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discussion

The Effect of Receiver Pressure on the Observed Flow Pattern in the Hydrostatic Extrusion of Bimetal Rods[1]

R. A. Kohser. [2] The present paper continues a series of publications based upon Lehigh research of bimetallic extrusion and drawing. As with its predecessors, it does an excellent job of defining the significant process variables and their relative roles in producing a sound or defective product. Several aspects, however, may well merit additional discussion or clarification:

(1) The authors make reference to a supporting analysis (reference [5]) as a useful guide in selecting the proper combination of process variables to produce a sound product. Simultaneously, however, they allude to the inability to either control or precisely define two of these process variables, namely, the core-matrix bond strength and the friction factor (m). Since the first of these variables plays a significant role in determining product quality, would the authors please comment on the relative usefulness of the support theory, its strengths and weaknesses, and its potential role in guiding future work?

(2) In the present paper, Figs. 5 and 7 present the results of similar extrusions performed with and without receiver pressure, the change in results being attributed to the increase in environmental pressure. One notes, however, that the fluid medium used to provide the hydrostatic pressure was changed from pure soy oil to a soy oil-kerosene mix when back pressure was added. To what extent might this change affect the results?

J. M. Alexander.[3] This is a most interesting piece of experimental work and is undoubtedly a valuable contribution to the "state of the art." However, I found it somewhat difficult to understand and interpret the results and would welcome some further explanations from the authors about certain symbols and the nomenclature.

In the first place, this discusser found it difficult to establish what the actual pressures are in any of the experiments. Pressures are referred to, for example, on the last page of the paper as "(100–140 P), (750–800 P), and 800 P." Although the discusser looked very carefully through the text he could not find anywhere the significance or meaning of the symbol P.

Secondly, the discusser is not sure he has understood correctly how to interpret the symbols referring to the "ratio chambers." According to the first paragraph on the third page, there are three chambers with ratios 3/1/2, 2/1/1, and 3/2/1/½. If we consider the first chamber with ratios 3/1/2, it is stated that the center number (number 1?) represents the pressure drop across the die. Does that mean that the first number (3) represents the extrusion pressure and that the last number (2) represents the back pressure (receiver pressure, in the author's terminology)?

Thirdly, although it is interesting to see the plots of reduction in area versus die-semi-cone angle for various values of the parameters Y, a, and chamber ratios, previous investigators have always presented results in the form of graphs of back pressure versus extrusion ratio for various values of the other parameters.

Lastly, although it is very important to have experimental results of this type, it is virtually impossible to use the results unless some attempt is made to link the observed phenomena with the material properties and other variables by means of appropriate theoretical analyses. Professor Avitzur has himself developed several theories for predicting extrusion pressures and other parameters and it is a pity that he has not included in this paper any attempt to predict or explain the observed results. There is also no reference in the paper to the simple theoretical analysis recently developed by Alexander and Hartley[4] for problems of this type. It might have been useful in this case.

A. R. Bobrowsky.[5] The authors are to be congratulated on producing a clear paper on several topics, especially on the mechanical failures of composite materials during fluid-to-fluid extrusion (hydrostatic extrusion into fluid pressure).

There are presented two types of core failure that are related, namely, waviness of the core material (Fig. 6) and separation (or breakup) of the core material into discrete pieces (Fig. 6).

This waviness has also been termed multiple necking, that is, the formation of many necks at regular intervals along the length of a core or central material in a composite. The separation of the core material into discrete pieces can sometimes be a final stage after initial waviness has occurred in which case the discrete pieces of core will be rounded or pointed, but separation of the core material can be produced also without initial waviness providing the core is sufficiently brittle. In the latter case, the ends of the core pieces can be flat (see Fig. 1).

These failure phenomena for composites are strikingly similar to those that have been found in Nature, to those that have been produced by pulling man-made composites in tension, and to those that have been produced only by lateral pressure on flat (sandwich-type) composites.

The wavy core has been found in rock formations where a relatively brittle ("competent") rock material is sandwiched between two layers of relatively ductile ("incompetent") material (reference [1]). The core material can become ductile under the hydrostatic pressure produced by the "hydrostatic head" of rock above the composite.

Such examples of waviness in rock composites have been photographed in natural rock strata in Wyoming and in Greenland, and published (reference [2]). In geology, the waviness of the core has been termed "pinch-and-swell structure."

The formation of discrete pieces of rocks in the cores of natural composites was so common in Nature as to be reported in print in the middle 1800's, and to be termed *boudinage* in the early 1900's. Boudinage means the formation of *boudins* ("little sausages," from the shapes of the pieces) in rock structures.

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[1] By J. M. Story, B. Avitzur, and W. C. Hahn, Jr., published in the Aug. 1976 issue of the JOURNAL OF ENGINEERING FOR INDUSTRY, TRANS. ASME, Series B, Vol. 98, No. 3, pp. 909–913.

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[4] Alexander, J. M., and Hartley, C. S., "On the Hydrostatic Extrusion of Copper Covered Aluminum Rods," *Proceedings of the NEL/AIRAPT International Conference on Hydrostatic Extrusion*, published by the Institution of Mechanical Engineers, June 1973, pp. 72–78.

