

Relationship Between Crystal Orientation and Stress-Corrosion Cracking in Alpha and Beta Brasses

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The crystallographic planes bounding intercrystalline stress corrosion cracks in two large-grained Alpha brasses and those followed by transcrystalline stress-corrosion cracks in large-grained beta brass were determined by X-ray diffraction methods. Intercrystalline stress-corrosion cracking in the alpha brasses originated between grains that, because of their relative orientation, had high interfacial energy contents. It is the relative orientation, not the crystallographic type, that determines the susceptibility to stress-corrosion cracking of alpha brass in grain boundaries approximately normal to the applied stress. Transcrystalline stress-corrosion cracking of beta brass occurred in grains that were oriented most favorably for slip, and in planes that were approximately normal to the applied stress. No plane or family of planes in beta brass was found to be particularly susceptible to stress-corrosion cracking. It is postulated that in each case cracking progressed by a film rupture mechanism.

1. Introduction

Stress-corrosion cracking, or season cracking, in brass was first reported in 1906 [1].¹ It has been the subject of many investigations and several comprehensive bibliographies have been published [2, 3]. The study of the stress corrosion of brass is particularly important from a mechanistic point of view because stress-corrosion cracking is predominantly intercrystalline in the face-centered alpha brass and mainly transcrystalline in the body-centered, ordered beta brass.

If corrosion occurs in unstressed alpha brass, it is generally of the pitting type; only two reports [4, 5] of intercrystalline corrosion have come to the author's attention. However, if the material is exposed under sufficiently high residual or applied tensile stress in an atmosphere containing ammonia and water vapor (the specific corrodent for brass), predominantly intercrystalline stress-corrosion cracks will develop.

An excellent discussion of the mechanism of stress corrosion in alpha brass was presented by Read, Reed, and Rosenthal [6] at the ASTM-AIME Symposium on Stress Corrosion in 1944. Read et al proposed the hypothesis that the grain-boundary regions in this brass have higher energy contents than the grain interiors, and therefore the grain boundaries have a greater susceptibility to corrosion. These workers discounted the possibility of a grain-boundary precipitate but suggested that lattice imperfections may explain the higher energy at the grain boundaries. In 1950 Robertson [7] suggested that relative grain orientation could be a factor in materials susceptible to intercrystalline stress-corrosion cracking. So far as the author knows, explanations of the mechanism of the transcrystalline stress-corrosion cracking of beta brass have not reached the same stage of development as those for alpha brass.

Following World War II a great deal of interest developed in the study of metal boundaries or inter-

faces and the results of a number of investigations were summarized in a symposium, "Metal Interfaces" [8], published in 1952. In this symposium it was pointed out that interfacial or grain-boundary energy is a function of the difference in orientation between the grains [9]. A number of investigators have shown that the interfacial energy increased to maximum values with increased difference in angular orientation between pairs of crystals for angles ranging from 12° for tin [10] to 29.8° for an iron-silicon alloy [11]. If the grain-boundary energy, and therefore the chemical activity of grain boundaries in alpha brass, increases with increased difference in orientation of adjacent grains, it is to be expected that the probability that a stress-corrosion crack would develop at a particular grain boundary would depend on the relative orientation (or degree of misfit) of the crystals meeting at that boundary. Cracks should occur most frequently between crystals whose relative orientations were in the range in which maximum grain-boundary energies have been obtained for other metals and may be expected for brass.

It is postulated that there is a greater probability of corrosive attack at the grain boundaries having the highest interfacial energies than at other points on the surface of the brass. The corrosive attack at these grain boundaries would form sharp notches. Those notches that were most favorably oriented with respect to the stress pattern in the metal would then act as points of stress concentration that would produce eventual rupturing of the protective film on the metal at the root of the notch. Stress-corrosion cracking would then proceed by a film-rupture mechanism, as discussed in an earlier paper [12].

As a part of the current study of the mechanism of stress-corrosion cracking, the crystallographic planes bounding stress-corrosion cracks at their origin and the angles between the crystallographic planes in the crystals on opposite sides of stress-corrosion cracks have been determined for specimens of two compositions of alpha brass.

¹ Italic figures in brackets indicate the literature references at the end of this paper.

