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# ANISOTROPIC BEND DUCTILITY IN SINGLE-PHASE COPPER ALLOYS

P. Parikh and E. Shapiro*

## INTRODUCTION

The useful strength of strip, which is to be fabricated into formed shapes, is often limited by its bend formability. This is particularly true when cold rolling is employed for strengthening since cold rolling reduces bend ductility and induces bend anisotropy. Cold rolling causes both crystallographic texture and mechanical fibering, and therefore, both these factors are potential contributors to anisotropic ductility. This paper attempts to identify the source of bend anisotropy in single-phase, copper-base alloys.

Bend ductility is often defined by a minimum radius at which a bend can be made without fracture. To make a bend, a localized area is deformed around a radius. If the bend radius is decreased, strain at the outer fibers is increased until, at some limiting radius, fracture occurs. The strain required to cause fracture decreases with increasing width-to-thickness ratio until a plane-strain stress condition is reached at the centre of the bend [2]. Further increases do not affect ductility. The reduced ductility in plane strain is caused by the increased principal tensile stress component associated with this stress state [3, 4].

Texture, as described by the plastic strain ratio R, influences the principal tensile stress component also because it changes the shape of the yield locus [5, 6]. With increasing R value, the principal tensile stress component in plane strain increases rapidly in the bi-axial tension stress quadrant of the yield locus, "texture hardening" [5, 7]. Accordingly, bend ductility should be reduced as R value increases. Mechanical fibering is thought to reduce bend ductility by acting as a strain concentrator.

In order to separate mechanical fibering effects from crystallographic effects on bend anisotropy, bend ductility measurements on undirectionally rolled and cross-rolled sheet were compared. Cross-rolling gives the same grain-aspect ratio in both longitudinal and transverse directions. If mechanical fibering is controlling, cross-rolled sheet samples should not show directionality, but unidirectionally rolled samples will. Other experiments were conducted to assess the dependence of bend ductility on the principal tensile stress component. If texture controls anisotropy, bend ductility in the longitudinal and transverse directions should be a unique function of the principal tensile stress component in plane strain, but not in uniaxial tension.

## EXPERIMENTAL PROCEDURES

Three single-phase, copper-base alloys--alpha brass, tin bronze and aluminum bronze-- were chosen for study. Compositions in weight % are given

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*Olin Brass, Metals Research Laboratories, 91 Shelton Avenue, New Haven, Conn. 06504, U.S.A.

in Table 1. All these alloys develop the "brass" type rolling texture [8]. This texture provides a large anisotropy of R values [5]. The brass alloy was obtained commercially as hot rolled plate about 12.7 mm thick. The bronze alloys were cast and hot rolled in our laboratories. All alloys underwent several cycles of cold rolling and annealing before the final cold reduction. A portion of the metal was cross-rolled by alternating rolling between the longitudinal and transverse directions after 5% cold reduction in each direction. The designation longitudinal and transverse directions are relative to the hot rolling direction. The alloys were fully recrystallized to a uniform grain size of about 0.02 to 0.03 mm before the final cold reduction. Processing was controlled in order to maintain the same thickness (0.76 mm) even after different amounts of final cold reduction.

The wrap forming bend test was used to determine bend ductility. In this test, a series of samples are bent 90° around different die radii. The specimen, about 19 mm wide so that plane strain is achieved, is clamped against the die and is formed to the die radius by a mandel. The dies have radii between 0.4 mm to 12.7 mm; increments between die radii are given in Table 2. The bend surface is examined for cracks with a 20X eyepiece. The fracture radius is the largest radius at which cracks are observed.

R values were calculated from length and width measurements on a tensile specimen before and after straining according to the equation:

$$R = \ln w_f/w_o \Big/ (\ln l_o/l_f - \ln w_o/w_f) \qquad (1)$$

where $l_o$ and $w_o$ are initial length and width, and $l_f$ and $w_f$ are length and width after straining. Tensile specimens were machined with parallel sides and a reduced gage section 12.7 mm wide and 50.8 mm long. Microhardness indentations defined an original length and width within the reduced section. These were used to measure final length and width to ± 0.025 mm using a toolmaker's microscope. R value was determined after straining the specimen to a load level just below the maximum load to avoid necking yet maximize total strain. All tests were made at a constant cross head speed of 0.51 mm/min. An average of two measurements is reported for each alloy in each final cold rolled condition.

