Orientation dependence of stress corrosion crack in cold rolled alpha brass

S. BANERJEE and P. BANERJEE

SYNOPSIS

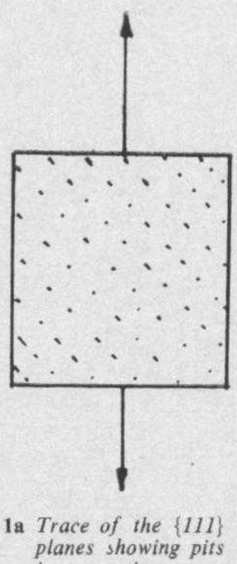
In moist ammonia atmosphere rolled alpha brass specimens under tensile load show the profile of fracture in a definite inclined plane to the direction of stress. This is related with the appearance of pits on the {111} planes in which resolved shear stress is maximum. A direct metallographic evidence has been obtained on the parallel arrangements of dislocation pits along the traces of {111} planes meeting the rolling plane {110}, which are the most susceptible sites for corrosion, supporting the recent hypotheses.

INVESTIGATIONS on susceptibility of 70-30 brass or cartridge brass to stress corrosion failure commonly known as season cracking was studied even before 1914.[1] Up to date the phenomenon has been investigated in its various aspects, namely (a) determination of the stress corrosion behaviour of 70-30 brass in various media, under different conditions of temperature, stress and strain,[1,2,3,4,5,6] (b) under various metallurgical conditions such as work hardening, heat treatment, grain coarsening and refining and alloying.[5,7] The results so far indicate that (i) ammonium atmosphere in presence of moisture is the most harmful environment, (ii) susceptibility decreases with increase in cold work beyond a minimum amount as well as with grain refinement for uniaxially loaded specimens, and (iii) small addition of individual elements such as Si, Ba, Mg, As, P increases the resistance to stress corrosion failure. Various hypotheses have been proposed to explain the phenomenon of stress corrosion failure of alloys. Some of them have been confirmed experimentally. A large number of investigators have studied the phenomenon in diverse alloys at different periods starting from as early as 1918. The knowledge is not yet complete to formulate a general theory to explain the phenomenology of stress corrosion failure of alloys. There is a general agreement that pure metals are not susceptible to stress corrosion failure,[8] and the failure is due to the combined effects of corrosion and stress. The confusion and disagreement lie in the share of responsibilities of the two agents, corrosion and stress, in the initiation and propagation of the crack resulting in fracture.

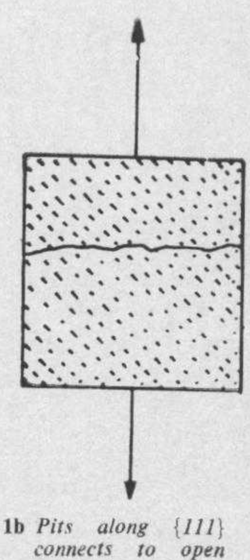
For systematic presentation, the different explanations offered so far about the phenomenon of stress corrosion failure may be conveniently split up in two different mechanisms : (1) initiation of crack (2) propagation of crack resulting in failure. The role of stress and corrosion in these two different phenomena may be then examined under these two heads.

Initiation of crack

There is a general agreement that crack is formed as a result of electrochemical nature of corrosion. Difference of potential exists between discrete areas of the structure of the metal and the anodic areas dissolve into the electrolyte. There is a depletion of material from the matrix and pits are formed. This generates a concentration of stress around the pit or depleted area