It is generally accepted that, in the two-phase alloy, stress-corrosion cracks will be intercrystalline in the alpha phase and transcrystalline in the beta phase. The stress corrosion of beta brass has not been as extensively studied as that of alpha brass. However, from the observations of stress-corrosion cracking in the two-phase system it has generally been considered that stress-corrosion cracking would be transcrystalline in a single-phase beta alloy. As a part of a study to determine why stress-corrosion cracking was intercrystalline in alpha brass and transcrystalline in beta brass, the crystallographic planes on which the transcrystalline stress-corrosion cracks had their origin were also determined for several specimens of large-grained beta brass.

2. Materials and Experimental Procedure

The two alpha brass alloys studied had the nominal compositions of 90 percent Cu-10 percent Zn (commercial bronze) and 70 percent Cu-30 percent Zn (cartridge brass). The beta brass had a composition of approximately 50 percent Cu-50 percent Zn. Ingots of these alloys approximately 1 by 1 by 8 in., cast in sand molds, had grain diameters ranging from $\frac{1}{8}$ to $\frac{1}{4}$ in. Sections containing equiaxial crystals were selected from these ingots for this investigation. In addition to these three cast alloys, large-grained specimens of the 90 percent Cu-10 percent Zn alloy were prepared by the strain-anneal method and were also used in this investigation.

Specimens having the shape and dimensions shown in figure 1 were machined from the ingots and the

rod. The flat surfaces of the specimens were repeatedly polished (using 000 metallographic polishing paper) and etched until Laue back reflection X-ray patterns indicated that the surfaces were free from cold-work. The end sections were then coated with a waterproof lacquer, leaving only the central 2 in. exposed to the corrosive medium. The specimens were loaded in tension under a stress of 5,000 to 6,000 lb/in.² and exposed in an atmosphere containing ammonia, water vapor, carbon dioxide, and air until stress-corrosion cracks appeared. Two surfaces, at right angles to each other, of a specimen of alpha brass containing stress-corrosion cracks are shown in figure 2.

To determine the crystallographic plane or planes bounding or followed by stress-corrosion cracks, the cracks studied should extend continuously from one surface of the specimen into an adjoining surface at right angles to the first. It is also necessary that the two crystals bounding the crack be continuous, so that surfaces A_1 and A_2 , figure 3, be surfaces of the same crystal machined at right angles to each other. Laue back reflection X-ray photographs were made of the crystal surfaces A_1 and A_2 of crystal A and projections of these surfaces, relative to their respective cubic axes, were plotted on stereographic nets, using the method described by Greninger [13]. The plot of surface A_2 , figure 3, was rotated through 90 deg about the N-S axis of the net, and the net was then superimposed on that for surface A_1 . If the cubic poles of the two nets coincided (within the experimental error), the surfaces A_1 and A_2 were

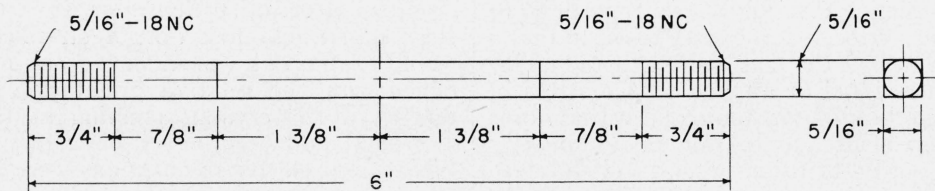


FIGURE 1. Stress-corrosion specimen.

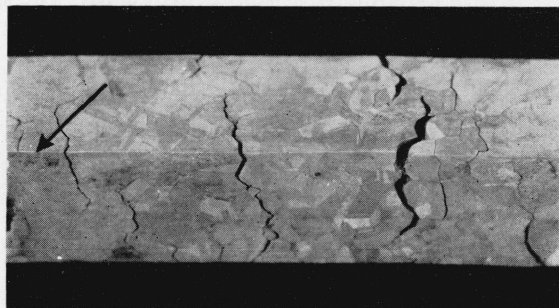


FIGURE 2.—Specimen showing stress-corrosion cracks extending from the corner (marked by arrow) into the adjoining surfaces of specimen. $\times 2$

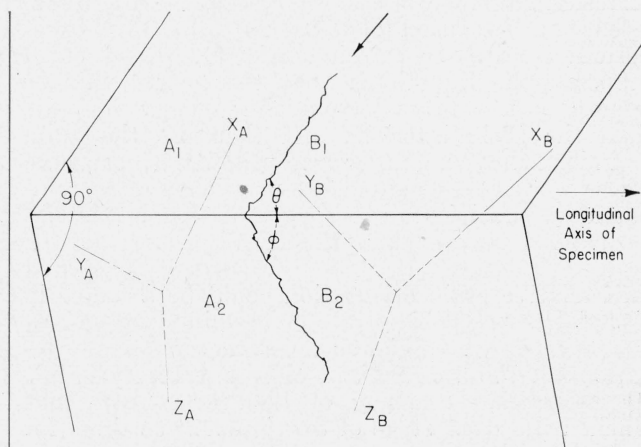


FIGURE 3. Schematic drawing of crystals A and B with stress-corrosion crack (indicated by arrow) making an angle θ with corner of specimen in face 1 and angle ϕ in face 2.

