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CHEVRON FRACTURE IN TUBE REDUCTION BY SPINNING

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INTRODUCTION

A common defect observed in plastic deformation through conical converging dies is the structural damage variously referred to as chevron fracture, cup-and-cone fracture, centerburst, cuppy core, and arrowhead cracks. Such fractures in the form of "cuppy" wire was first described in the literature by Harris [1]. The important role of geometrical variables in preventing these fractures was outlined by Jennison [2]. Subsequent work by a number of researchers [3 - 12] clearly established the fact that two factors played a role in the initiation and propagation of such fractures, namely, deformation geometry and material characteristics.

The parameters involved in deformation geometry are die angle, reduction, and friction. The smaller the die angle and/or the greater the reduction, the less the tendency for the material to undergo structural damage. As for the role of friction, higher friction is desirable in extrusion and undesirable in wire and rod drawing.

Material characteristics that play a role are the extent and nature of impurities and inclusions, and the presence of voids prior to deformation. The mechanism of fracture appears to be based on defects generated either at inclusion-matrix interfaces or at pre-existing voids. These observations have then led to considerations of the beneficial role of superposed hydrostatic pressure in enhancing the ductility of the material and, thus, delaying the initiation of structural damage [9]. In addition, the strain hardening capability of the material has been shown to have a beneficial role as a deterrent to structural defects in drawing and extrusion [8, 12].

An overriding consideration in the interrelationship of the factors discussed above is the role of the hydrostatic stress in the deformation zone. Slip-line field analysis, as applied to sheet or strip drawing in plane strain, indicates that under certain conditions a tensile hydrostatic state of stress exists in the centerline of the strip, Figure 1. The level of this stress is reduced, or it can become compressive, as the die angle decreases or as the reduction increases. As expected, a reduction of the tensile hydrostatic state of stress reduces or eliminates centerline fracture.

Another analysis is due to Avitzur [13] who has suggested that in axisymmetric cases central burst occurs when the velocity field is as shown in Figure 2, namely, the plastic zone (which is an annulus) does not extend to the centerline. The rigid zone III moves faster than rigid zone I, the interface separates and fracture takes place. Again, one can readily see that the two main variables in enlarging the plastic zone are die angle and reduction.

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The phenomenon of chevron cracking occurs not only in extrusion or drawing of solid cylindrical bodies or in drawing of sheet or strip, but it has also been observed in cold extrusion of steel tubes to reduce their wall thickness [14]. Circumferential fractures occur on the inside surface of the tubes (adjacent to the mandrel) and the tendency to fracture increases with decreasing reduction and increasing die angle. The arrowhead cracks, which are symmetrical with respect to the axis of the tube, point towards the direction of extrusion, just as they do in drawing or extrusion of solid sections.

TUBE SPINNING EXPERIMENTS

In all the studies cited in the literature, the die is in full contact with the circumference of the round workpiece, or it covers the full width of the strip in plane strain drawing. In this paper, it will be shown that such fractures also occur in tube spinning where contact with the roller comprises only a small fraction of the workpiece circumference, Figure 3. The process, described by the author in detail in reference [15], deforms the material incrementally. In backward spinning, the process is like tube extrusion; in forward spinning it is like drawing.

During extensive experimentation to study fundamental relationships in this process, it was observed that under certain conditions circumferential cracks developed on the inside surface of the spun tubes. Three materials were tested: Aluminum alloys 7178 and M580 (an experimental alloy) in the fully annealed condition, and 81B45 steel in the as-received condition. Internal diameters were D_m = 33 cm and the original wall thickness t_o = 19 mm. The mandrel rpm was N = 150. Two rollers were used, with an axial speed of 15 cm/min. The roller angle α was 30 deg.

In some preliminary experiments with wall thickness reductions of 20 - 30 percent, it was observed that circumferential cracks developed on the inside surface of the tubes, adjacent to the mandrel, Figures 4, 5, 6. It was first thought that a lowering of reduction would alleviate this situation. However, this approach failed in that cracks were again generated. The next approach was to increase the reduction. It was discovered that, for the particular roller geometry used, a minimum reduction per pass of 50 percent (for t_o = 19 mm) was required in order to avoid cracking of the inner surfaces. This was true for both forward and backward spinning.

