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FRACTURE INITIATION AND PROPAGATION DURING STRIP DRAWING

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INTRODUCTION

During the drawing of metal strip a number of structural changes occur in the metal as they do during any deformation process. These include the generation of structural damage as well as the development of a crystallographic texture and a distinctive dislocation substructure [1-9]. By structural damage is meant the aggregate of voids and cracks initiated at second phase particles or inclusions. The degree of structural damage that is developed is a function of the particular process conditions under which the strip is drawn and the cleanliness or general second phase particle content of the material being drawn. Under some processing conditions in multipass drawing operations "arrowhead cracks", a series of internal macrofractures, are observed to develop. These are in essence the two dimensional analog of the fractures in "cuppy" wire described by Harris [10] and Boghen, et al [11] and are closely related to the "center bursts" observed in extrusion. The mechanism whereby this general type of fracture develops should be most easily deducible from a study of this phenomenon in strip drawing because of the greater simplicity of the two dimensional deformation and the relative ease of analysis compared with axisymmetric deformation processes.

EXPERIMENTAL PROCEDURE

The development of fractures of this type was studied in two different materials, 6061-T6 aluminum alloy and unleaded half-hard commercial alpha-beta brass, nominal composition 60 Cu-40 Zn. The aluminum alloy was picked because of the large number of second phase particles and the amount of previously obtained data on structural damage accumulation in this alloy. On the other hand, the brass contained a metallic second phase and had a lower rate of strain hardening. It was lead-free to eliminate the complicating factor of a wide distribution of soft lead particles. Strip drawing was carried out at room temperature under low friction conditions. No attempt was made to establish the exact boundary between conditions that lead to the formation of arrowhead cracks and those causing only structural damage in drawn strip. Neither were the limiting conditions determined where full development of arrowhead cracking occurred yet where none of these cracks propagated to cause complete fracture of the strip during drawing. A preliminary survey showed that drawing this brass at 25% reduction per pass (RPP) produced no outward evidence of progressive failure when dies having a 15° die semiangle were used but caused a substantial degree of arrowhead cracking when 30° dies were employed. The wide angle dies generate a significantly greater hydrostatic tension at the strip midplane during drawing [1]. This condition was chosen for the more detailed study of cracking in brass. Fracture during processing was also studied in the

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6061-T6 aluminum alloy during drawing at 34% RPP with dies having semi-angles of 30°.

RESULTS

At 25% RPP with 30° dies, the brass survived the first draw with no external evidence of internal fracture development. During the second pass, however, surface markings having the appearance of "stretcher-strains" in steel began to appear occasionally. They extend completely through the strip and are regions of localized necking. After the third pass, during which these markings, shown in Figure 1, became both more numerous and more pronounced, the average thickness of the strip was 0.0833 inch, but was as low as 0.0816 inch at some of the most severe areas of local strain. An attempted fourth pass resulted in fracture of the strip. Longitudinal sections were made at various locations across the width of this strip at least one of which included these markings. Outside the region of the strain markings the damage to the brass was found to consist primarily of a substantial density of voids near the midplane of the strip. These were frequently interconnected to form small longitudinal cracks. The voids and cracks were somewhat more severe in the region of the markings. When a section was taken directly through the strain markings, however, a series of large arrowhead fractures was evident, Figure 2, pointing in the drawing direction. Fracture of the strip was initiated at two nearby but offset arrowhead cracks which resulted in a stepped fracture front when viewed normal to the strip surface. The fracture edge consisted of two V-shaped grooves running normal to the drawing direction connected by a tear region to produce the step in the front. The V-shaped fracture edge was obviously the result of propagation of subsurface arrowhead cracks to the strip surface under the drawing stresses.

Extensive metallographic examinations of the series of 6061-T6 aluminum alloys, drawn under a wide variety of conditions where the stress state is severe, revealed a profusion of nuclei of these fractures at a much earlier stage in their development. One is shown in Figure 3. All tend to have some variation of the characteristic shape that is indicative of their method of formation. This shape very frequently is nearly symmetrical with respect to the front and the rear of the strip; such symmetry is also shown by an intermediate-sized nucleus in the brass; Figure 4. From the more well developed nuclei in these materials, it is obvious that the growth of these nuclei takes place in such a manner that eventually only the "ears" of a nucleus that are toward the back of the nucleus grow, the resultant internal crack taking on the appearance of an arrowhead pointing in the direction in which the strip is being drawn.

In more heavily drawn brass strip, not only is the appearance of the fracture nuclei asymmetric, but so also is the deformation. As the metal is increasingly deformed there is a tendency for the shear strains to become localized in fairly narrow bands of "heavy slip". These markings can be seen quite easily on visual observation of etched brass samples although they are somewhat difficult to photograph. The orientations of these local bands of heavy shear are such that they lie in directions that tend to parallel the two forks of the arrowhead cracks; that is to say, on either side of the center line the bands are oriented such that as the strip surface is approached, the markings tend to roughly parallel the die surface. From the symmetry of the deformation, one might expect that the bands from either side would disappear at the center line of the strip. In actuality, they appear to extend somewhat beyond the center line, producing a region where this strong localized shearing is taking place in

both directions. This is also shown in Figure 5 for brass, with the total picture shown schematically in Figure 6. The fact that the shearing strains tend to concentrate in bands oriented as described above is independent of the prior existence of fracture nuclei was shown by drawing under high pressure where fracture was prevented.

