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# Discussion

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## DISCUSSION

### R. A. Kohser[2]

**Part 1 Upper Bound.** This paper provides one of the few, if not only, lower bound solutions for ring compression and once again a highly complex solution has been well presented.

Since lower bounds are rarely used in a predictive sense, the solution takes significance only when coupled with the companion upper-bound—the magnitude of the gap indicating the possible error or discrepancy in the solution. Although different friction distributions are used, friction for the lower bound is everywhere less than or equal to that for the upper bound, thereby still permitting a valid comparison of the solutions. No such comparison has been presented, and I would like you to comment as to whether such a comparison was made and if so, comment on the results.

In addition, the work reveals a possible explanation of certain inadequacies noted in the current ring test calibration (i.e., friction factors in current test procedures may be too high—several report $m > 1$). I, for one, would like to see a comparison such as Fig. 8 of the paper developed for the "standard" 6:3:2 ring geometry to show the magnitude of the effect of shifting the neutral radius. Has such a comparison been prepared or was one considered?

**Part 2 Lower Bound.** A highly technical derivation has been well presented. The current analysis complements others of the same problem. While others may be more powerful, they achieve this at the expense of a numerical computer-based solution. Here a rigorous solution requires computer minimization of an analytical equation with respect to only one variable: namely *Rn*, and by using an approximation, the problem can be solved on a pocket calculator.

The solution presented has already been used to recalibrate the theoretical curves for the ring compression test and the results have been well received, a fact that indicates the quality of the work.

One point that should be clarified is the use of the value of *Rn* (the neutral radius) determined from a previously performed simpler analysis as a starting point for the current solution under certain conditions. Could you comment on the validity of this approach?

## Author's Closure

The authors are grateful to Dr. Kohser for his kind comments and for the opportunity to go deeper into the relation between the upper and lower bounds. Since most of the following reply will allude to the relation between the upper and lower bounds it will be best to combine the discussion to both papers.

The first question inquires if the position of $R_n$ neglecting the bulge, as determined by the solution of References [2–4], of Part 1 of this work (Paper No. 77-WA/PROD-2) can serve as a first approximation for the finding of the position of the neutral radius for the present solution (Eqs. (13) and (14) of Part 1) for bulge. The answer is that doing so may expedite the work, especially for those cases when $R_n < R_i$ and the first approximation is determined explicitly by equation (7.15a) of Reference [4] of Part 1. The corrected solution by the present paper is close to the first approximation, minimizing the number of iterations required. Convergence rate of course depends on the numerical method employed. When graphs like Fig. 3 of Part 2 are constructed and friction factor $m$ increases incrementally, one may consider using the $R_n$ value found for the previous friction as a first approximation for the next point.

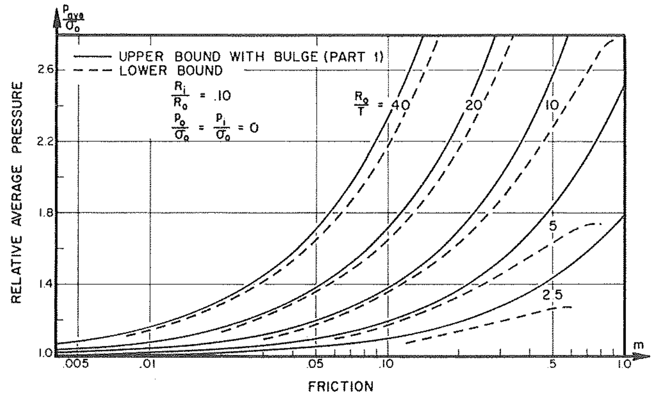


**Fig. 9 Comparison of upper bound and lower bound on the relative average pressure.**

The next question is addressed to the relations between the upper and lower bounds presented in the two related papers. The authors concur with the observation made by Dr. Kohser that the relation between the flat distribution of interface friction, associated with the upper bound and the trapezoid shape of shear by Fig. 1 of Part 2 for the lower bound, make the two solutions the bounds of an exact solution, when shear is assumed to be $\tau = m\,\sigma_0/\sqrt{3}$. This observation was made in Reference [1] of Part 2 and was a corner stone for this work. The first submitted manuscripts centered around this motif. Finally after years of struggle to publish this work reference to the solution as two bounds to the same condition was deleted in the final form of the publication because this was made a compulsory condition for the publication of this work! When the upper and lower bounds