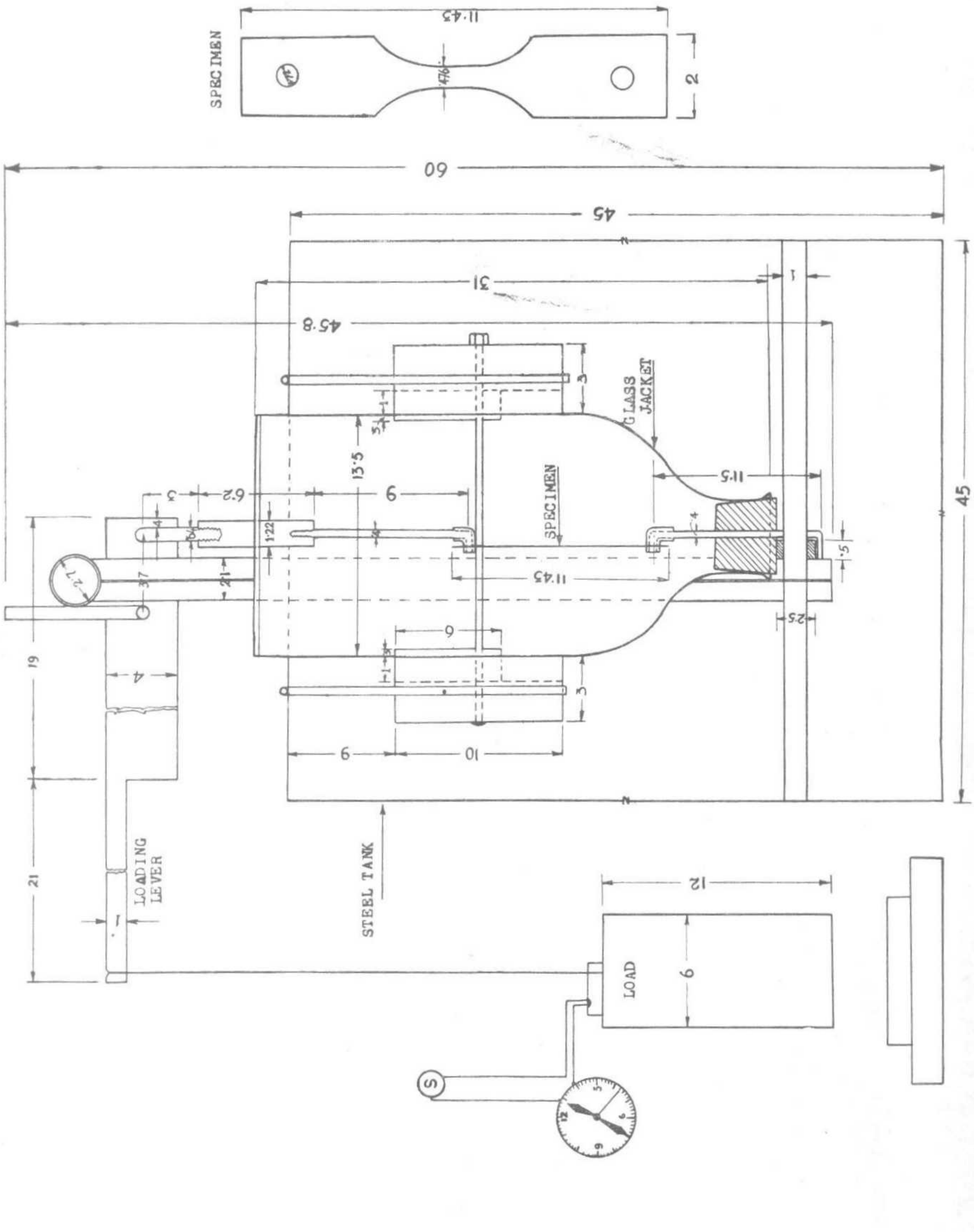


1a *Trace of the {111} planes showing pits in ammonia*



1b *Pits along {111} connects to open crack along the direction of stress*

Messrs S. Banerjee and P. Banerjee, Indian Institute of Technology, Kharagpur.



2 *Apparatus used for stress corrosion testing on moist ammonia atmosphere* due to stress applied and crack or discontinuity is initiated. The anodic locality has been proposed to be different by different investigators.[18]

They are :

(a) Stacking fault ribbons (Swan and Nutting).

(b) Aggregates of dislocations held up by Cottrell-lomer barriers (Robertson and Tetelmon).

(c) Slip planes where short range order has been disrupted by plastic deformation (Swan and Thomas et al.).