Rectilinear axes corresponding to cubic poles are indicated by X_A , X_B , etc.

considered to be faces machined normal to each other from crystal A. In the study of intercrystalline cracking a similar check was made on crystal B. The angles, θ and ϕ that the stress-corrosion cracks made with the common edge of the specimen were determined on surfaces 1 and 2, respectively, with a toolmaker's microscope. These angles then being known, the traces of the stress-corrosion crack could be plotted on the stereographic projections for the two surfaces of the crystals [14], and the normal to the plane of fracture could also be plotted on each projection.²

In order to determine the difference in orientation between the two crystals bounding intercrystalline stress-corrosion cracks, the angles between the cubic poles³ and the normals to the planes of fracture in the two crystals were measured using a Wolf net. From these data the normals to the plane of fracture in any crystal could be plotted in a single 100, 110, 111 stereographic triangle, and if the fracture was intercrystalline the angle between the normals to the planes bounding the fracture was determined.

3. Results and Discussion

The corners of the specimens were points of stress concentration and examinations of the specimens indicated that stress-corrosion cracks originated there. This fact and the rectangular cross section of the specimens made possible the determination of the crystallographic plane or planes followed by or bounding the stress-corrosion cracks.

3.1. Alpha Brass

The orientations of the planes bounding 13 intercrystalline stress-corrosion cracks in 70-percent-Cu-30-percent-Zn brass and 11 cracks in 90-percent-Cu-10-percent-Zn brass were determined. Data were obtained from four different specimens of each alloy, each of which contained more than one

² The normals plotted on the projections for surface 2 of crystals A or B must be brought into coincidence with those on surface 1 by the same rotation that will bring the cubic poles into coincidence. In the case of intercrystalline fractures, if the projection for surface 1 of crystal A is superimposed on that for surface 1 of crystal B so that their N-S poles, previously aligned with a fixed point on the specimen (longitudinal axis), coincide, the normals to the fractured surface will also coincide; similar results are also obtained for surface 2. It is thus seen that there is no ambiguity as to the normal to the plane of the stress-corrosion crack.

³ The cubic poles of crystal A are designated orthogonal axes X_A, Y_A, Z_A , and the angles between the normal and these poles are designated P_x, P_y , and P_z , respectively. Angles determined on face 1, designated P_{z1} , etc., were checked by the determination of angles on face 2 designated P_{z2} , etc. As a further check use was made of the expression

$$|\cos P_{z1} \cos P_{z2}| + |\cos P_{y1} \cos P_{y2}| + |\cos P_{x1} \cos P_{x2}| \pm \Delta = 1$$

Δ was the cosine of the angle of closure; if it were larger than 0.010 it indicated the need for rechecking the measurement of the angles. An average value for P_x , etc., could then be obtained as follows:

$$\cos P_x = \pm \sqrt{|\cos P_{z1} \cos P_{z2}| \pm \Delta / 3}$$

The angles for crystal B could be similarly determined and designated Q_x , etc. The angle, a , between the crystallographic planes on opposite sides of the fracture can then be determined analytically (providing P_x, P_y, Q_x, Q_y , etc., are selected in the order of decreasing magnitude of the angles for each crystal) from the following expression:

$$\cos a = |\cos P_x \cos Q_x| + |\cos P_y \cos Q_y| + |\cos P_z \cos Q_z|$$

In the cubic system a unique solution for the angle between two crystallographic planes generally cannot be obtained. The angle determined either graphically or analytically by the methods described above is the smallest angle between the two planes.

stress-corrosion crack. The results, plotted in a single stereographic triangle, are shown in figure 4.

The crystal boundaries and the consequent intergranular cracks do not necessarily follow the same crystallographic planes throughout their entire lengths. Hence at different points on the boundary between two crystals the bounding planes may be different. In this investigation the bounding crystallographic planes were determined not only at the incidence of cracking but also at some other points along the continuous path that was representative of the general path or trend of the crack between the same two crystals. Poles of the latter planes were distributed in the same general way as those shown in figure 4. The distribution of the normals to all of these planes both at the incidence and along the general path of the crack is random. These data definitely indicate that it is the angle at which the crystallographic planes intersect that determines the susceptibility of a particular grain boundary, in alpha brass, to the development of stress-corrosion cracks.