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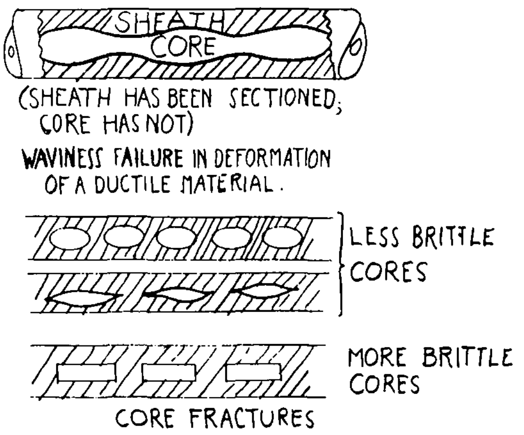

Fig. 1 Typical core failures in elongational deformation of sheath-core composite materials

The resemblance between boudinage and the formation of discrete pieces in the authors' paper is so striking as to suggest that current explanations for the formations of boudins in Nature may indeed have application in helping to understand how some of the authors' results may have come about.

It should be noted that the correct explanation for these deformational and fracture behaviors of composite materials was generally unknown as late as the 1950's, as displayed in reference [3] (Nadai) where the breakup of the core into pieces of regular length was attributed to "sliding as a deck of cards."

The reason why the plastic flow of rocks under pressure can be held to be similar to the flow of metals and similar materials is that all crystalline materials appear to become ductile under sufficient environmental pressure. It is well known in the rock-mechanics field that stress-strain diagrams of rocks made ductile while under pressure are similar to those of metals. In the absence of massive inhomogeneity and/or anisotropy, the flow of all ductile solids during the same plastic deformation tends to be the same.

Variations in ratios of strengths and/or ductilities of sheath and core materials give rise to core-fracture and core-deformation behavior similar to some in the authors' paper (reference [1]).

There are examples of core-sheath behavior of composites other than rocks. These examples tend to be more convincing to some people than just examples of rock-rock composites. One can find examples closer to metal-metal composites in composition as well as examples further. Finally, one can cite results of metal-metal composite materials.

In the area of metal-nonmetal composites, reference [1] describes boudinage in simple tensile pulling, where the core material is dead brittle, namely, pyrex glass, and the sheath material is a material not only ductile but one that recrystallizes at room temperature, namely, lead. The breakup of the core is as pictured in the last drawing of Fig. 1, with the boudins (discrete pieces of core) being completely square-ended.

This, then, is an added relationship, namely, that simple tensile pulling (under pressure, to tend to make the brittle component(s) ductile) can produce multiple necking as well as the repeated regular breakup of core material into discrete pieces.

We now mention several factors that tie closer together some of the results of the authors on hydrostatic and fluid-to-fluid extrusion with results from simple tensile pulling.

1 Bridgman showed in the early 1900's that lateral pressure alone produced necking and fracture failures identical with those produced by simple tensile stress under all-sided pressure of equal magnitude. He also produced the analysis, now well-known, that demonstrated the equivalence of these two stress states. Also, he contributed the terminology "pinch-off" to describe the necking failure in tension of solid specimens subjected only to lateral pressure.

2 Ramberg (reference [2]) correctly attributes pinch-and-swell rock shape (waviness) to pinch-off, since only lateral pressure is present. It does not matter that his "specimens" are of the flat sandwich-composite type.

3 Bobrowsky (reference [4]) submits experimental evidence that hydrostatic extrusion and fluid-to-fluid extrusion are indeed drawing processes, where the differential pressure causes metal to extrude (draw) through a die, much as a person sucks a length of spaghetti into his mouth. This is neither a ram (compression) extrusion action, nor is it a wire-drawing (tensile) operation. The fluid-extrusion action instead is a hydrostatic compression of the billet, an urging of the metal through the die by a combination of differential axial pressure and lateral pressure, opposed by friction stresses.

The major difference between hydrostatic extrusion and tensile tests is that the walls of the extrusion die react on the specimen with variable compressive stress along the length of the die, whereas the lateral stresses are uniform on the outer diameter of a tensile specimen.

The filaments in a filamentary composite are under different lateral stresses than the O.D. of the sheath material, due to difference in compressibility of the two materials. Reference [5] shows analytically how this difference in compressibility of sheath and core can alter the lateral stress between the two to a value different from the external pressure, both for filamentary and particulate composites. Other publications (e.g., reference [6]) describe experimental results along these lines.

Multifilament composites of W in 90/10 brass, when pulled in tension, showed multiple necking and then boudin-type fracture along the lengths of the filaments, in published results. The behavior of these metal-metal composites in tensile tests is like the behavior of the authors' specimens in hydrostatic and fluid-to-fluid extrusion.

As the waviness developed in the W filaments, voids opened in the brass sheathing material near the necks in the W. This was seen by both radiography and sectional examination. It can be surmised that the lateral Poisson's-ratio stress in the brass, applied to the W, tended to diminish when the neck formed, due to the W pulling away from the brass, with accompanying void formation preferentially in the material with lowest hydrostatic component of stress, that is, near the neck.

The authors present an explanation for multiple necking (among others) derived from the relative Poisson's ratios of sheath and core materials causing transverse stresses, somewhat like the analysis of reference [5].

The conclusions seem to be:

(*a*) there are great similarities in composite-specimen behavior in simple tension and in hydrostatic and fluid-to-fluid extrusion, at least;

(*b*) flow patterns of ductile composite solids (and homogeneous solids, as a separate situation) can be similar independently of whether the solids are both metals, part-metal part-ceramic, both ceramics, or (reference [2]) cheese and plasticene;

(*c*) flat (single-filling sandwich) and filamentary composites can behave similarly; and

(*d*) one would expect differences along hardness traverses of sections in the authors' specimens.

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