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A method for evaluating friction using a backward extrusion-type forging

G. Shen

Department of Industrial and Systems Engineering, the Ohio State University, Columbus, OH, USA

A. Vedhanayagam

Battelle Columbus Division, Columbus, OH, USA

E. Kropp and T. Altan

Engineering Research Center for Net Shape Manufacturing, the Ohio State University, Columbus, OH, USA

Industrial Summary

A method is proposed for estimating the value of the shear friction factor using a backward extrusion-type forging. This method uses forging load multiplied by the bottom thickness in a backward extrusion test as a measure to calibrate the friction factor. The advantages of the proposed method are: (1) the friction factor can be determined for forming processes where the interface pressure is high and new surface generation is large, e.g., cold forging and precision forging, and (2) the value of the friction factor can be determined continuously during the forming process. Thus, the performance of a lubricant during the entire test can be monitored.

1. Introduction

In an earlier study, metal flow and lubrication were investigated by isothermally forging aluminum 7075 using two different tests: ring and bucket forgings [1]. The study illustrated that the ring test is useful in determining the friction factor, *m*, for a given lubrication and specified forging conditions. However, in a ring test, metal flow and die geometry are simple, the forging pressure is relatively low and the new surface generated during deformation is small. Therefore, in a ring test the friction characteristics of a forging lubricant cannot be adequately evaluated. The "bucket" test, which is similar to a backward extrusion, was used to further evaluate lubricants. In a "bucket" test, the forging pressure is high and the new surface generated, i.e., the magnitude of

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Correspondence to: G. Shen, Department of Industrial and Systems Engineering, the Ohio State University, Columbus, OH 43210, USA.

metal flow, is large. In the earlier study [1], the performance of lubricants in a "bucket" test was compared by the web thickness achieved under a pre-designated press load, or vice versa. However, this kind of discrete comparison is not adequate for investigating the performance of lubricants under practical forging conditions.

The objectives of the present study are: (1) to investigate four lubricants (one was used in the earlier study [1], the others were being selected later) in the forging of an aluminum–lithium alloy using ring and "bucket" tests; and (2) to propose an approach to generate friction-calibration curves for a "bucket", or a backward extrusion-type of forging test [2].

2. Ring test for lubricant evaluation

The ring compression test is a very important test in metal forming process analysis. It can be used as a test for flow stress evaluation [3], and, most widely, it is used as a method for lubricant evaluation [4]. In this test, a ring is compressed between two flat platens. The change of the inner diameter (ID) of the ring is very sensitive to interface lubrication conditions. Thus, the variation of the ID of the compressed ring is used as a measure to evaluate lubrication and friction [5].

Two reductions in height were selected for the ring tests and three tests were conducted for each reduction in height. The process conditions used in these tests are given in Table 1.

Four lubricants were investigated in the current study, designated LUB-A, LUB-B, LUB-C (all water-based) and LUB-D (oil-based). LUB-A is a molybdenum disulfide (MoS_2) based product: this lubricant costs 10 times more than an ultra-pure graphite based lubricant. LUB-B and LUB-C were developed for the isothermal forging of aluminum. LUB-D was the best oil-based (non-leaded) lubricant selected from the earlier trials [1].

The experimental load–stroke curve obtained for each lubricant is presented in Fig. 1. These curves are obtained from the mean value of three measurements at each stroke position, indicated in the figure. From Fig. 1, it is seen

TABLE 1

Process conditions used in the ring test

Ring material	aluminum–lithium alloy
Die material	H13
Press speed	20 in/min (0.33 in/s)
Billet temperature	675 °F
Die temperature	660–690 °F
Reduction in height	50% and 77%
Ring size	OD : ID : height = 35.56 : 17.78 : 11.85 mm

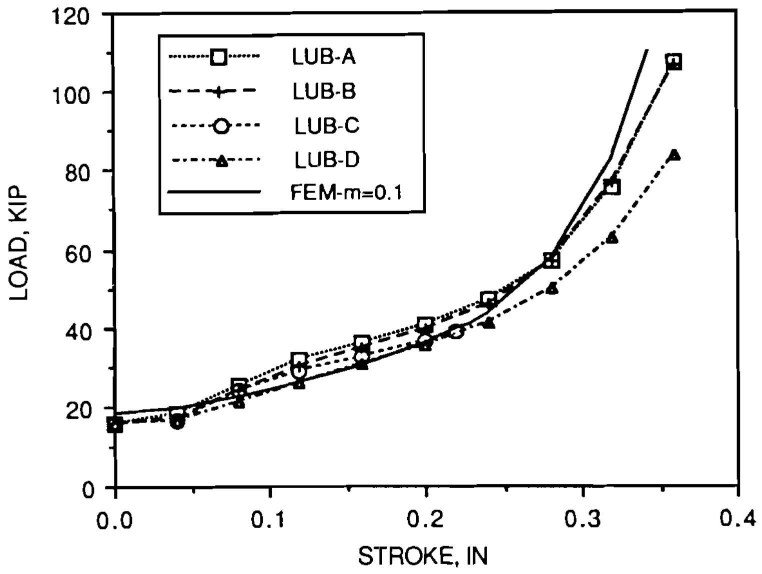


Fig. 1. Load-stroke curves obtained from ring tests and the FEM simulation for $m=0.1$. (1 kip = 6.895 MPa; 1 in = 25.4 mm)

that the load–stroke curves for LUB-A and LUB-B are almost identical and that the load–stroke curves for LUB-C and LUB-D are also almost identical.