The angles between the crystallographic planes in the paired crystals of the two alloys, determined by the methods described above, are given in table 1. Values were rounded to the nearest degree and are given in order of increasing magnitude.

For more than 70 percent of the cracks studied, the angles between bounding crystallographic planes at the origin of cracking were in the range of 13° to 23°, inclusive; the minimum angle for all the pairs of crystals studied was 8°. Angles of 13° to 23° are in the range in which maximum grain-boundary energies have been reported for the face-centered metals silver [15] and lead [16], as well as for tin [10] and an iron-silicon alloy [11].

No experimental data for brass have come to the author's attention; however, a value of 22.2° has been reported for copper [17]. The data indicate that the intercrystalline stress-corrosion cracking in

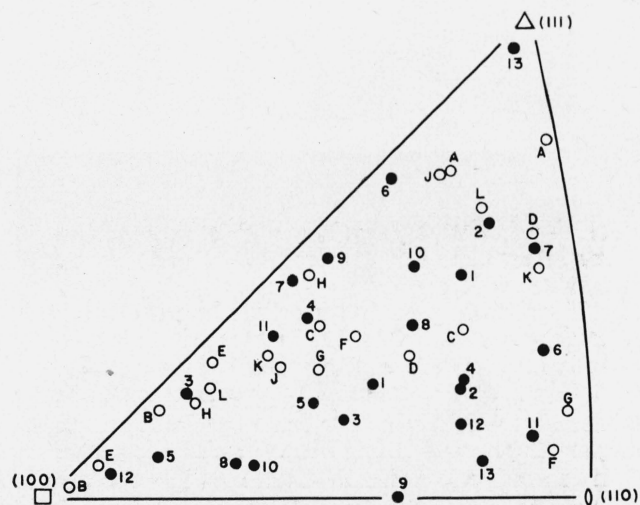


FIGURE 4. Locations of normals to planes along which the stress-corrosion cracks originated.

●, 70% Cu-30% Zn brass; ○, 90% Cu-10% Zn brass. Numbers or letters correspond to crystal pairs given in table 1.

TABLE 1. Angles between crystallographic planes bounding stress-corrosion cracks and resolved tensile stresses on planes of crack, as a fraction of the applied tensile stress

70% Cu-30% Zn			90% Cu-10% Zn		
Crystal pair ^a	Angle between crystallographic planes	Resolved tensile stress	Crystal pair ^a	Angle between crystallographic planes	Resolved tensile stress
	deg			deg	
1.....	11	0.891	A.....	8	0.834
2.....	13	.903	B.....	11	.976
3.....	13	.629	C.....	11	.961
4.....	14	.917	D.....	13	.804
5.....	14	.982	E.....	14	.978
6.....	18	.917	F.....	18	.927
7.....	19	.966	G.....	20	.998
8.....	19	.895	H.....	20	.879
9.....	21	.991	J.....	21	.903
10.....	21	.819	K.....	23	.968
11.....	23	.760	L.....	26	.951
12.....	30	.438			
13.....	32	.946			

^a Numbers or letters correspond to poles shown in figure 4.

alpha brass is associated with grain boundaries that may be expected to have high energy contents.

It is suggested that in an environment containing the ammonium ion, galvanic cells will be set up with the high-energy grain boundaries as the anodes and the grain faces or other lower-energy areas as the cathodes. The circuits are completed through the interior of the alloy. The metal will be dis-

solved at the grain boundary anodes and the resulting pits will have the appearance, in cross section, of sharp notches with their apexes on the grain boundaries. On the exposed surfaces of the grains the ratio of anodic to cathodic areas will generally be much larger than those of the grain boundary areas to their cathodes. Hence pits formed on the exposed surfaces of the grains will be much shallower and will have a more rounded cross section than those formed at grain boundaries. In the absence of stress, pitting in either case will become more or less self-limiting, because of polarizing effects, and inter-crystalline corrosion extending to any appreciable depth will be extremely rare. On the other hand, sharp notches centered on grain boundaries and favorably oriented with respect to either residual or applied tensile stress patterns will act as regions of stress concentration. As the notches become sufficiently deep or the stresses sufficiently high, the protective film on the brass at the roots of the notches will be ruptured, exposing metal that has an electrochemical-solution potential approximately $\frac{1}{2}$ v more negative than the metal covered with an atmospherically formed film or with corrosion products [12]. The unfiled, or unprotected, metal will corrode rapidly until failure occurs or until polarizing effects or shifting stresses permit reforming of the protective films. Corrosion will then be general until stress concentrations again rupture the protective film.

