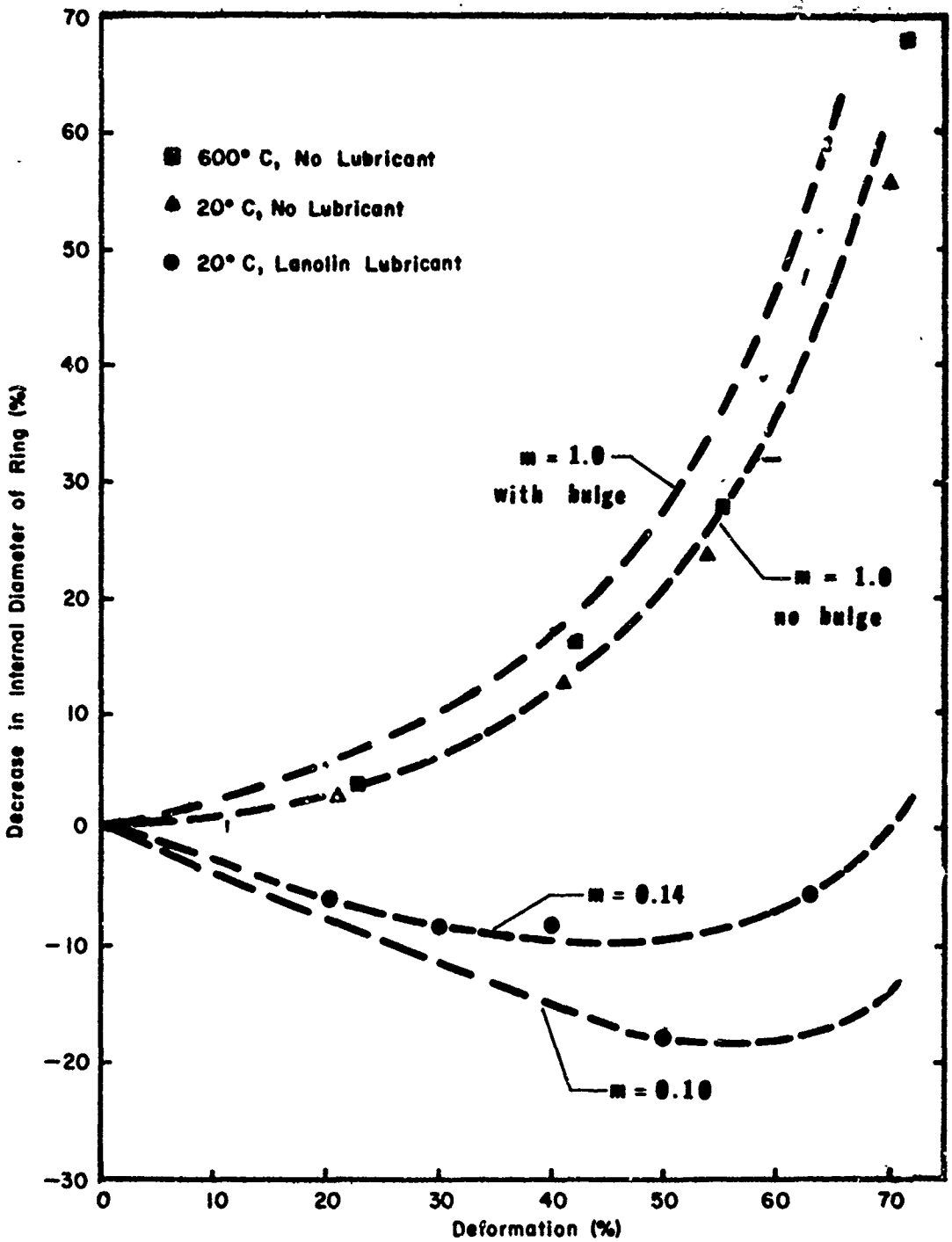

Figure 7. Comparison of Experimental and Theoretical Curves for Interface Friction Factors for Aluminum Rings, 6:4:2.