Plane-strain tension tests were performed according to the procedure of Lee and Backofen [9]. All tests were made at a constant cross head speed of 0.51 mm/min. Load versus displacement curves were recorded. The maximum load divided by the original area is reported here as ultimate plane-strain strength (UPSS). An average of two measurements is reported

## EXPERIMENTAL RESULTS

The aluminum bronze alloy was unidirectionally and cross-rolled to total cold reduction of 20% and 40%. Figure 1 plots the bend radius versus ultimate tensile strength; lines of approximately constant R value are indicated. Data for this figure are tabulated in Table 3. The higher R value conditions show lower bend ductility at a given strength level irrespective of the rolling technique employed.

Figure 2 plots the bend radius versus ultimate tensile strength for the brass and tin bronze each unidirectionally cold rolled various amounts.

Data for this figure are tabulated in Table 4. The bend ductility decreases and anisotropy increases with increasing tensile strength for both alloys. Figure 3 is a plot of bend radius versus ultimate plane-strain strength for the same conditions as in Figure 2. A unique curve for each alloy results irrespective of testing direction.

## DISCUSSION

The results support the view that crystallographic texture is the source of bend anisotropy in single-phase copper alloys. A quantitative relationship between bend ductility and ultimate plane-strain strength in the appropriate direction is indicated. In addition, these findings appear consistent with the effect of tensile stress state on ductility through true fracture work criterion of Cockcroft and Latham [3].

The increased bend anisotropy at higher cold reductions commonly observed for the more solute-rich (lower stacking fault energy) copper alloys is consistent with the development of a "brass type" deformation texture. We have not, however, attempted to use pole figures to quantify any relationship between the deformation texture and the measured R values. The R values are higher than those reported for annealed FCC metals, implying some contribution to anisotropic flow from non-crystallographic sources.

## CONCLUSION

Bend anisotropy in single-phase, cold rolled, copper alloys is attributed to crystallographic texture rather than mechanical fibering. The plastic strain ratio, R, can be used to account for crystallographic texture effects on bend ductility and anisotropy. Higher R values reduce ductility at a given strength level regardless of the state of mechanical fibering. This is due to the effect of texture on the magnitude of the principal tensile stress component in plane strain. Bend ductility is a unique function of this stress component.

## ACKNOWLEDGEMENT

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Table 1 Alloy Compositions

| Alloy | Composition by Weight Percent |
|---|---|
| Alpha Brass | 30% Zn, 70% Cu |
| Aluminum Bronze | 2.8% Al, 1.8% Si |
| Tin Bronze | 5.5% Sn |

Table 2 Die Radii Increments

| Die Radius, mm | Increments between Radii, mm |
|---|---|
| 0.2-3.2 | 0.4 |
| 3.2-4.8 | 0.8 |
| 4.8-12.7 | 1.6 |

Table 3 Bend Properties of Unidirectionally and Cross-Rolled Aluminum Bronze

| Condition | Orient. | Ultimate Tensile Stength, MPa | R Value | Bend Radius at 0.76 mm Gage in mm |
|---|---|---|---|---|
| A. Unidirectionally Rolled | | | | |
| 20% CR | Long. | 731 | 1.1 | 1.2 |
| | Trans. | 745 | 2.8 | 2.8 |
| 40% CR | Long. | 841 | 1.2 | 2.4 |
| | Trans. | 841 | 3.5 | 3.2 |
| B. Cross-Rolled | | | | |
| 20% CR | Long. | 696 | 1.2 | 1.6 |
| | Trans. | 717 | 1.8 | 1.2 |
| 40% CR | Long. | 821 | 2.5 | 3.2 |
| | Trans. | 772 | 1.2 | 1.6 |

Table 4 Bend Properties and Strengths of Alpha Brass and Tin Bronze

| Alloy | Condition | Orient. | UTS, MPa | UPSS, MPa | Bend Radius at 0.76 mm Gage in mm |
|---|---|---|---|---|---|
| Alpha Brass | 30% CR | Long. | 531 | 586 | 0.8 |
| | | Trans. | 538 | 634 | 1.2 |
| | 50% CR | Long. | 621 | 669 | 2.4 |
| | | Trans. | 655 | 751 | 4.8 |
| | 60% CR | Long. | 669 | 710 | 3.2 |
| | | Trans. | 703 | 779 | 6.4 |
| Tin Bronze | 40% CR | Long. | 607 | 669 | 0.8 |
| | | Trans. | 648 | 765 | 2.0 |
| | 60% CR | Long. | 717 | 758 | 1.6 |
| | | Trans. | 765 | 903 | 4.0 |