Figure 1 also gives the load–stroke curve predicted by FEM simulation, using the code DEFORM [6] with a shear friction factor, $m=0.1$. It is seen that at the early stage of the deformation, the load–stroke behavior predicted by the FEM simulation is close to that obtained from experiments. After the stroke exceeds 0.23 in (50% reduction in height), the FEM simulation predicted a higher load. There are two possible reasons for this over-prediction:

(1) The experimentally obtained flow stress curve for this Al–Li alloy (after the correction for deformation heating) showed a little flow-softening effect. However the flow stress model used in the FEM simulation ignored this effect by assuming that the flow stress did not vary with strain.

(2) In the test, the ram slowed down at the final stage of deformation. However, the FEM simulation assumed a constant ram speed. The purpose of the FEM simulation was to generate the decrease in inner diameter of the ring versus reduction in height for calibrating the four lubricants investigated in this study. Therefore, these two possible reasons were not further investigated.

Figure 2 shows the decrease in ID versus reduction in height (friction-calibration curve) generated by FEM simulations, for shear friction factor, m, equal to 0.05, 0.1, and 0.2 (the shear friction factor is defined by $\tau=m\bar{\sigma}/\sqrt{3}$, where τ is the friction shear stress and $\bar{\sigma}$ is the flow stress of the ring material). The decrease in ID versus reduction in height, obtained from the experiments, for each of the lubricants is also presented. As mentioned earlier, three tests were conducted for each lubricant at each reduction in height. Therefore, Fig. 2 gives three data points for each lubricant at each reduction in height.

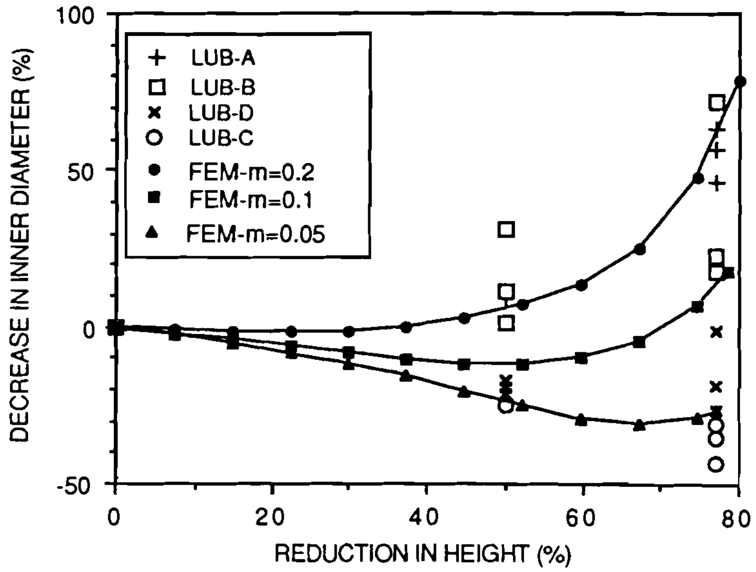


Fig. 2. Determination of shear friction factors, *m*, for the four lubricants, using calibration curves generated by FEM simulations.

The comparison of experimental data with friction-calibration curves, generated by FEM simulation, gives the shear friction factor, *m*, for each lubricant as follows: LUB-A, $m=0.2$; LUB-B, $m=0.1$–0.2; LUB-C, $m=0.05$; and LUB-D, $m=0.07$. Thus, LUB-C and LUB-D have a lower friction factor than LUB-A and LUB-B.

3. Characteristics of the ring test

In a ring test, both the forging load and the decrease in inner diameter are influenced by friction. However, the friction-calibration curve, Fig. 2, considers only the latter as a measure for interface friction. The reason is that the former, i.e., the forging load, is not sensitive to friction.

From Fig. 1, it is seen that the difference in load for the four lubricants is not large, especially at a reduction in height less than 45%. Pawelski et al. [7] observed a similar phenomenon in their experimental ring tests with steels at hot working temperatures. In their ring tests with lubricants and without lubricants, the load versus reduction of height curves were nearly identical up to 35% reduction.

Figure 2 shows that, for various lubricants, the differences in decrease in inner diameter versus the reduction in height of the ring are considerable. Therefore, the decrease in inner diameter of a forged ring is a good measure of the interface friction in a ring test. The load–stroke curve is not very sensitive to interface friction in ring tests because two factors influence the forging load in this test: (1) the forging pressure, i.e., the average value of the normal stress at the interface; (2) the contact area between the ring and the upper die. These two factors have a tendency to cancel each other at relatively low value of reduction in height.