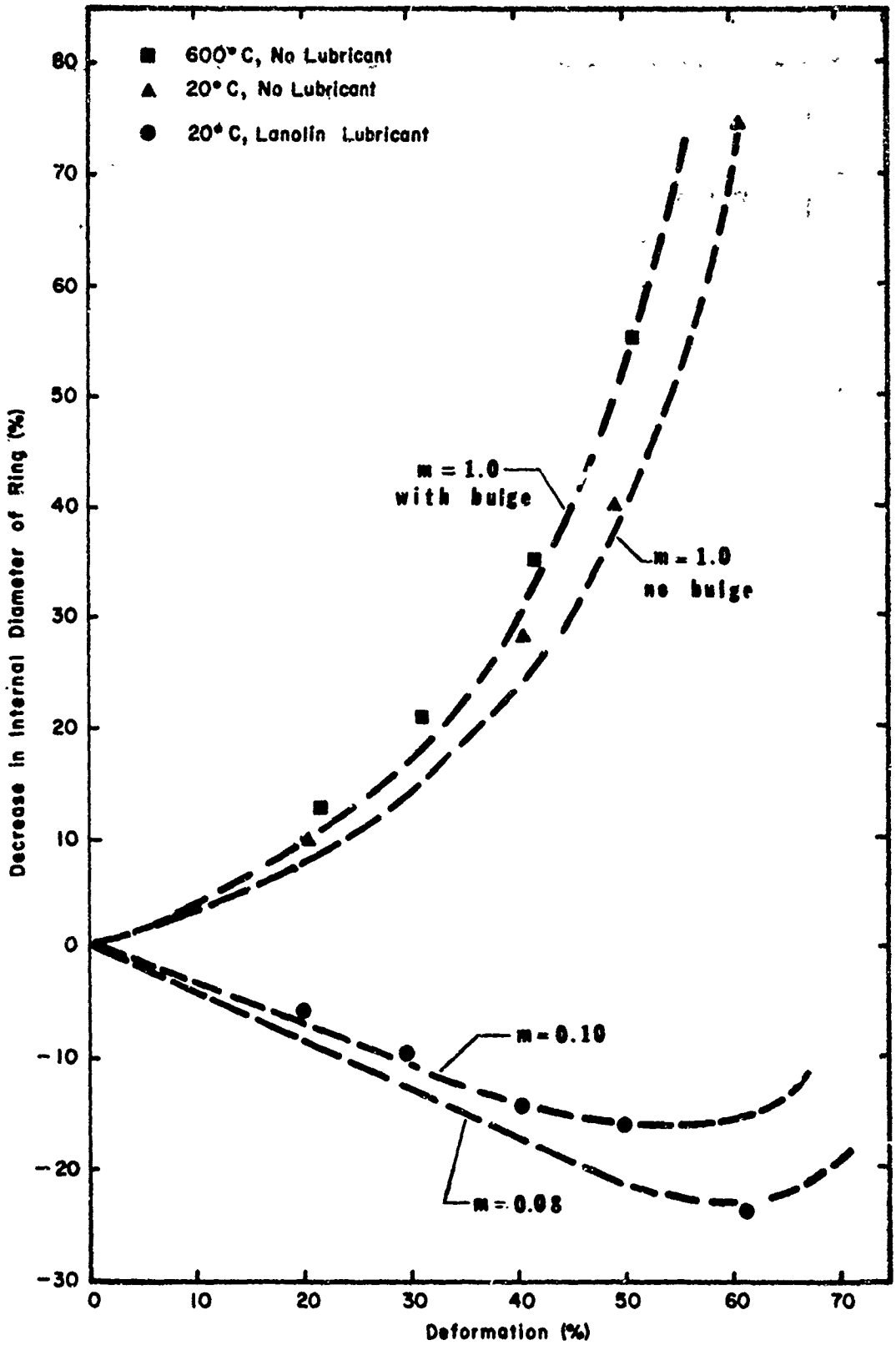

Figure 8. Comparison of Experimental and Theoretical Curves for Interface Friction Factors for Aluminum Rings, 6:3.2:2.