The interpretation here is that with α = 30 deg and such a large reduction, the plastic zone under the roller contact area now extended fully to the inner surface of the tube wall. (It is to be noted here that, with tubes, the inner surface of the tube in contact with a rigid mandrel is analogous to the centerline in drawing or extrusion of solid cylindrical bodies).

The extension of the plastic zone to the inner surface also meant that changes in the original surface finish of the inside of the tube would take place. This is analogous to making a hardness test on pieces of flat materials of progressively decreasing thickness and inspecting the underside of the specimen. Towards this purpose, a setup was built so that an originally constant wall thickness tube could be spun with a continuously increasing reduction, as shown in Figure 7. A mild steel tube with an original and constant inside surface finish of 100 μin rms was spun in this manner. The new surface finish was then measured corresponding to each level of reduction and was plotted, as shown in Figure 8.

Mild steel was chosen for this experiment because it did not exhibit any chevron cracking.

The surface finish improved with increasing reduction and, at a reduction of around 50 percent, the finish stabilized at 10 μin. This was the same finish as that of the mandrel; the surface of the inside of the tube was now a replica of the mandrel surface and the plastic zone had penetrated fully throughout the thickness of the tube.

DISCUSSION

Although it is the first time that chevron fracturing appears to have been reported in the literature in an incremental deformation process, such as spinning, it is obvious that the mechanism leading to it is similar to that discussed earlier in this paper. Because of the practical difficulties involved, the roller angle α was not changed in these experiments. It is clear, however, that lowering α will require a lower reduction per pass to obtain a fully developed plastic zone under the roller. It should be noted, on the other hand, that a low α will also lead to excessive circumferential strains, thus resulting in a loose part of the mandrel. In fact, at α = 0 deg the process becomes ring rolling where wall thickness reductions are accompanied by large increases in the diameter of the workpiece. As for the roller velocity V_a, no apparent effect on fracture was observed.

As for the location of the circumferential cracks in Figures 4 - 6, it was observed that they were rather random and that some of these originated at the roots of the tool marks left from machining the bore.

Because of the necessity of applying a minimum reduction to avoid fracture, the question may now be raised as to whether fracture occurs when reductions per pass are of the order of a few percent only. Experimental evidence in spinning indicates that small reductions do not lead to chevron cracking. Spinning at small reductions becomes a process somewhat similar to surface rolling or shot peening, thereby work hardening the surface of the tube and imparting compressive residual stresses. This also means that somewhere below the outer surface of the tube the residual stresses become tensile. For this reason, if a spun part is too tight on the mandrel one simply takes a very light final reduction; the tube begins to get loose on the mandrel and can then be easily removed. It is interesting to observe that, as also reported by Cockcroft [7] in his experiments with cold extrusion of steel, there is an intermediate range of reductions where chevron cracking occurs; there are, therefore, safe regions at low and at high reductions for all these processes.

From these discussions, the important role of the roller geometry is quite evident. As can be seen in Figure 7, actual rollers are comprised of an angle α, followed by a small radius ρ, then a short land of one degree or so negative, followed by a relief angle. Using this same roller, it was observed during experiments that as the original tube wall thickness decreased (i.e., experiments with different original wall thickness tubes) the minimum reduction to avoid chevron cracking decreased from the 50 percent discussed earlier in connection with 19 mm thick tubes. The explanation for this is quite simple in that, because of the radius ρ, as the quantity $(t_o - t_f)$ decreases the effective die angle decreases from its original α value. This means that a full plastic zone can be developed at a lower reduction for thinner wall tubes. It is interesting to note that, for drawing and extruding of solid cylindrical bodies, it has been recommended that to avoid chevron cracking the corners between the conical and the cylindrical portions of the die should be rounded [13]. This location is, of course, the same as the region of the radius ρ of the roller used in spinning.

CONCLUSIONS

It has been shown that chevron fracture can take place in incremental deformation processing and that it is not unique to drawing or extrusion. Fracture occurs under conditions similar to those observed with axisymmetric parts.