Figure 3 shows two load–stroke curves obtained from FEM simulations with different friction shear factors ($m=0.12$, and $m=0.18$), for a Ti–6Al–4V ring with the same dimensions as the Al–Li ring, (see Table 1). The load–stroke curves for the two cases ($m=0.12$, and $m=0.18$) are very close until the stroke is around 0.21 in, which corresponds to 45% reduction in height. The same observation is also made in Al–Li ring tests in Fig. 1. Figures 4 and 5 show: (1) the forging pressure versus reduction in height; and (2) the contact area between the ring and the upper die versus reduction in height, respectively. It is well known that the forging pressure increases with increasing interface friction. However, the contact area behaves in a reverse manner. For the lower friction shear factor, $m=0.12$, the contact area is larger because the ring expands outward and for a higher friction shear factor, $m=0.18$, the contact area is smaller because the ring contracts inward. As a result the forging loads for both cases, $m=0.12$ and $m=0.18$, are close to each other in the test until the ring is deformed more than 45% reduction in height. This discussion illustrates that, in a ring test, the load–stroke curve is not sensitive to interface friction. However, the change in inner diameter is the sensitive parameter and therefore it is used to evaluate the interface friction.

Another important characteristic of the ring test is that the flow stress behavior variation in the thickness direction influences the friction-calibration curve. For the same lubrication condition:

(1) Rings compressed under isothermal (dies and ring have the same tem-

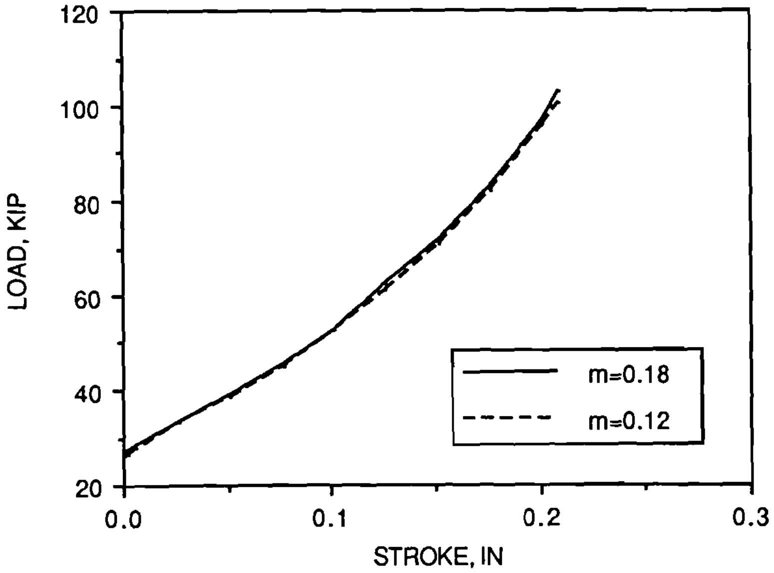


Fig. 3. The load-stroke curves obtained from FEM simulations with two different friction shear factors for a Ti-6Al-4V ring compression test with a ram velocity of 0.2 in/s.

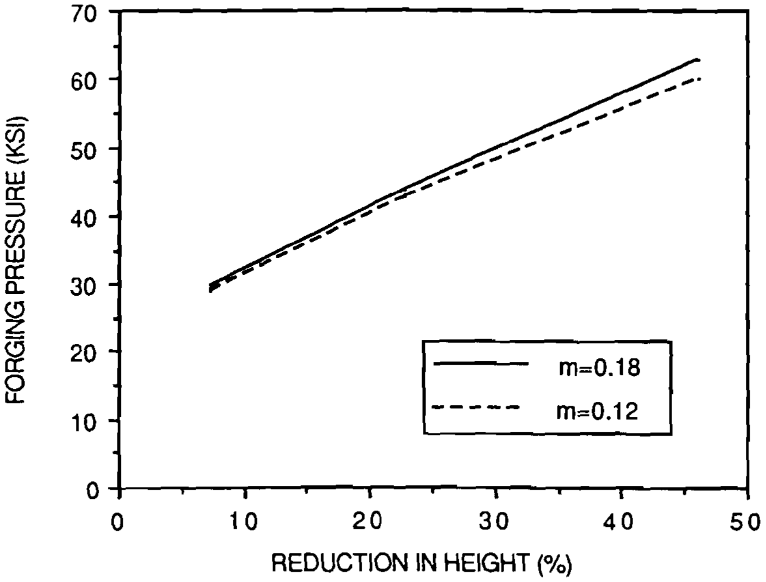


Fig. 4. Forging pressure versus reduction in height obtained from FEM simulations with two different friction shear factors for a Ti-6Al-4V ring compression test with a ram velocity of 0.2 in/s.