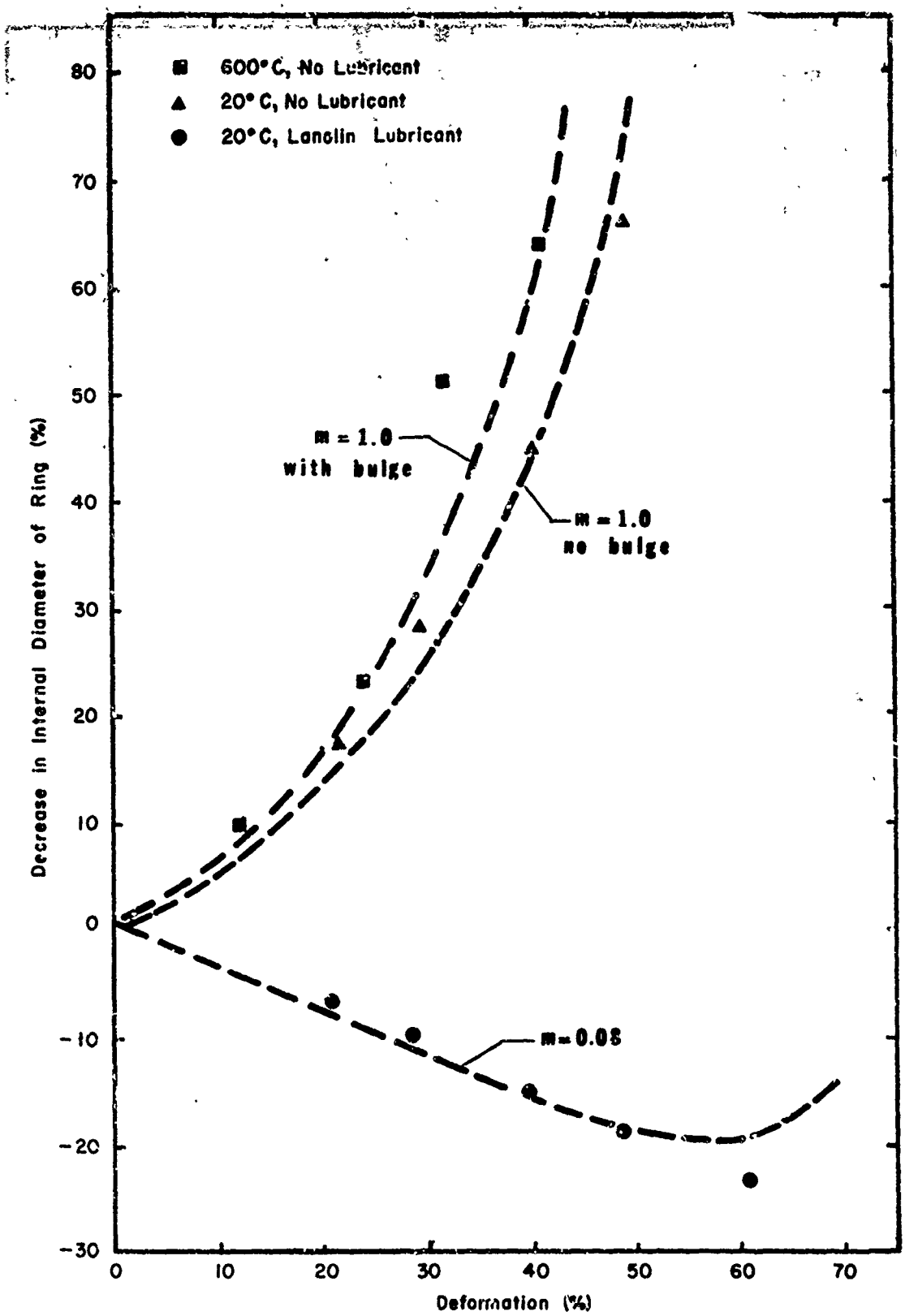

Figure 9. Comparison of Experimental and Theoretical Curves for Interface Friction Factors for Aluminum Rings, 6:2.4:2.