DISCUSSION

Any proposed mechanism for fracture or the production of macroscopic fracture nuclei during strip drawing must account for a number of experimental observations. The state of stress plays the major role in determining whether or not fracture will take place; intense local shearing is not in itself sufficient to initiate fracture. This is also confirmed by the shear strain distribution in less heavily deformed strips in which there is an obvious gradient of shear strain from the center to the edges of the strip, the center having had significantly less shear deformation. Despite the fact that the metal near the edge of the strip is undergoing greater shear deformation, the fractures are nucleated near the strip midplane where the stress state is primarily hydrostatic tension compared with hydrostatic compression directly under the die. It is also necessary to account for the distinctive shape of the fracture nuclei and the asymmetry of the growth of the fractures from these nuclei with respect to the direction of drawing of the strip. The role of hard inclusions or second-phase particles must also be established.

The proposed mechanism of fracture is as follows. Fracture initiation is primarily at inclusion-matrix interfaces, cracked inclusions or at pre-existing holes in the metal. Grain-boundary triple points are likely sites for the formation of oxides or other inclusions and also these regions lack deformation compatibility. Unless the local stress state is sufficiently compressive to suppress inclusion-matrix interface separation and prevent void growth, the voids, once nucleated, grow by a "ductile cracking" mechanism [12,13] aided by a tendency to increasing shear strain concentration with increasing cold-work. When the particles exist in groups, as is frequently found in wrought materials as a result of the elongation and possible disintegration of stringers during prior processing, the voids around such groups of particles will rapidly link up to form an especially elongated void. Since the overall strain pattern in strip drawing is one of decreasing thickness and increasing length, each individual void will be lengthening while the intervoid spacing in the thickness direction continues to decrease as deformation increases. There is evidence from the examination of transverse sections of drawn strips that there is also some lateral spreading of these voids. Between any two of these closely spaced, ribbon-shaped voids, then, there is a thin strip of metal which is not in fact exposed to the overall local triaxial stress state but which is constrained to elongate under a more or less uniaxial or biaxial tensile stress as the metal surrounding this pair of voids is deformed. This strip of metal then separates locally upon further eleongation of the strip by ductile cracking, by necking, or by a localized shearing. This is shown schematically in Figure 7 and is illustrated by the example in Figure 3.

The initial propagation of fracture from such a nucleus probably occurs in a more or less symmetrical manner, the four "ears" of the nucleus growing in the directions of maximum shear that result from the axial tensile stress. Continued symmetric growth cannot take place because of the asymmetric nature of the shearing strains in the outer regions of the strip. Hill [14] shows that there is an intense shearing of the metal in a direction opposite to the drawing direction as the metal enters the die, followed by a reverse shearing in the drawing direction as the metal leaves the die. Hence, when the "ears" of the nucleus begin to extend in a thickness direction beyond the central region where shearing is likely in either of the maximum shear stress directions, only along that direction on which the intense shearing takes place as the strip leaves the die do the "ears" continue to grow. As these "ears" change over into elongated cracks on further growth, they tend to concentrate the strain still further. This concentration of shear strain produces an observed re-orientation of the elongated voids existing in the path of the growing crack, aligning them along the shear direction and exposing them to axial tensions across their thickness. This further contributes to crack propagation. The "ears" then grow by a modified Mode II crack displacement with an increasing average tensile stress across the crack planes as the exit side of the die is approached. If the rate of growth of these cracks is stable, which it is in many instances since it is growing laterally in a region where the hydrostatic component of the stress tends to be increasingly compressive, then the metal will contain these arrowhead-shaped cracks if drawing is halted. Since the metal between the crack and the die cannot support a stress normal to the plane of the strip, it merely stretches to conform to the elongation of the sound metal surrounding it, the latter occurring with the aid of die pressure, however. This produces the observed "stretcher-strain" marks (Figure 1). If the rate of increase in tensile stress with deformation as a result of loss in cross-sectional area becomes sufficiently great in the remaining ligament, the result will be complete fracture of the strip by the further growth of the arrowhead cracks.

