Discussion

W. S. Wagner[6] and E. V. Crane.[7] This valuable study co-ordinates residual stresses with the originating stresses which occur during metalworking, in a revealing manner. It seems probable that the demonstration would apply in much the same manner to the general problems of wire drawing and cold drawing of bar, etc.

The conclusion that load was not influenced by speed (at least within conditions of the test) is a matter in which there seems to be divergent opinion. Impact extrusion of the same aluminum reaches speeds perhaps one thousand times faster than the maximum test speeds in the subject paper. Internal and external friction conditions contribute to differences in resistance.

The strain gage on a 2500-ton mechanical press extruding 4.7 steel rocket projectiles, subjected only to normal variations in temperature, die wear, and efficacy of phosphate-stearate coating, showed load variations from 1700 tons to 3000 tons. In the tensile testing of steels at various speeds and temperatures Nadai[8] found substantial increase of ultimate true stress at any particular temperature with strain rates per sec and rising from 8.55×10^{-4} to 600. Baldwin and Beiser of Case[9] found substantial change in the cold-heading limit of carbon and stainless steels in speed ranges from 10^{-2} to 10^{4} ipm. Clark of Case[10] found substantial reduction of punching load as punch speed increased from 0.00017 to 8.70 ips.

The changes which must take place as metal passes through an orifice during plastic work would appear to be well illustrated in the work of Frisch and Thomsen.

Figs. 3 to 7 of the paper compare a dynamic plastic-flow condition just inside an orifice and a relaxed condition just beyond the orifice. The difference between the two conditions as represented by the curves would seem to be an elastic springback. The residual stresses in the bar beyond the orifice are no longer affected by the high radial compressive stresses within the orifice where the stresses were originally set up. This same relaxation and elastic springback probably would be reflected in a slight increase in bar diameter just after it issues from the orifice. It would be difficult, if not impossible, to measure this dynamic change, but it should be related to the similar change in diameter of a stream of water issuing from a sharp-edged orifice. Do the authors feel that elastic springback upon removal of the radial compressive forces just within the orifice will account adequately for differences between the two curves in Fig. 7 ?

C. T. Yang.[11] The writer wishes to congratulate the authors on their excellent work done in analyzing the problem of residual stresses in extrusion. He would like to point out a few things which might be of interest to them.

It seems to the writer that once the metal in extrusion reaches a point close to the die opening, it is not strained any more going through the die. This can be shown from the extrusion pattern, Fig. 9, and the slip-line pattern, Fig. 10 of this discussion.

[6] E. W. Bliss Company, Canton, Ohio.

[7] Chief Engineer, E. W. Bliss Company, Canton, Ohio. Mem. ASME.

[8] "High-Speed Tension Tests at Elevated Temperatures—Parts II and III," by A. Nadai and M. J. Manjoine, Journal of Applied Mechanics, Trans. ASME, vol. 63, 1941, p. A-84; vol. 66, 1944, p. A-217.

[9] "Why Is Stainless Steel Hard to Cold Head?" by W. M. Baldwin, Jr., and C. A. Beiser, *Iron Age*, vol. 175, January 13, 1955, pp. 82–85.

[10] "Punching of Medium Carbon Steel," by S. K. Clark, ASME Paper No. 54—SA-35.

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On the extrusion pattern it is shown that the metal is not strained further near the die.

In the slip-line field near the die opening (shaded area) the metal is plastic-rigid. In other words, it moves as a rigid block and will not change in strain. The writer thinks the metal extruded relaxes along line AC and not at die AD in the slip-line field.

