passes with their attendant problems of lubrication, galling, and forced extraction of mandrels. Uninterrupted drawing can be continued until an ID slightly larger than the finished size is reached. At this stage the core is extracted by fusion, reeling, or stretching and the tube is given one or two ironing passes over a mandrel rod to produce the desired dimensions.

Owing to the load carrying ability of a metallic ductile core, operations using powder as a barrier permits heavier drafting schedules than those where solid powder cores are used. The metal rod (Al, Cu, mild steel) neutralizes the low hardness and initial low apparent density of the fill and in most cases it can be removed easier than a solid powder fill. Reeling on a three stand skew-roll straightener loosened the powder barrier of a composite core so that it could be shaken out whereupon the center rod was freely pulled out. However, reeling of tubes packed with solid oxides or metal powder was unsuccessful.

There was no problem in disposing of sugar used for center packing. With a sugar-metal composite core, the central rod could be pulled out by hand from a moderately heated, hard-drawn tube which could then be washed internally and annealed, if needed. Other fusible or soluble substances like a salt or glass may replace either the sugar or oxides where conditions warrant. The corrosivity of various salts must be carefully considered in such a case.

Structural Soundness and Surface Quality. The importance of freedom from cracks at the ID surface is obvious and the mechanism of crack formation from longitudinal wrinkles during alternate sinking and mandrel drawing passes has been discussed earlier [3]. Because of the unknown prior history of the tubes used here, detailed study of the ID surface topography was not deemed justifiable. It appeared, however, that the fine and increasingly dense powder within should prevent any incipient longitudinal wrinkle from "closing" and converting into a notch. This expectation was supported by subsequent observations made on copper tubes annealed at 535 and 820 deg C to produce alternately fine and coarse grain. After sinking to 0.280 in. OD the hole in a fine grained tube remained reasonably round but in the coarse grained material it was severely distorted into an irregular polygon. With an Al_2O_3 powder-Cu rod core, however, the severe "orange peel" effect and disfiguring of the interior in the coarse-grained tube could be totally suppressed. With the sugar-copper core the improvement was less spectacular but nevertheless undeniable.

Surface Finish. The appearance of a surface which bears slip-lessly against a ductile core or a powder layer is dull and "textured" despite its structural soundness. One final draw over a polished inside tool will suffice to impart a high finish to the ID surface and to secure the desired diameter.

Suitability for Warm Drawing. Certain metals and alloys are difficult to work at room temperature. Extruded W and Mo must be worked from about 150 to 600 deg C or even higher because of their high transition temperatures. These temperatures can be gradually reduced as deformation progresses.

A tube filled with a disposable refractory powder is more suitable for warm working than an empty one because of the relatively large heat capacity of the quasi-solid cross section. By the time the final ironing or sizing operation is performed, the tube may have received enough prior deformation to withstand these operations at quite low temperature thereby alleviating much of the difficulties connected with the drawing of a hot tube on a much colder inside tool (e.g., mandrel).

Experiments on fabrication of refractory tubing by these and related methods are presently in progress and their results will be reported at a future date.

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DISCUSSION

Paul Loewenstein[2]

In the introduction to this paper, the authors state that identical principles have been used in the hot extrusion of UO_2 and other ceramics, at Nuclear Metals, as in the fabrication of sheathed heating elements, and the drawing of tubes filled with particulate solids. I would like to point out that in the extrusion at very elevated temperatures of oxides and carbides, true plastic flow of the crystals takes place. This is shown by the resulting elongated grain size of the extruded ceramics, as well as by X-ray preferred orientation measurements.[3] During the reduction in area of oxide bodies at room temperature, such as described by the authors, deformation takes place by the sliding of particles over each other, rather than true plasticity. This sliding action may also result in the breaking up and smoothing out of particle surfaces. In our experience, it becomes almost impossible to deform ceramics by this method once the ceramic has attained a very high density.

We have found a swaging operation to be useful for loosening dense ceramic cores, such as used by the authors either as a method of removal of the ceramic core or as a method of permitting further deformation by drawing. A special design of the swaging dies for this application is needed with dies having more pronounced ovality than usual.

We feel that in many cases, direct contact between the particulate matter and the tube should be avoided. In this case, it is possible to encase the particulate matter in a thin tube of another metal such as copper, which can be removed by chemical or mechanical means, after the operation. This method can also be used to eliminate almost completely the early stages of "sinking" which is needed to consolidate the particulate solids in the method described by the authors. In this case, the particulate solids encased in the thin metal tube are given a preliminary consolidation by swaging or drawing, and are then introduced into the tube to be drawn.

The methods used by the authors at the Argonne National Laboratory offer an excellent solution to the problem of internal cracking of small diameter tubing which is becoming increasingly important with the more stringent requirements of the nuclear and space industry, and with the development of more sophisticated inspection equipment capable of revealing such defects.

Authors' Closure

The authors appreciate these thoughtful comments by Dr. Loewenstein whose important and extensive work in this and related areas is, of course, widely known. They recognize that the potential of the "powdered center" method is considerable and that the future may bring yet other interesting applications of this technique.

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