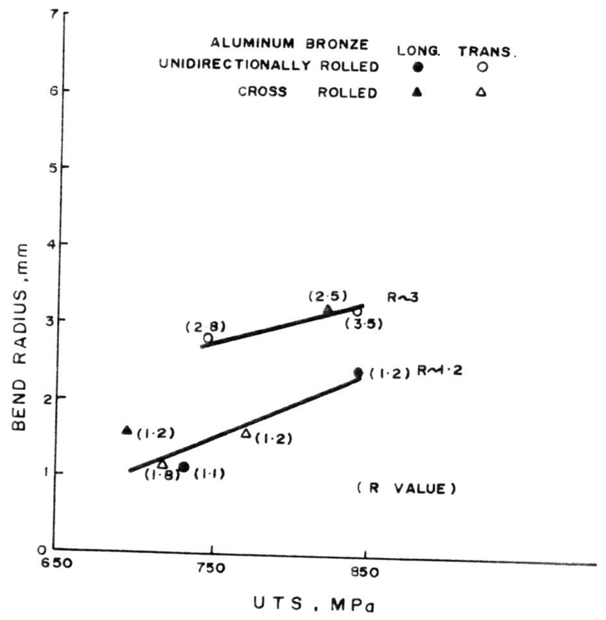

Figure 1 Bend Radius at Fracture Versus Ultimate Tensile Strength for Unidirectionally and Cross-Rolled Aluminum Bronze Showing Lines of Approximately Constant R Value. The Designation Longitudinal and Transverse Directions are Relative to the Hot Rolling Direction

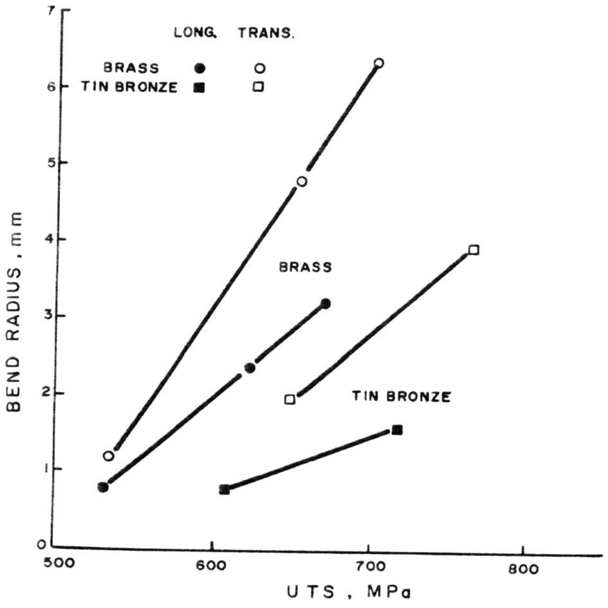

Figure 2 Bend Radius at Fracture Versus Ultimate Tensile Strength for Alpha Brass and Tin Bronze Showing Bend Anisotropy. The Designation Longitudinal and Transverse Directions are Relative to the Rolling Direction

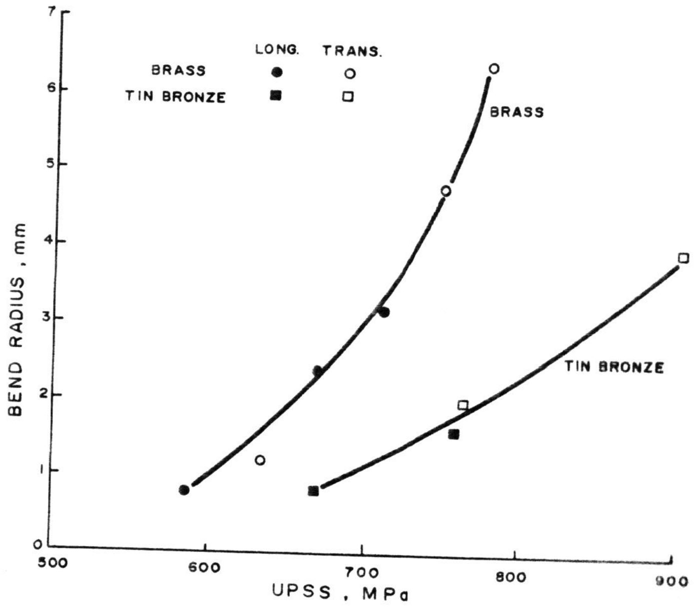

Figure 3 Bend Radius at Fracture Versus Ultimate Plane Strain Strength for Alpha Brass and Tin Bronze Showing a Unique Curve for Each Alloy. The Designation Longitudinal and Transverse Directions are Relative to the Rolling Direction