In experimental confirmation of this theory, tensile

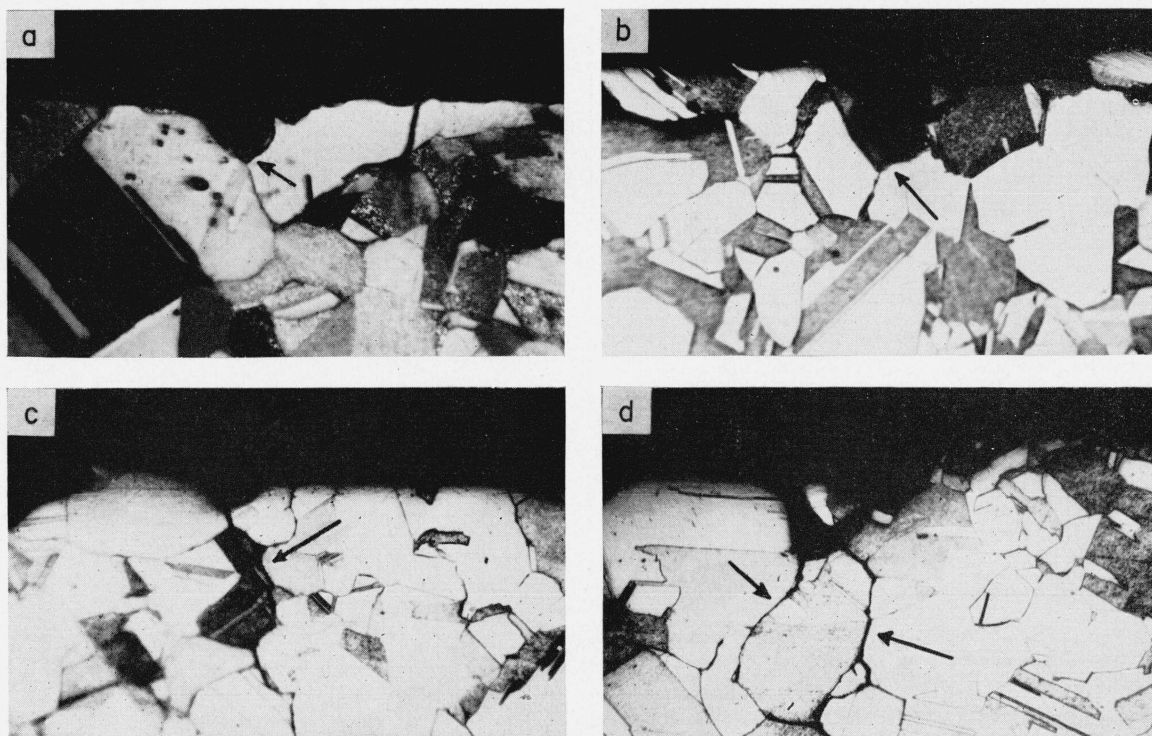


FIGURE 5. Development of a stress-corrosion crack.

Photomicrographs a and b, pits (marked by arrows) developing at grain boundaries. Photomicrographs c and d, intercrystalline stress-corrosion cracks (marked by arrows) extending into the metal from the roots of cracks. Etched with $\text{NH}_4\text{OH} + \text{H}_2\text{O}_2 + \text{H}_2\text{O}$.

× 250

specimens of fine-grained cartridge brass were exposed under a tensile stress of approximately 45 percent of the yield strength in an ammonia, carbon dioxide, water vapor, and air atmosphere for periods ranging from 2 to 8 hr. Specimens exposed for 2 to 4 hr contained pits with their apexes at grain boundaries, as is shown in figure 5, a and b. The first evidence of stress-corrosion cracks was found in specimens exposed for 6 hr. These cracks extended from the roots of pits into the alloy along the grain boundaries in some of these specimens (fig. 5, c and d).