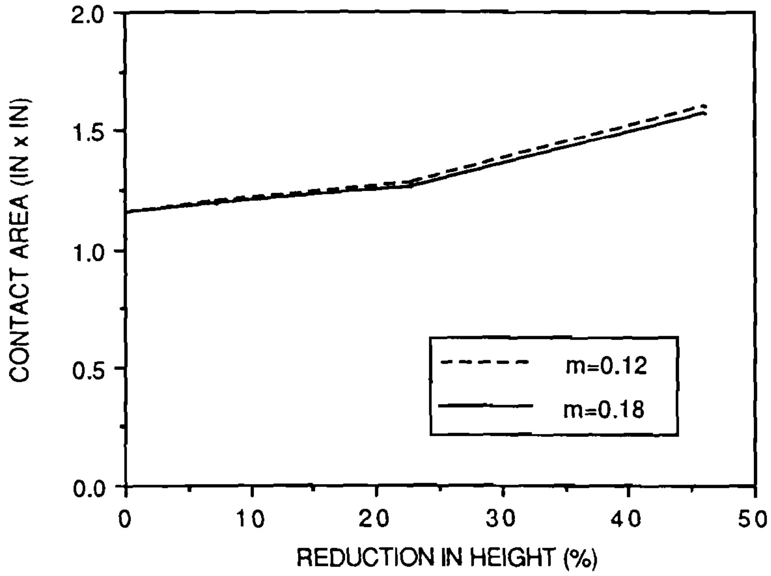


Fig. 5. The contact area versus reduction in height obtained from FEM simulations with two different friction shear factors for a Ti-6Al-4V ring compression test with a ram velocity of 0.2 in/s.

perature) and a nonisothermal (dies and ring have a different temperature) condition will generate different friction-calibration curves.

(2) Rings made from different materials will generate different friction-calibration curves, especially under non-isothermal conditions. Hence, there is no "universal" ring-test friction-calibration curve. The friction-calibration

curves must be defined for the specific ring material under specified ring- and die-temperatures and ram-speed conditions.

4. "Bucket" test for lubricant evaluation

In addition to ring compression tests, the "bucket" test was also used for lubricant evaluation (Figs. 6 and 7). This part was chosen for two reasons:

(1) The geometry is more complex when compared to the ring, thus a practical forging condition with large surface generation can be represented.

(2) For the same specimen thickness the forging pressure is much higher in a "bucket" test than in a ring compression test (see Fig. 8). Thus, friction can be evaluated under geometry and pressure conditions which are representative of practical forging operations.

The process conditions used in the "bucket" test are given in Table 2.

The conventional method for the evaluation of lubricants through a "bucket" test is to compare the forging load and the bottom thickness of the forged bucket [1]. For the same material and process conditions, "good" lubrication will result in:

(a) a lower forging load when the same bottom thickness is obtained, or
(b) a thinner bottom thickness under the same forging load, or
(c) both a thinner bottom thickness and a lower forging load in an operation.

The final forging load for each test was obtained from the *time versus stroke and load curves* recorded in the experiments. The bottom thickness of the "bucket" was obtained by averaging the thickness measured at four locations of the bottom of the "bucket" with a coordinate measuring machine. The results of the "bucket" test for four different lubricants are summarized in Tables 3 and 4. The corresponding die temperatures in "bucket" tests are also provided in these tables. However, it can be seen from the data that, with the die temperature ranging from 660–690°F, there is no significant influence of the die temperature on either the forging load or the bottom thickness.

The comparison of results obtained from ring tests and "bucket" tests shows that the "best" lubricant selected by the two tests is not the same. In the ring test, LUB-C is the "best", but in the "bucket" test, LUB-D is the "best", i.e., gives the thinnest bottom thickness for a given forging load (see Tables 3 and 4). The difference between the two tests is that the ring test is a type of open-die forging with a lower forging pressure, whilst the "bucket" test is an extrusion–type forging with a higher forging pressure. The difference between the two lubricants is that LUB-C is a water-based lubricant and LUB-D is an oil-based lubricant. Therefore, it can be concluded that in the present study:

(1) for the same lubricant, the lubricity might vary when the forging pressure varies;