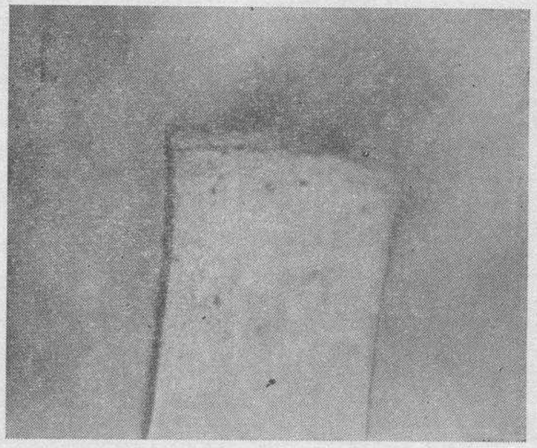
(d) Material exposed at cracks in surface films (Forty and Humble).

(e) Any inhomogeneity in structure such as difference in concentration of solute atoms, precipitates, phases and grain boundaries.[9,10] Speiser et al. has proposed that dislocations pile up adjacent to grain boundaries and regions of solute segregation act as specific sites for failure by intergranular cracking. All these act as discrete anodic areas and pits are created by their dissolution in the electrolyte.

Stress is said to assist in an indirect manner[11] by rupturing apart from the film of corrosion product initially formed on the anodic areas thereby exposing these to further attack or, by inducing precipitation of phases[12] which act as anodic areas. Stress is also believed to accelerate the rate of corrosion.[13]

Propagation of cracks

Diverse explanations have been forwarded about propagation of crack resulting in failure. Although there is a general agreement that stress and corrosion are jointly responsible for propagation of crack, a school of investigators[8,14,15,16] propose that cracks propagate as alternating steps of slow anodic attack resulting in extension of crack in small magnitude and of sudden mechanical fracture resulting in a greater yet microscopic extension. According to them the fracture is brittle in alpha brass as the crack propagates through the cathodic matrix which is harder because the solute concentration in these areas is higher than the anodic areas impoverished of the solute. Nielsen[17] explains that the brittle fracture is triggered by the wedging action of the build up of corrosion products at cathodic areas near the advancing edge of the crack. Contrarily Tromans and Nutting[18] found that mechanical brittle fracture step was absent in alpha brass and hence they concluded that continuous accelerated corrosion was the principal mechanism of crack propagation. This conclusion is in agreement with the proposal of Dix,[9] that selective corrosion proceeds along more or less continuous anodic paths. Igarshi et al.[19] have offered a different explanation for the phenomenology of crack propagation. According to them at initial stages fine



3 *Macrophotograph of stress corroded specimen showing the fracture inclined to the rolling plane (110); sample was 50% cold rolled 70–30 brass* ×8

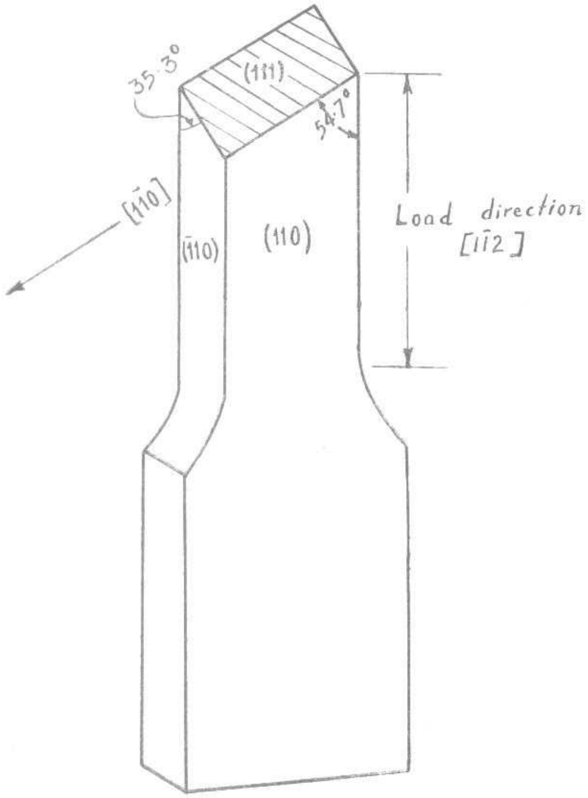
cracks appear along the traces of (111) and (110) planes, which later arrange themselves to the direction of stress. Failure occurs when these cracks connect. The phenomenon is shown hypothetically in Fig. 1.