The residual stresses in the large-grained specimens of alpha brass were believed to be extremely small. The resolved tensile stresses on the planes of the stress-corrosion fractures were computed as fractions of the applied tensile stress and are given in table 1. It is seen that for most specimens the resolved tensile stress was 85 percent or more of the applied stress. Thus, the stress patterns were generally in such directions as to produce stress concentrations at the roots of notches formed by the corrosive process. This satisfied one of the conditions for the propagation of stress-corrosion cracks.

There was no appreciable difference between the results obtained on the cast and fully annealed wrought specimens of the 90-percent Cu-10-percent Zn alloy from the same heat.

3.2. Beta Brass

Eighteen crystals of beta brass (from four specimens) containing 47 transcrystalline stress-corrosion cracks were studied. The normals to the crystallographic planes on which these cracks were believed to have originated were determined and are plotted in a single stereographic triangle in figure 6. It is seen from these data that there is no plane or family of planes in beta brass that is particularly susceptible to stress-corrosion cracking.

If the stress-corrosion cracking of beta brass is associated with the rupture of the protective film, as is believed to be the case for alpha brass, it must be associated with either elastic or plastic deformation of the material. Webb [18], Rinehart [19] and Good [20] have shown that single crystals of beta brass are very anisotropic in the elastic range. Young's modulus is 8.2 times as great in the [111] direction as in the [100] direction, and the shear modulus is 12.8 times as great in the [100] direction as in the [111] direction. It was also shown that there is a linear relation between $1/E$ or $1/G$ and $f(l, m, n)$, where $f(l, m, n) = (l^2m^2 + n^2m^2 + n^2l^2)$ and $l, m,$ and n are the direction cosines of the normals to any crystallographic plane with respect to the cubic axes. The values of $1/E$ and $1/G$ have been computed for both the directions parallel to the stress axis and those normal to the transcrystalline stress-corrosion cracks studied and are given in table 2. It is recognized that, because of the restraining effects of the neighboring crystals, the strain produced in a given crystallographic direction in a crystal in a polycrystalline aggregate may be different from that calculated for a single crystal.

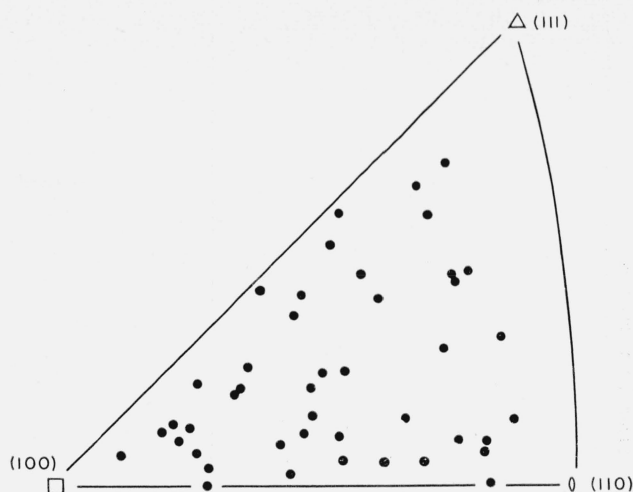


FIGURE 6. Normals to planes containing transcrystalline stress-corrosion cracks in beta brass.

Data obtained at the Bureau indicated, however, that there was greater elastic tensile strain for a given stress in polycrystalline grains of cast beta brass, oriented so that the [100] directions were closer to the tensile axis, than for grains with the [100] directions oriented 10° or more from that axis. Most of the crystals studied in this investigation, however, were so oriented that the [100] directions made angles greater than 10° with both the tensile axis and the normals to the planes of fracture. Hence, the possibility of microscopic plastic deformation by slip was considered. The critical shear stress for slip may be defined as $\tau = \sigma \cos \phi \cdot \cos \lambda$, where σ is the applied stress, and ϕ and λ are the angles between the direction of the applied stress and the slip plane and the slip direction (in the slip plane), respectively. Slip in beta brass has been reported [21] to occur on the (110) planes in the [111] direction. The angles that both the tensile axes and the normals to the planes, on which the stress-corrosion cracks were believed to originate, made with the various (110) planes and the [111] directions (lying in the respective (110) planes) were measured for each crack studied. The products of the cosines of these angles were determined for each pair of angles for each stress-corrosion crack, and the maximum value or values are given in table 2. The values obtained for the normals to the planes upon which stress-corrosion cracking originated are plotted in figure 7. There were also available orientation data for 81 large crystals in two polycrystalline beta brass tensile specimens. The values of the product $\cos \phi \cdot \cos \lambda$ (with respect to the tensile axes of the specimens) were determined and are also plotted in figure 7. If the probability of slip in a given crystal increases as the value of $\cos \phi \cdot \cos \lambda$ approaches 0.5, it is seen that there is a greater probability of slip in the crystals containing stress-corrosion cracks than in the randomly selected crystals in the tensile specimens.