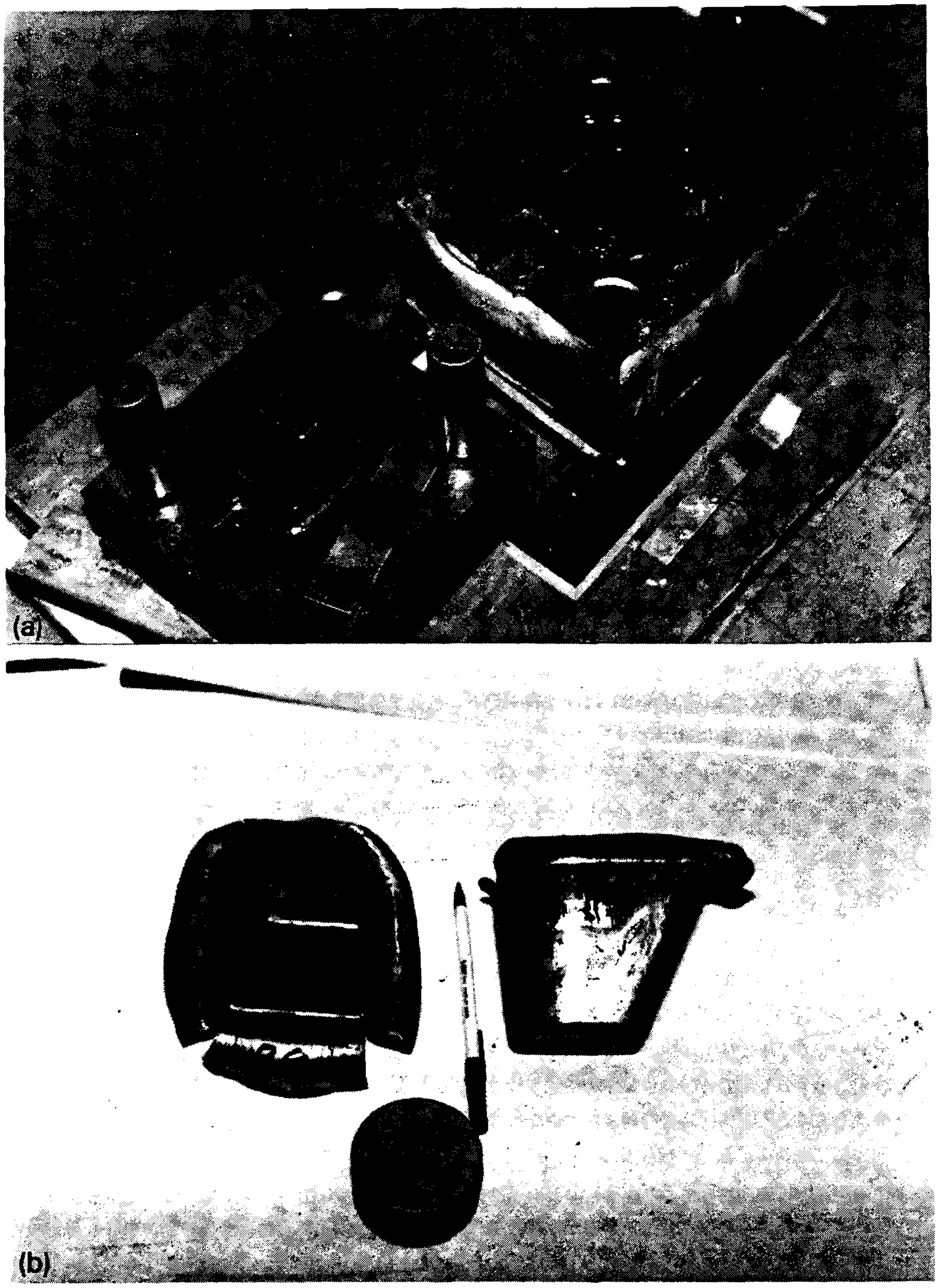
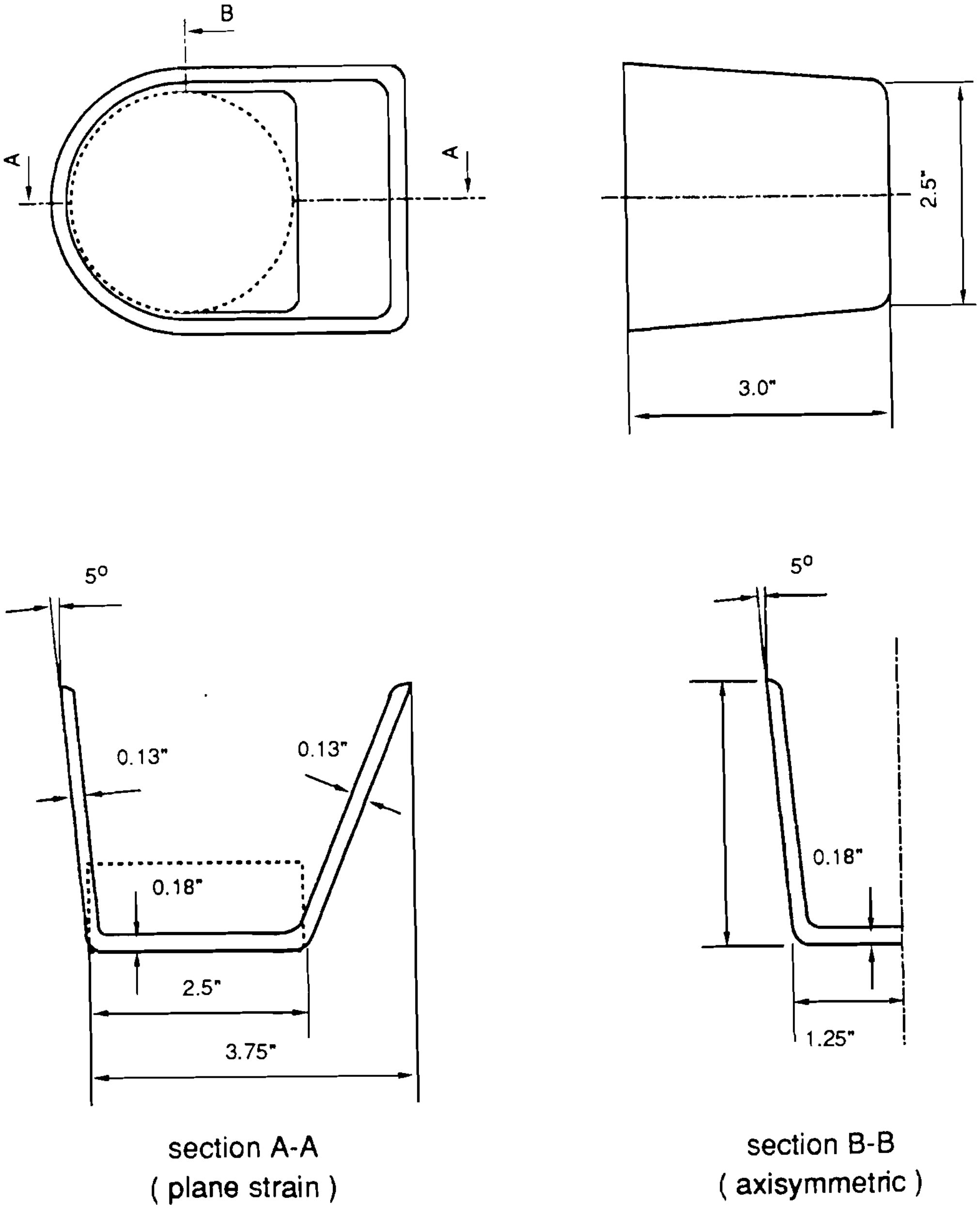