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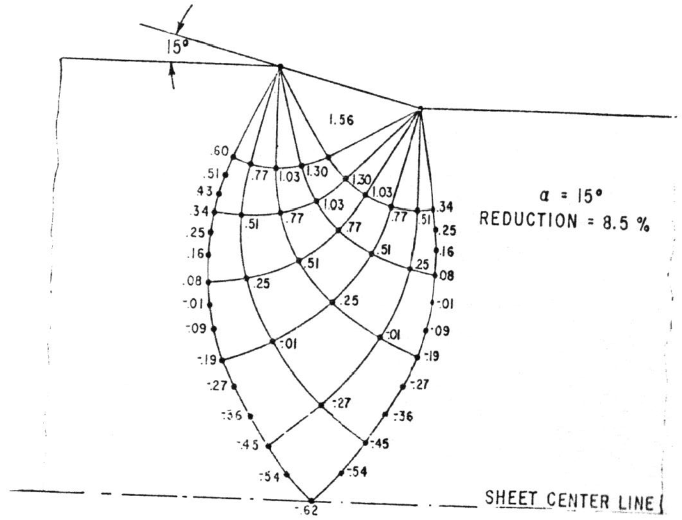

Figure 1 Distribution of Hydrostatic Stress in Sheet Drawing. Numbers Refer to the Ratio of Hydrostatic Stress to Yield Stress. Negative Numbers are Hydrostatic Tension (Reference 9)

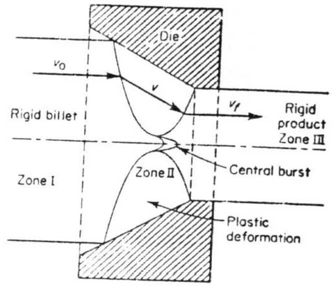

Figure 2 Deformation geometry in Axisymmetric Extrusion or Drawing (Reference 13)

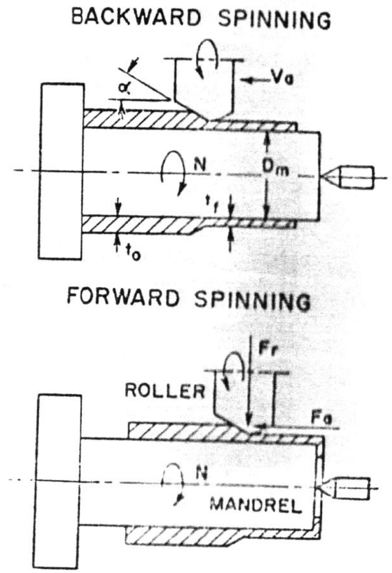

Figure 3 The Tube Spinning Process

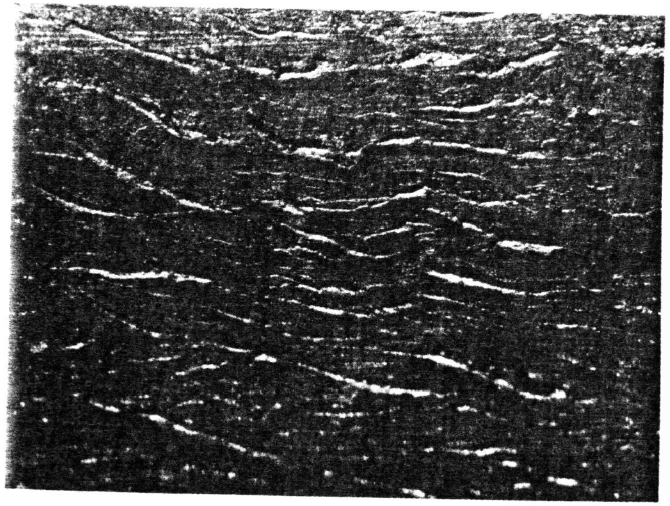

Figure 4 Circumferential Cracks on the Inside Surface of 7178 Aluminum Tube Spun at Less than 50 percent Reduction, (50X)