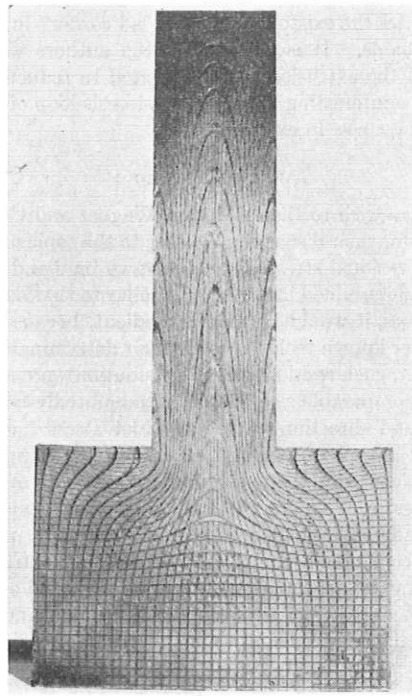

Fig. 9 Extrusion Pattern

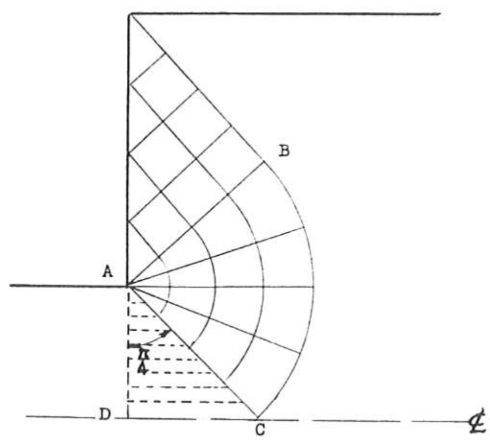

Fig. 10 Slip-Line Pattern

From this concept the stresses in the billet at a point very close to the die opening is the same as the residual stresses in the extruded bar. This can be proved by Figs. 5 and 6 of the paper. Comparing the axial residual stresses σ_z' measured and the computed axial stresses in the billet and the extruded bar, it is seen that the measured residual stresses σ_z' are very close to the values of the axial stresses, σ_z in the billet at $z = 0.2$ in. rather than the residual stresses calculated in the extruded bar.

The measured residual-stress σ_z' curve agrees well with the axial stress σ_z curve (at $z = 0.2$ in.) at the central portion and becomes worse in agreement as it approaches the wall of the die.

This also can be explained by the slip-line pattern. Near the wall the plastic-rigid region (shaded) tapers down to zero; that is, near the wall the strain still changes while the metal is going through the die and thus near the wall the metal is not completely relaxed.

The writer wonders if the authors could give some information concerning the relationships of the residual stresses with the reduction ratio and also with the die angle.

To the writer the existence of the "dead corner" in extrusion is still questionable. It is hoped that the authors will do some work to find the extrusion pattern related to reduction ratio.

It would be interesting to see the hysteresis loop of the loading and unloading curve in extrusion.

Authors' Closure

The authors wish to thank Messrs. Wagner and Crane as well as Dr. Yang for their discussion relating to the topic of this paper.

While the residual stresses in cold-drawn bars and wires could probably be determined in a manner similar to that demonstrated by the authors, it would be more expedient, because of size, to resort to other known techniques for their determination.

If, however, such residual-stress distribution were available for products of comparable size, it would undoubtedly be found that magnitude and direction of the residual stresses are strongly affected by the type of forming process, temperature, and speed.

It is not clear why there should be divergence of opinion, as noted by Messrs. Wagner and Crane, regarding the constancy of extrusion load. The load becomes constant only under steady state and special conditions of the test, i.e., low extrusion speed, room-temperature deformation, and well-lubricated cylinder wall and die surfaces. Under these conditions each element of metal in the billet absorbs a definite amount of deformation work independent of time as it transforms into another element in the extruded bar. This fact was adequately demonstrated by the calculations made in a recent paper[12] in which the average extrusion pressure was calculated by a work of deformation method using experimental strains and mechanical properties of the aluminum as determined under comparable conditions from compression tests. It was noted that the experimental and calculated extrusion pressures agreed well and that strain-rate effects were absent.

The authors agree with Messrs. Wagner and Crane that the difference between the two curves in Fig. 7 is, to a minor degree, probably due to radial springback but that the change in stress pattern from $z = 0.2$ inches to a point past the die opening is primarily due to afterflow at the die corners.

Dr. Yang has used the ideal plastic solid as a model for comparison of the actual behavior of a real metal during extrusion. While we agree that the slip lines obtained for an ideal plastic solid are a good solution to a first approximation, such a solution fails to give the exact details within the transition region, between the fully plastic zone and the elastic zone. Thus, for example, the line AC of Fig. 11 does not really exist as a line of zero axial stress, but rather the axial stress drops gradually to zero in the triangular zone ADC. It is therefore currently not useful to speculate on the residual-stress distribution in an extruded bar by referring to a slip-line field for an ideal plastic solid.

Dr. Yang's question with regard to data based on different reduction ratios and die angles must unfortunately be answered in the negative. However, these questions show clearly the need for further research in this field.

[12] "Plasticity Equations and Application to Working of Metals in the Work-Hardening Range," by E. G. Thomsen, Trans. ASME, vol. 78, 1956, p. 407.