A study of the data in table 2 indicates that in many cases both the probability of slip ($\cos \phi \cdot \cos \lambda$)

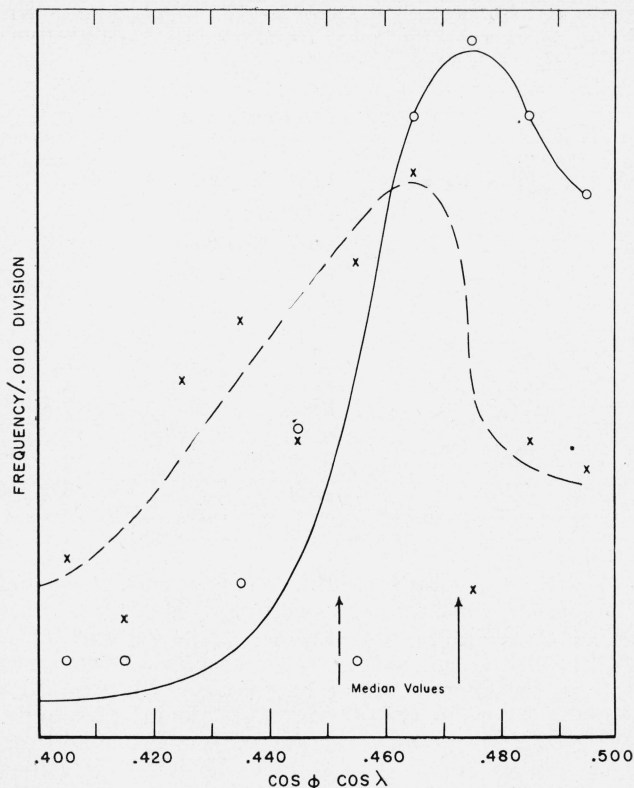


FIGURE 7. Frequency distribution of the product $\cos \theta \cos \lambda$.

Values from table 2 are weighted so that they can be plotted on the same scale as data from randomly distributed crystals. ϕ = angle between normal to slip plane and stress-corrosion crack; λ = angle between the normal to stress-corrosion crack and the slip direction lying in the slip plane. Critical resolved shear stress = $\sigma \cos \phi \cos \lambda$. O, crystal containing stress-corrosion cracks; X, randomly distributed crystals.

and the reciprocal of the shear modulus (shear strain per unit shear stress) are large not only for stresses parallel to the stress axis but also for those normal to the stress-corrosion crack. Generally, in other cases, if one of these values is small the other is large.⁴

Smith [22] found experimentally that the grain-boundary energy of beta grains in an alpha-beta brass is only about three-quarters that of the alpha boundaries. If the grain-boundary energy in this alloy increases with increased difference in orientation of the crystals, as has been shown for certain other metals, it may be expected that pitting will occur at certain high-energy boundaries more readily than on grain surfaces. Hence, some stress-corrosion cracks may be expected to originate at grain boundaries in the beta brass by the same process described for alpha brass. Metallographic examinations at the Bureau showed that a small percentage of the stress-corrosion cracks do originate at grain boundaries. However, these become transcrystalline before they have penetrated to the depth of a full grain into the metal. Evidently factors other than high-energy grain boundaries determine the

⁴ In crystal 9 both $\cos \phi \cos \lambda$ and $1/G$ are small; however, $1/E$ has a value of $3.65 \text{ cm}^2/\text{dyne} \times 10^{-12}$. It is suggested that in this case the film rupture resulted from elastic tensile strain.

paths followed by stress-corrosion cracks in beta brass.

It is postulated that regions of stress concentration produced by pitting corrosion (or in a few instances by grain-boundary attack) in beta brass nucleate microscopic slip in the suitably oriented crystals. This slip ruptures the protective film (formed in the atmosphere or in the corroding medium) exposing narrow areas of film-free metal that are anodic to the film-covered metal, and stress-corrosion then progresses as was indicated for alpha brass. In further support of this thesis it should be noted that plastic deformation has been reported [23] and shown [24] to be associated with the transcrystalline stress-corrosion cracking of magnesium alloys. In the Bureau, slip lines have recently been found associated with transcrystalline stress-corrosion cracking of type 304 stainless steel.