Tromans and Nutting[18] with the help of electron-micrograph, also confirmed this observation but according to them pits and not fine cracks form at the areas of high dislocation density. Linking up of these pits results in fracture. When the region of high dislocation density passes through the grain boundary the fracture is intergranular and, when through planes, usually (111), the fracture is transgranular.

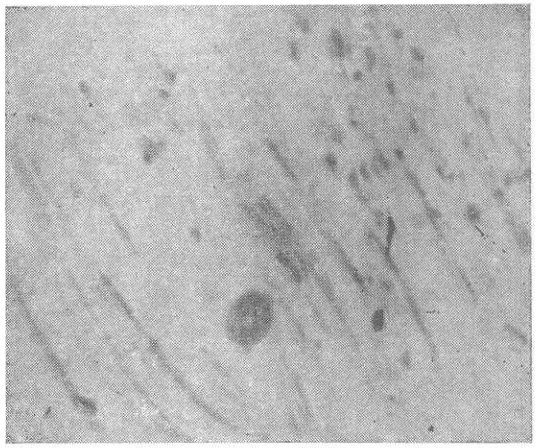
Experimental procedure and results

An apparatus for test at constant load, as shown in Fig. 2 was fabricated for testing the susceptibility of the alloys to stress corrosion failure while in atmosphere of the corrosive media. The temperature of the media can be controlled to a limited extent with the help of the water bath and immersion heater surrounding the containers. The time of failure is automatically recorded in an electric timer operated by the lever stressing the specimen. The load on the specimen can be varied by changing the load on the lever. The tester is calibrated suitably. For creation of ammonia vapour atmosphere, the specimen was surrounded with punctured rubber balls containing 16% ammonia solution which provided an atmosphere of 68·9% air, 27·8% ammonia and 3·3% moisture.

A brass having the composition 73% copper and 27% zinc was prepared in the laboratory. Brass sheets ·081 cm thick with varying percentage of cold work were chosen to make ·476 cm wide gauge length specimens. The specimens were stressed under a load of 6·7 kg/mm^2. The results of the variation of cold work with time of failure is presented in Table I. The results show that at initial stages of cold work, the time of failure decreases in comparison with the annealed specimen and



3a *The inclination of plane of fracture*

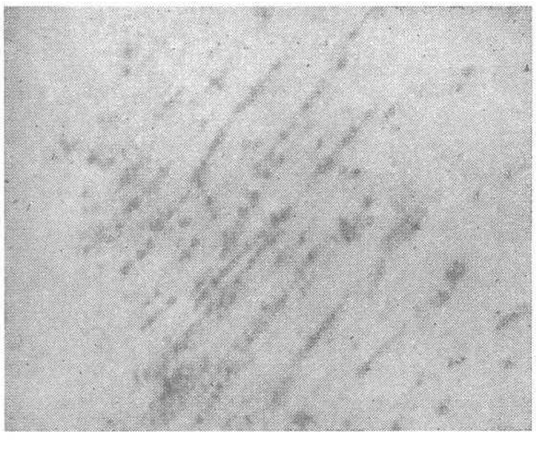


4a *Same as Fig. 4, showing that pits in a line connect and get oriented normal to the direction of stress and form the path of propagation of crack* ×1395

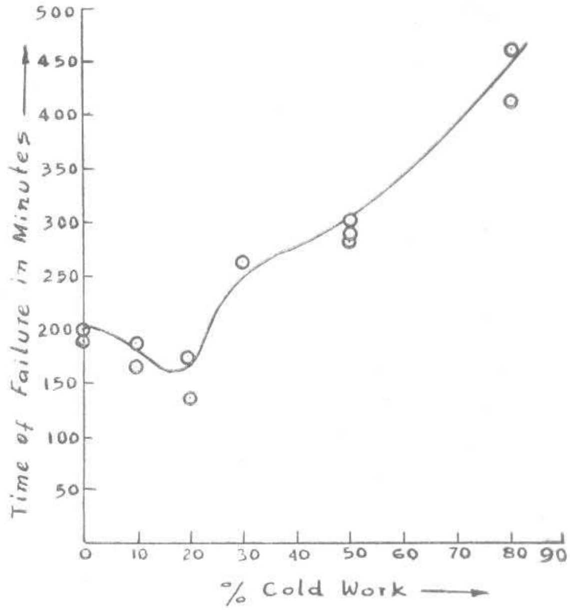
TABLE I **Average value of the time of failure of specimens recorded against percentage cold work**