Fig. 6. "Bucket" test: (a) tooling; (b) billet and final shape [1].



section A-A
(plane strain)

section B-B
(axisymmetric)

Fig. 7. Dimensions of the bucket used for evaluation of forging lubricants [1]. The billet before deformation is indicated with broken lines and was 2.5 in diameter × 1.4 in height.

(2) the water-based lubricant is suitable for the open-die forging with a lower pressure and the oil-based lubricant is suitable for the extrusion-type forging with a higher pressure.

These conditions, however, cannot be generalized before additional studies are conducted with different alloys and part geometries.

The interface friction-factors for each of the four lubricants investigated were determined using the FEM (DEFORM) generated calibration curves (Fig. 2). However, these friction-factor values can only represent the behavior of

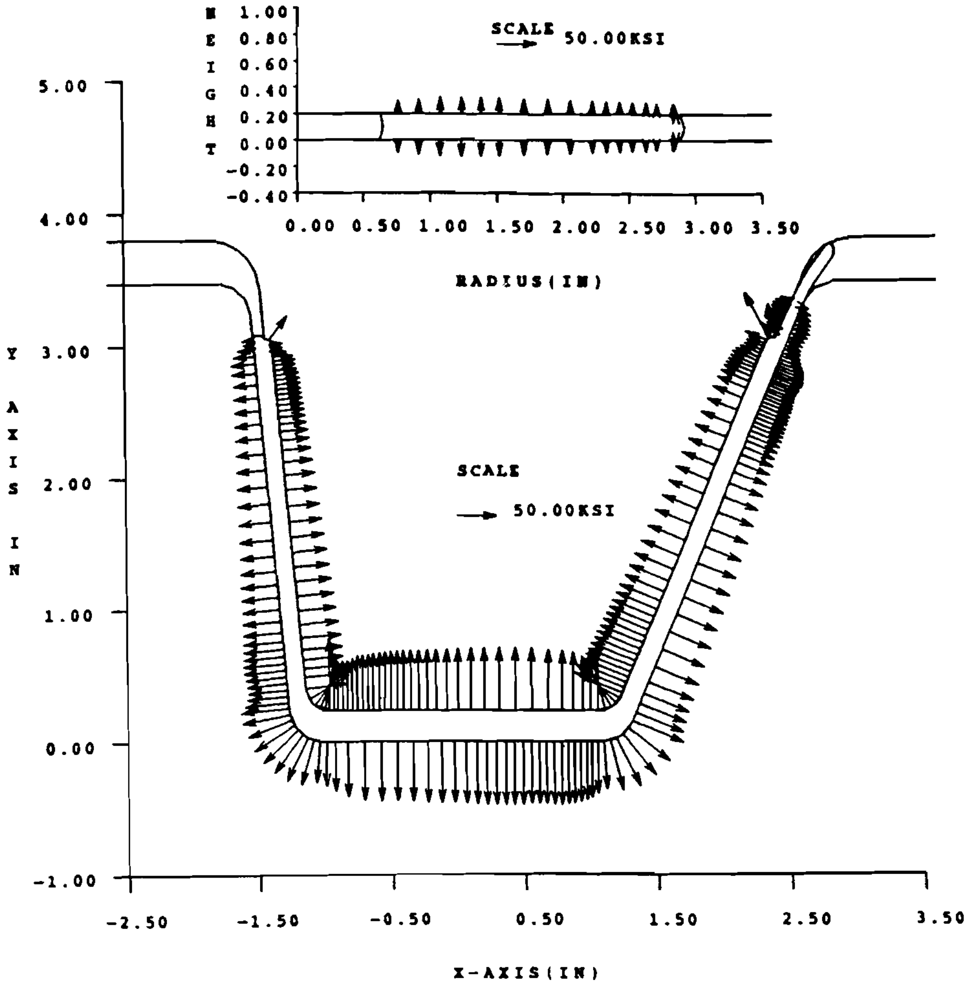


Fig. 8. Comparison of the forging pressures for the ring and "bucket" test [1].