4. Summary

The crystallographic planes followed by stress-corrosion cracks in beta brass and the angle between the planes in the crystals on either side of the intercrystalline cracks in alpha brass were determined by X-ray diffraction methods for specimens of beta brass and two compositions of alpha brass.

The crystallographic planes bounding intercrystalline stress-corrosion cracks in alpha brass and on which the stress-corrosion cracks originated in beta brass were randomly distributed. There was no plane or family of planes that was particularly susceptible to stress-corrosion cracking.

About 70 percent of the stress-corrosion cracks studied in alpha brass originated between crystals in which the bounding planes were oriented at angles of 13° to 23° to each other. This is the range in which the maximum interfacial energies have been reported for other materials. It is suggested that in a corroding medium the grain boundaries having the highest energies become the loci of pits. In the absence of stress these pits are most probably self limiting, but with the application of favorably oriented tensile stresses they act as areas of stress concentration that may produce rupture of the normal protective film at the roots of the pits. This film-free metal is rapidly attacked and early intercrystalline failure of the metal may result.

Assuming that there is a critical resolved shear stress for slip in beta brass, it was shown that there was a greater probability of slip occurring in crystals containing transcrystalline stress-corrosion cracks than in randomly distributed crystals. It is postulated that in a corrosive medium, microscopic slip, most probably nucleated by pitting, ruptures the protective film on the surface of the metal. The film-free metal is rapidly attacked and transcrystalline failure of the brass results.

The resolved tensile stresses normal to the stress-corrosion fractures were generally 80 percent or more of the applied tensile stresses in both the alpha and beta brasses, thus indicating that these stresses were favorably oriented for the propagation of stress-corrosion cracks.

TABLE 2. Probability of slip, $f(\cos \phi, \cos \lambda)$ and reciprocals of elastic and shear moduli of stresses applied along the stress axis and normal to transcrystalline stress-corrosion cracks in beta brass. $f(\cos \phi, \cos \lambda) = \cos \phi \cos \lambda$ where ϕ and λ are angles between the stress axis (or ϕ' , λ' , normal to the fracture) and the slip plane and slip direction respectively

Crystal	Stress parallel to tension axis			Angle between tension axis and normal to stress corrosion crack	Resolved tensile stress normal to stress corrosion crack	Stress normal to stress-corrosion crack		
	$\cos \phi \cos \lambda$	$1/E$	$1/G$			$\cos \phi' \cos \lambda'$	$1/E$	$1/G$
		$cm^2/dyne$	$cm^2/dyne$	deg			$cm^2/dyne$	$cm^2/dyne$
1	0.455	1.24×10^{12}	4.64×10^{12}	38	0.788	0.481, 0.476	3.37×10^{12}	1.35×10^{12}
				21	.934			
				11	.982			
2	.462	1.43	4.33	22½	.924	.500	1.97	3.45
				26	.899			
				15	.966			
				13	.974			
3	.496	3.00	1.90	17	.956	.447	2.85	2.30
				6½	.994			
				14½	.968			
				19	.946			
				23	.921			
4	.406	.79	5.25	41	.755	.447	3.73	2.35
				21½	.930			
5	.495	3.01	1.90	35	.819	.370	.87	5.08
				38	.788			
				37½	.793			
				14	.970			
				24½	.910			
				17½	.954			
6	.470	3.55	1.08	18	.951	.489	2.53	2.60
				5½	.995			
				11	.982			
7	.379	.48	5.75	12	.978	.404	1.28	4.55
8	.463	3.46	1.20	23	.921	.475	1.57	3.95
				14½	.968			
9	.419	3.65	0.85	9½	.986	.487, 0.483	3.30	1.45
				18	.951			
10	.477	2.86	2.12	19½	.943	.438	1.15	4.73
11	.489	1.68	3.95	18½	.948	.464	1.23	4.65
				8	.990			
				8½	.989			
				11½	.980			
				12½	.976			
12	.454	3.53	1.10	25½	.903	.473	3.25	1.55
13	.491	2.98	1.93	27	.891	.464	2.23	3.08
				24	.914			
14	.413	2.57	2.56	15	.966	.468	1.42	4.37
15	.459	3.68	0.85	32	.848	.442	1.40	4.37
16	.408	1.30	4.50	34	.829	.410	.97	5.00
17	.484	2.80	2.20	34½	.824	.457	1.37	4.40
18	.487	2.93	2.00	17	.956	.482	1.50	4.20

* In those cases where two values were approximately the same both are given.

5. References

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