REFERENCES

1. ROGERS, H. C., LEECH, R. C. and COFFIN, Jr., L. F., Final Report, Contract NOw-63-0617-c, Bureau of Naval Weapons, July 1964.
2. ROGERS, H. C., LEECH, R. C. and COFFIN, Jr., L. F., Final Report, Contract NOw-65-0097-f, Bureau of Naval Weapons, November 1965.
3. ROGERS, H. C. and COFFIN, Jr., L. F., Final Report, Contract NOw-66-0546-d, Bureau of Naval Weapons, June 1967.
4. ROGERS, H. C. and COFFIN, Jr., L. F., CIRP Intern. Conf. on Manufacturing Technol., Ann Arbor, Mich., ASTME, Dearborn, Mich., 1967.
5. COFFIN, Jr., L. F. and ROGERS, H. C., ASM Trans., 60, 1967, 672.
6. ROGERS, H. C. and COFFIN, Jr., L. F., Int. Jnl. of Mech. Sci., 13, 1971, 141.
7. ROGERS, H. C., Final Report Contract N00019-68-C-0147, Naval Air Systems Command, March 1969.
8. ROGERS, H. C., "Metal Forming: Interrelation Between Theory and Practice", Plenum Press, New York, 1971, 451.
9. GUINDIE, A. T., M.S. Thesis, Drexel University, 1972.
10. HARRIS, F. W., Trans. AIME, IMD, 1928, 518.
11. BOGHEN, J., LEYMONIE, C. and HERENGUEL, J., Rev. Met., 60, 1963, 1241.
12. ROGERS, H. C., Acta Met., 7, 1959, 750.
13. ROGERS, H. C., Trans. AIME, 218, 1960, 498.
14. HILL, R., "The Mechanical Theory of Plasticity", Oxford Univ. Press, London, 1950, Chapter VI.

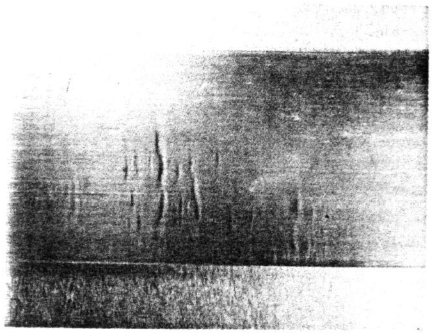

Figure 1 "Stretcher-strain" markings on strip of 60-40 brass after a total reduction of 56% using 30° dies and 25% reduction per pass. Full size.

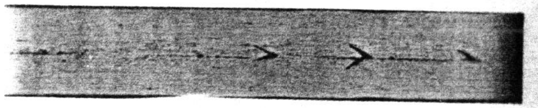

Figure 2 Longitudinal section through the brass strip shown in Figure 1. Direction of drawing is to the left. The surface strain markings are above the region of the internal fractures. 12.5x.

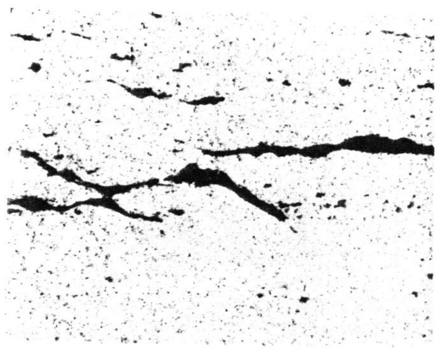

Figure 3 Fracture nucleus at an early stage of development in 6061-T6 aluminum alloy. Longitudinal section. Plane of strip horizontal. 465 X.

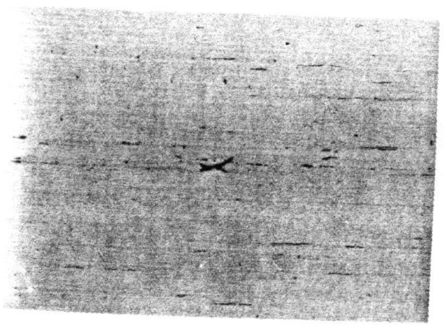

Figure 4 Fracture nucleus in a 60-40 brass strip drawn to 73% reduction at 28% reduction per pass, 30° dies. Longitudinal section. Plane of strip horizontal. As-polished. 50 X.

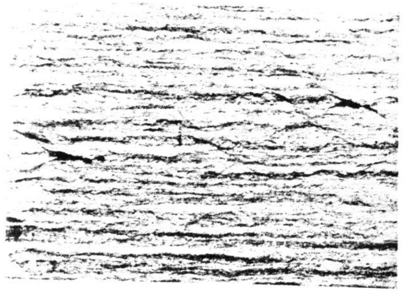

Figure 5 Localized shear bands or "heavy slip" in etched 60-40 brass. Cold drawn 73%. Strip midplane. Drawing direction to the right. 160 X.

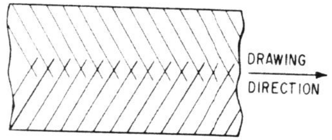

Figure 6 Schematic illustration of the orientation of localized shear bands in a heavily drawn strip.

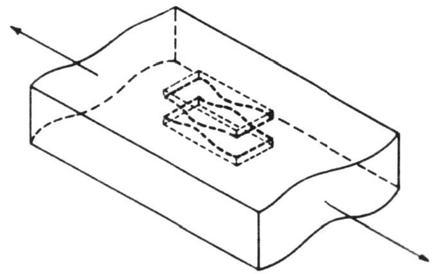

Figure 7 Schematic diagram of formation of a fracture nucleus in drawn strip.