TABLE 2

Process conditions used in the "bucket" tests

Billet material	aluminum-lithium alloy
Die material	FX-2
Press speed	20 in/min (0.33 in/s)
Billet temperature	675°F
Die temperature	660-690°F
Reduction in height	40% and 87%
Billet size	2.5 in diameter × 1.4 in height

the lubricants under low forging pressure, as just discussed. Therefore, an attempt has also been made to estimate a friction factor using the "bucket" test. For this purpose, a new method for evaluating the friction factor is suggested.

TABLE 3

Final load and bottom thickness values obtained from “bucket” tests

Lubricant name	Specimen No.	Forging load (ton)[2]	Bottom thickness (in)	Die temperature (°F)
LUB-A	1	700	0.411	675
	2	700	0.447	690
LUB-C	5	700	0.426	680
	6	700	0.307	675
LUB-D	9	584	0.261	690
	10	601	0.293	680
LUB-B	13	700	0.405	680
	14	700	0.383	675

[a] 1 ton = 8.896 kN

TABLE 4

Load and bottom thickness values obtained at an intermediate stage (40% reduction in height) in “bucket” tests

Lubricant name	Specimen No.	Forging load (ton)	Bottom thickness (in)	Die temperature (°F)
LUB-A	3	280	0.795	670
	4	305	0.795	680
LUB-C	7	296	0.797	680
	8	266	0.801	670
LUB-D	11	236	0.791	670
	12	406	0.807	660
LUB-B	15	342	0.798	678
	16	298	0.800	673

5. Determination of the friction factor with the “bucket” test

The quantitative determination of the friction factor, or coefficient, requires:

(1) A friction sensitive parameter that can be used as a friction-calibration factor (for example, the internal diameter in the ring test).

(2) Theoretically determined standard friction-calibration values (for example, percentage of decrease in ID versus percentage of reduction in height generated by FEM, slab, or upper-bound analysis for ring tests).

For the “bucket” test, the forging load and the bottom thickness together can be chosen as the friction-sensitive parameter because a good lubricant results in both lower load and thinner bottom thickness in this forging (see Tables 3 and 4). The forging load versus reduction in height of the bottom alone does not vary much with friction, (see Fig. 9). Therefore, the forging load multiplied by the bottom thickness, Fig. 10, was chosen as the sensitive parameter to calibrate the friction factor in a "bucket" test.

In this proposed method, curves of forging load multiplied by the bottom thickness versus reduction in height (of the original billet), obtained by FEM

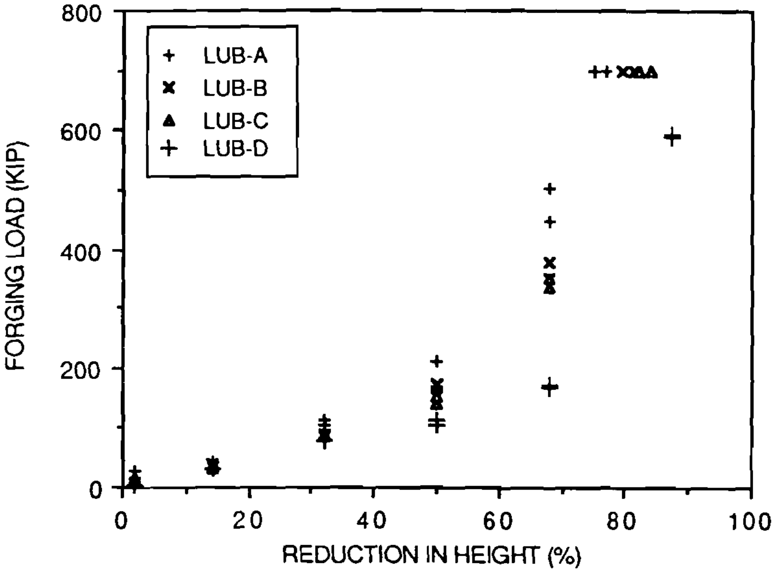


Fig. 9. Forging load versus reduction in height obtained in "bucket" tests. (This plot does not give results that can clearly illustrate the effect of friction.)