% cold reduction	Time to failure (min.) average 70-30 brass
Annealed	193
10-15	172
20	155
30	256
50	290
70-80	439

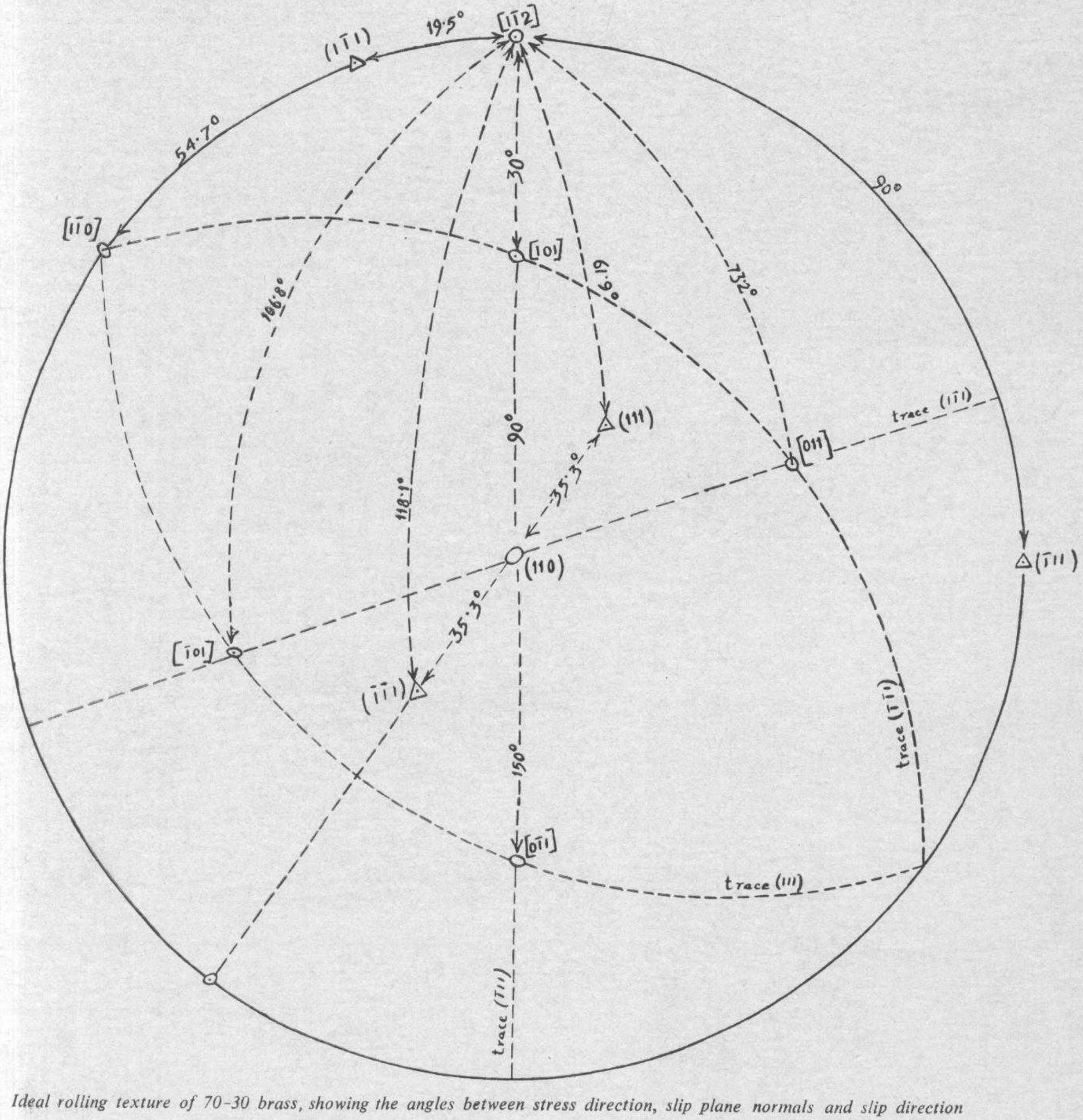
later increases at higher amount of cold work. The profile of fracture for specimens cold reduced to above 30% was noted to be an inclined plane to the direction of stress, as shown in Fig. 3 for a 50% cold reduced specimen. The surface of another specimen was prepared