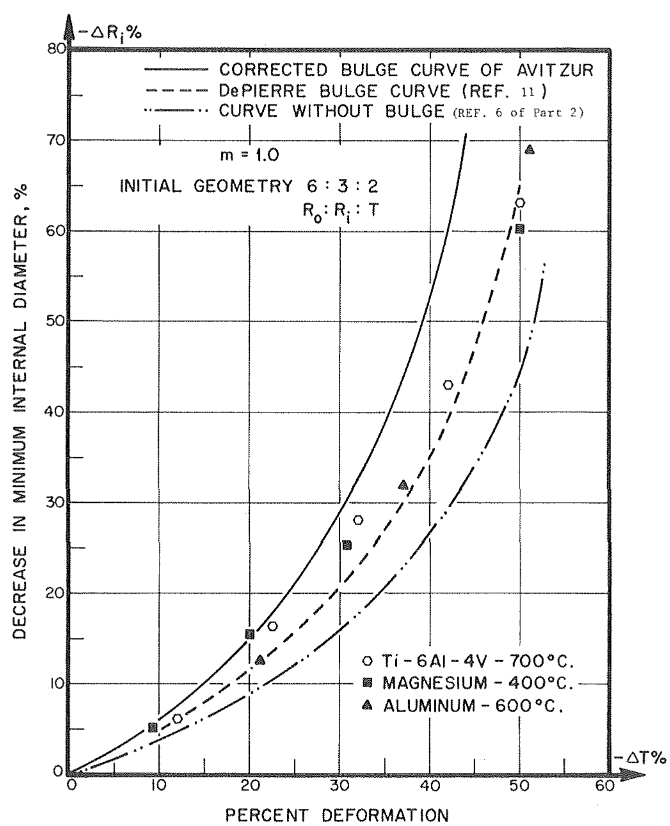


**Fig. 10 Calibration curve comparison for ring test.**

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are compared Fig. 9 results. For comparison of upper and lower bound for solid disc forging see Chapter 7 of Reference [4] of Part 1 and Chapter 2 of Reference [9].

The value of the lower bound solution is enhancing the upper bound solution since together they provide bounds to the exact solution. The error in each solution cannot be greater than the gap between the two, and the direction of the error is determined. But the lower bound solution provides also an insight to a better understanding of the distribution of interface friction and pressure distribution between the workpiece and the platens (see the trapezoids of Figs. 1 and 4–7 of Part 2). *One can then accept the friction distribution obtained* through the lower bound as more realistic than the flat distribution of Part 1. Another upper bound solution for friction distribution by the trapezoidal field can then be derived. The new upper bound will then be lower than that shown in Fig. 9 closing further the gap between the upper and lower bounds.

In Reference [1] of Part 2 the lower and upper bound solutions were instrumental in constructing graphs depicting the position of the neutral radius as a function of geometry and friction. Higher values of $R_n$ are predicted by the lower bound solution than by the upper bound solution. If calibration curves were constructed from the lower bound solution for the neutral radius, their corresponding characteristic line would have been at higher position than displayed by Fig. 4 of Reference [11] *and friction above* $m = 1$ *will not have been* determined.

If the solution for ring with bulge as presented in Part 1 is properly programmed, the characteristic curves shift upward with respect to the previous calibration curves (11) based on the analysis with no bulge. For example in Fig. 10 the correctly developed curve for $m = 1$ provides an excellent fit for the data provided in Fig. 4 of Reference [11]. To construct such graphs care must be exercised in handling the bulge, and the computer program (and computer time) become too excessive for present day hand calculators. A larger capacity computer is desired.

Criteria for the choice of the geometry of the ring as studied in Reference [12] show that the 6:3:2 ring is not always the best choice. Furthermore while the analysis of ring forging is the basis for most present day studies for the determination of friction and flow strength for forging, the calibration curves are not the only means to accomplish that goal. In References [13, 14 and 10], other methods are offered by Dr. Kohser and Avitzur. The pros and cons of each method are evaluated.

The upper and lower bound solutions for disc and ring forging provide excellent means for the experimental determination of friction and flow strength in forging. The work at Wright-Patterson Air Force Base has provided this tool the visibility it deserves. The authors wish *to close this discussion with the suggestion that the utilization of these* tools can be developed further and require cautious implementation if they are to be successful. On many occasions in the past companies failed in their effort, blaming the concept, while the fault was in misunderstanding the concept or blindly utilizing calibration curves with wrong ring geometry (see Reference [12]) or where other methods (References [10, 13 and 14] and [3 and 4] of Part 1) might have been more appropriate. And once more, thanks to Dr. Kohser for his discussion.

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