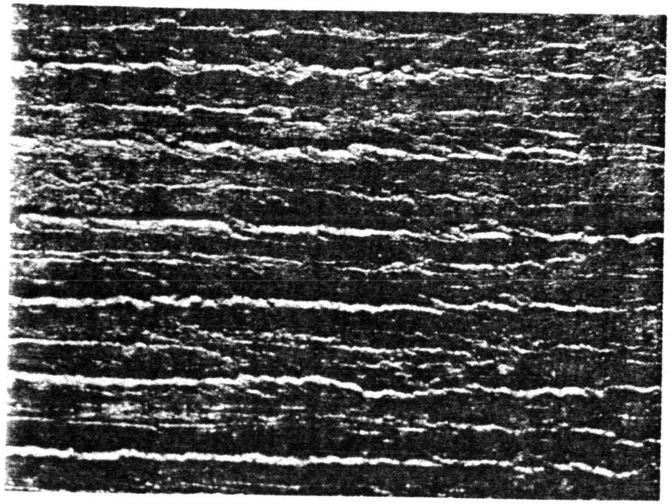

Figure 5 Cracks in M580 Aluminum Alloy Tube, (50X)

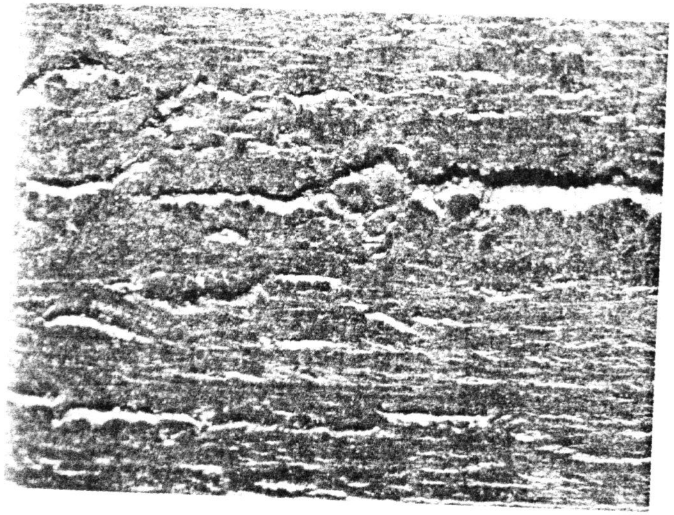

Figure 6 Cracks in 81B45 Steel Tube, (50X)

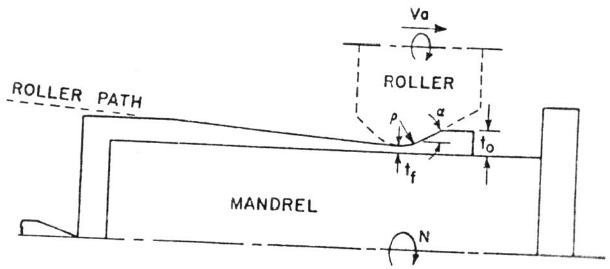

Figure 7 Test Setup to Subject Tubes to Continuously Increasing Wall Reduction by Spinning

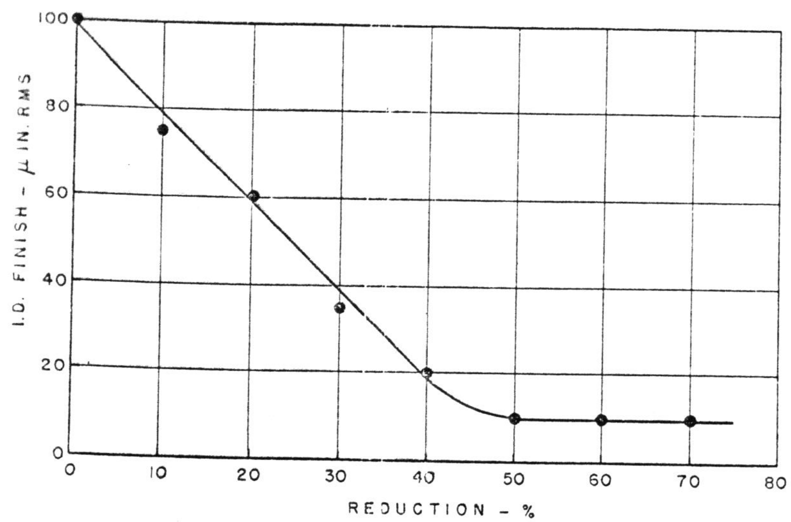

Figure 8 Dependence of Inside Surface Finish on Percent Reduction for Mild Steel Tube Spun on Test Setup Shown in Figure 7. Mandrel Surface Finish was 10 μin rms