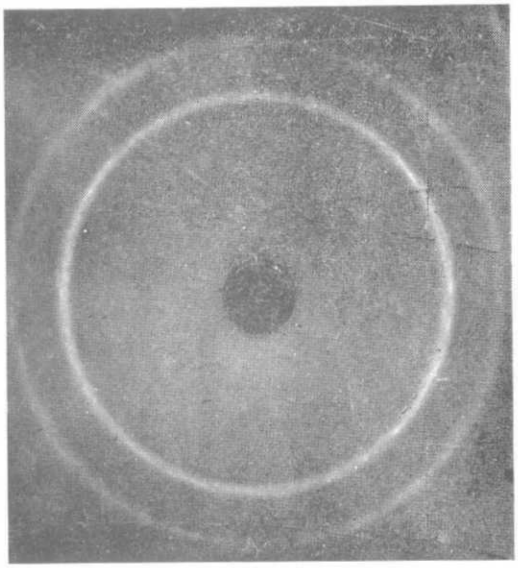
4 *Microphotograph of 50% cold worked specimen, stressed in moist ammoniacal atmosphere after polishing ; parallel and linear arrangement of dislocation pits inclined at an approximate angle of 54° to the stress direction* ×2121



5 *Dependence of time of failure of the specimens with percentage cold reduction*

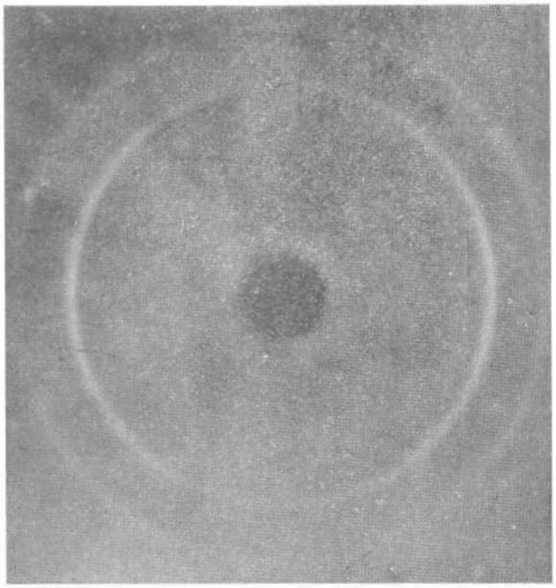


6 Ideal rolling texture of 70–30 brass, showing the angles between stress direction, slip plane normals and slip direction



7 *Transmission pin hole photograph of 15% cold rolled 70–30 brass with copper K-alpha radiation. The line broadening of reflection may be noted suggesting appreciable lattice strain ; no sign of preferred orientation*

by polishing in usual metallographic method followed by electro-polishing in 20 parts nitric acid and 80 parts methanol (voltage 10–12) to reveal the surface details of corrosion phenomenon. The resulting micrograph is given in Fig. 4



8 *Transmission pin hole photograph of 50% cold rolled 70–30 brass with copper K-alpha radiation ; the Debye ring for 111 reflection showing discontinuity due to preferred grain orientation*

Discussions

The following aspects of stress corrosion behaviour of the alloy may be explained as follows:

Irregularities in the time of failure with respect to different amounts of cold work are shown in Fig. 5. The shorter time of failure as indicated in Fig. 5 at the initial stages of cold work may be explained to be due to the generation of dislocations on the slip plane and their subsequent piling up at the grain boundaries catalysing the corrosion of the grain boundaries. This has been experimentally verified by Tromans and Nutting,[18] who found that the intergranular crack was formed from series of pits initiated at dislocation pile ups adjacent to grain boundary.