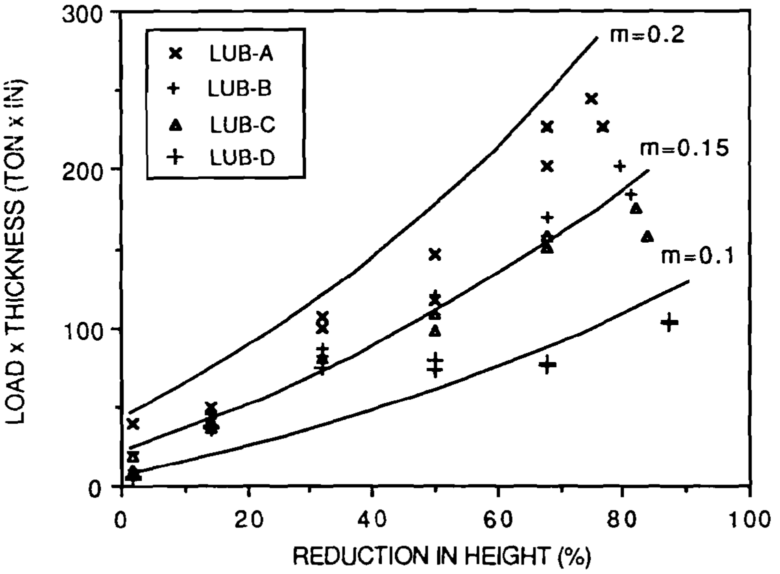


Fig. 10. Proposed method for estimating the friction coefficient in "bucket" tests. Data points in this plot were obtained from experimental bucket forgings. Calibration curves were obtained from FEM simulations.

simulations, represent standard friction-calibration curves for different shear friction factors, *m*. The application of the finite element method (FEM) in metal forming provides a powerful tool for the analysis of metal forming problems [8]. The FEM code, for example, ALPID/DEFORM, developed at Battelle Columbus Division [9,10], can link the detailed mechanics of the deformation together with the load and the position of material boundaries. Thus, it is possible to generate more sophisticated friction-calibration curves by FEM simulations than it is usually done by other methods of analysis. However, two-dimensional or axisymmetric geometry is more suitable for computation efficiency and accuracy. Therefore, the proposed geometry for the future "bucket" test is an axisymmetric bucket or cup instead of the non-symmetric bucket used in the present study (Fig. 7). The calibration curves predicted by FEM simulations (Fig. 10) may not be very accurate in the current study, because the 3D deformation of the non-symmetric bucket was approximated as a combination of axisymmetric and plane-strain deformation, as suggested earlier [1].

The proposed method for evaluating interface friction in a "bucket" test offers a distinct advantage, compared to the ring test. The experimental value of the friction-sensitive parameter, i.e., the load multiplied by the bottom thickness versus the reduction in height, can be obtained easily from the load and stroke versus time curves recorded in the experiment. Thus, the experiment can provide a continuous set of values: as many as desired. This is preferred for evaluating the performance of the lubricant at any deformation stage of interest in the "bucket" test. In the ring test, the friction sensitive parameter, i.e., the decrease in inner diameter, must be obtained by stopping the test and measuring the deformed ring, or alternatively a very elaborate technique for continuous measurement of the ring OD must be used and the ID must be calculated by considering the bulging of the internal and outside surfaces. Consequently, in the ring test only a limited number of values at selected stages of deformation may be obtained.

The friction-calibration curves presented in Fig. 10 may be presented in an alternative way by using the *load×bottom thickness/average flow stress* as a friction-calibration factor. Thus, performances of the same lubricant for different materials may be compared. However, this alternative must be further investigated prior to establishing a generally valid procedure.

6. Conclusions

The following conclusions are drawn from this investigation.

(1) In ring tests, with high and low interface friction conditions, two factors influence the forging load, i.e., the forging pressure and the contact area between the ring and the dies. These parameters compensate each other up to

around 40% reduction in height. Thus, the load–stroke curves obtained from ring tests are not sensitive to interface friction condition.

(2) In forging aluminum alloys, the same lubricant may perform differently under different forging conditions. The water-based lubricants appear to be suitable for forging conditions where the forging pressure is low and the amount of new surface generation is small. The oil-based lubricants appear to be suitable for extrusion-type forgings where the forging pressure is high and the new surface generated, i.e., the magnitude of metal flow, is large.

(3) The ring test is a good method for evaluation of lubricants at a low forging pressure and the "bucket" test is a good method for evaluation of lubricants at a high forging pressure.

(4) Calibrating friction factors, or coefficients requires: (i) a friction-sensitive parameter and (ii) "standard" friction-calibration values. The FEM simulation can provide the standard friction-calibration values very accurately, even for very large and non-isothermal deformations.

(5) The interface friction factor for forging of a "bucket"-type part, can be calibrated (determined quantitatively) by forging an axisymmetric bucket or cup. The forging load multiplied by the bottom thickness is a friction-sensitive parameter. The FEM simulation can generate "standard" friction-calibration curves (forging load multiplied by the bottom thickness versus reduction in height plots) and give distinguishable results for different interface friction conditions.

(6) The advantage of the "bucket" test over a ring test is that the experimental value of the friction-sensitive parameter, i.e., the load multiplied by the bottom thickness versus the reduction in height, can be obtained from the load and stroke versus time curves recorded in the experiment. Thus, the test can provide as many experimental values as desired, throughout the deformation process. In the ring test, the friction-sensitive parameter, i.e., the decrease in inner diameter, is obtained usually by stopping the test and measuring the deformed samples. Therefore, only a limited number of values may be obtained in a given test.

(7) There is no "universal" friction-calibration curve: the friction–calibration curves must be generated for the specified material under specified temperature and deformation-speed conditions.

Acknowledgements

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