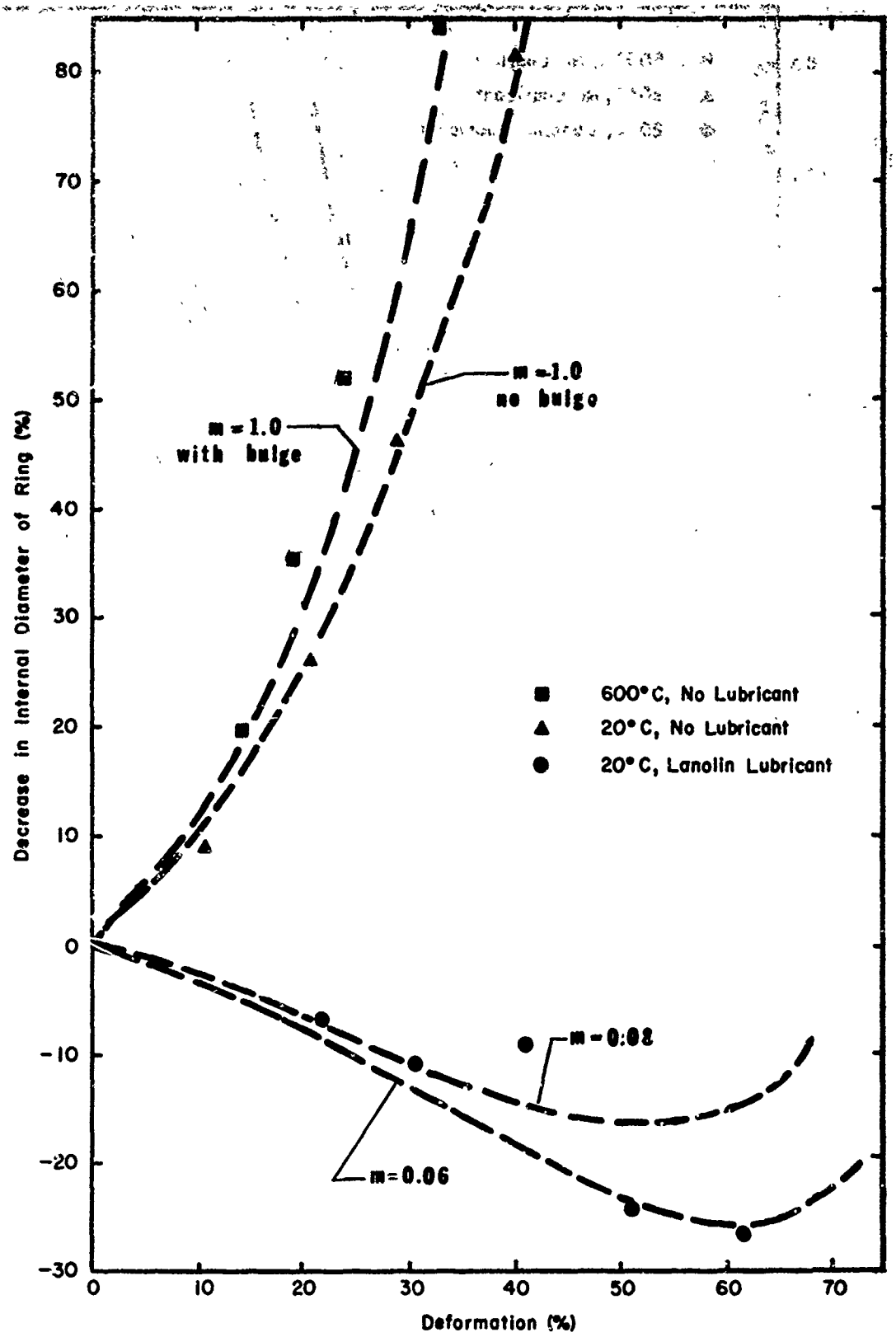

Figure 10. Comparison of Experimental and Theoretical Curves for Interface Friction Factors for Aluminum Rings, 6:1.6:2.