The increase in the time of failure with larger amount of cold work has been explained by Rosenthal and co-workers to be due to overlapping of grain boundaries which creates difficulty in easy propagation of crack through the grain boundaries. But the explanation does not appear to be tenable as time to failure of severely cold worked samples when loaded both along and across the rolling direction has been found to be more or less equal.[5] Present work confirms that the fracture of the sample taking longer time to failure is transcrystalline as has been reported by Dodd[20] and Edmunds.[5]

The angle of inclination of plane of fracture appears to be due to the nature of preferred orientation caused by more than 50% cold reduction. Tromans and Nutting have found that transgranular cracking propagates through (111) planes in cold rolled brasses.

As orientation approaches the ideal state, the slip planes become inclined at 35·3° and 90° to the rolling plane. That is when the ideal texture is (110) $[1\bar{1}2]$ then the (111) and $(\bar{1}\bar{1}1)$ planes are at an angle of 35·3° to the rolling plane, the other two planes are at an angle of 90° to the rolling plane. Since the loading of the specimens are along the rolling direction $[1\bar{1}2]$, the maximum shear stress is on (111) and $(\bar{1}\bar{1}1)$ planes as calculated from the stereographic projection in Table II. Hence the fracture should

TABLE II **Calculated shear stress values on different slip planes in the slip direction for which the stress is maximum**

Index of the slip plane	Slip directions	Maximum resolved shear stress=T cos Cos$\phi\lambda$ φ=Angle between the normal to the plane and load direction λ=Angle between the load direction and slip direction
(111)	$[1\bar{1}0]$ $[0\bar{1}1]$ $[\bar{1}01]$	T. 0·4078 in $[0\bar{1}1]$
$(\bar{1}11)$	[101] [110] $[0\bar{1}1]$	least
$(1\bar{1}1)$	[110] [011] $[\bar{1}01]$	T. 0·2724 in [011] or $[\bar{1}01]$
$(\bar{1}\bar{1}1)$	[101] [011] $[1\bar{1}0]$	T. 0·4078 in [101]

propagate along (111) and ($\bar{1}\bar{1}1$) planes and the resulting plane of fracture should be inclined approximately at 35·3° to the rolling plane. The profile of fracture in the failed cold worked specimens measured to be 36°. This angle indicates the texture to be approaching ideal as shown in the stereographic projection Fig. 6 and X-ray photographs Fig. 7 and Fig. 8. The Fig. 3 as mentioned earlier is a photograph of the profile of the crack. In the cold worked material that the path followed is the dissolution of dislocations on the octahedral planes has been confirmed by metallographic observation and deduction of the position of octahedral plane in the stereographic projection. The Fig. 4 shows parallel and linear arrangements of dislocation pits inclined at an approximate angle of 540° to the [$1\bar{1}2$] direction. This observation is confirmed by calculations as given in Appendix and shown in Fig. 4.

Conclusion

Since the pits are located along the octahedral planes they may be considered to have formed on dislocation sites. The propagation of pits towards the interior following the trace of octahedral plane also confirms this conclusion. A metallographic evidence has been obtained to prove that dislocation sites initiate stress corrosion failure. The micrograph 4a also indicates that the individual pits in a line connect and get oriented normal to direction of stress and form the path of propagation of crack.

Acknowledgement

The authors are grateful to Prof. P. G. Mukunda for preparation of X-ray report, to Dr S. C. Sircar for helpful suggestions, to Prof. P. R. Dhar and to the Director of Indian Institute of Technology, Kharagpur, for encouragement.

This investigation and publication of result have been possible because of the financial assistance and permission received respectively from the Ministry of Defence, Government of India.

References

1. Read, T. A., Read, J. B. and Rosenthal, H. : Symposium on stress corrosion cracking of metals, Philadelphia, 1944, p. 90.
2. Lynes, Wilson. : Cor. vol. 22, No. 4, p. 113, April 1966.
3. Lynes, Wilson. : Cor. vol. 21, No. 4, April 1965.
4. Forty, A. J. and Humble : Philosophical Magazine 8, vol. 247, 1963.
5. Edmunds, G. : Symposium on stress corrosion cracking of metals, Philadelphia, 1944, p. 67.
6. Johnson, H. E. and Leja, J. : Cor. vol. 22, p. 178, 1966.
7. Wilson, T. C., Edmunds, G., Anderson, E. A. and Pierce, W. M. : Symposium on stress corrosion cracking of metals, Philadelphia, 1944.
8. Barnalt, S. : Corrosion, September 1962, p. 322t.
9. Mears, R. B., Brown, R. H. and Dix, E. H. : Symposium, on stress corrosion cracking of metals, Philadelphia, 1944, p. 323.
10. Uhlig, H. H. : AIME conference, Physical metallurgy of stress corrosion fracture, Pittsburgh, April 1959, p. 1.
11. Swan, P. R. and Embury, J. D. : High strength materials, Edited by V. F. Zackay, 1964, p. 327.
12. Edeleanu, C. : Stress corrosion cracking and embrittlement, Symposium, 1954, Boston, p. 126.
13. Hoar, T. P. and West, J. M. : Journal of Proceedings of Royal Society, vol. 268A, 1962, p. 304.
14. Forty, A. J. : Physical metallurgy of stress corrosion fracture, Metallurgical Society Conference, 1959, Pittsburgh, p. 99.
15. Edeleanu, C. : Physical metallurgy of stress corrosion fracture, Met. Soc. Conference, Pittsburgh, 1959, p. 91.
16. Takano, Michinori and Shimodaira, Saburo : Nippon Kinzokn Grakkai, Si, 1965, 19(5), 553–557.
17. Nielsen, N. A. : Physical metallurgy of stress corrosion fracture, Met. Soc. Conference 1959.
18. Tromans, D. and Nutting, J. : Corrosion, May 1965, p. 143.
19. Igarshi, I., Igarshi, T. and Kinukawa, A. : Journal of Japan Institute of Metals, 20, No. 5, 294–295 (1956) May.
20. Ohtani, N. and Dodd, R. A. : Corrosion, vol. 21, 1965, p. 161.

APPENDIX

The rolling plane (110) and the octahedral planes (111) or ($\bar{1}\bar{1}1$) belong to the zone axis [uvw] satisfying :

$$1\cdot u + 1\cdot v + 0\cdot w = 0$$
$$1\cdot u + 1\cdot v + 1\cdot w = 0$$
$$\text{or} \quad -1\cdot u - 1\cdot v + 1\cdot v = 0$$

Solving this, the zone axis appears to be [$\bar{1}10$] or [$1\bar{1}0$] and the angle between [$\bar{1}10$] and [$1\bar{1}2$] for a f.c.c. lattice will be given by

$$\cos\rho = \frac{u_1u_2 + v_1v_2 + w_1w_2}{\sqrt{u_1^2+v_1^2+w_1^2}\ \sqrt{u_2^2+v_2^2+w_2^2}}$$

where $u_1\ v_1\ w_1$ and $u_2\ v_2\ w_2$ represent the direction and ρ is the angle between them.

Putting [$\bar{1}10$] for [$u_1\ v_1\ w_1$] and [$1\bar{1}2$] for [$u_2\ v_2\ w_2$]

$$\cos\rho = \frac{-1-1}{\sqrt{2}\,.\,\sqrt{6}} = -\frac{1}{\sqrt{3}} = -\ 0{\cdot}5786$$

or $\rho = 54{\cdot}7°$ taking the value of the complementary angle.

Hence the zone axis [$\bar{1}10$] or [$1\bar{1}0$] should be inclined at an angle of 54·7° to the stress direction [$1\bar{1}2$]. The microphotograph Fig. 4 shows the parallel zone axes at an approximate angle of 54° to [$1\bar{1}2$] direction.