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DISCUSSION*

R. N. Wright[1] (*written discussion*)—The authors have used the terms Stage I and Stage II to categorize fatigue crack propagation phenomena and have implied that the former has a crystallographic nature and that the latter is noncrystallographic. I think it is important to point out that the terms as used by Forsyth[2] were defined in a significantly different manner. Forsyth referred to Stage I growth as growth along a slip plane by some unslipping or reverse slip process, and described Stage II as being characterized by the appearance of striations and by growth roughly perpendicular to the axis of maximum tensile stress.

While Forsyth's Stage I is clearly crystallographic in nature, it is not fair to say that Stage II is free from substantial crystallographic influence. In particular, the "brittle striations" observed by Forsyth in Stage II growth in strong aluminum alloys involved local crack growth along {100} planes even though the overall macroscopic growth plane was roughly perpendicular to the axis of maximum tensile stress. Similar observations have been reported by Pelloux recently at the Brighton conference. Furthermore, crack propagation planes in coarse-grained materials can be observed by the naked eye to change from one grain to another even while the "average" plane of growth corresponds closely to the plane of maximum tensile stress. Examples of this have recently been observed in silicon-iron by A. S. Argon and me in work now in press.

Thus, while it may be useful to categorize fatigue crack propagation as crystallographic and noncrystallographic, these categories are not, strictly speaking, the conventional definitions of Stage I and Stage II crack propagation. Though continuum mechanical considerations may dictate the overall growth plane of Forsyth's Stage II, local growth planes and local growth rates can be highly dependent on crystallography.

M. Gell (*author's closure*)—A precise and unique definition for the two stages of fatigue crack propagation is difficult to obtain. If one looks care-

* The discussion and closure which follow concern the paper, "The Fatigue Strength of Nickel-Base Superalloys," by M. Gell, G. R. Leverant, and C. H. Wells on pp. 113–153.

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[2] Forsyth, P. J. E., *Acta Metallurgica*, AMETA, Vol. 11, 1963, pp. 703–715.

fully at the definitions of Stage I and Stage II as originally given by Forsyth and then repeated by him and his co-workers in a number of papers,[3,4,5] differences can be found. In addition, by observing characteristics of fatigue crack propagation in a wide range of materials, it can be seen that no single definition covers all cases. For example: (1) Stage II fracture surfaces may or may not exhibit striations, (2) Stage I fractures may or may not show striations, (3) Stage II fractures may be microscopically crystallographic or they may not, (4) Stage I fractures may be macroscopically crystallographic or they may not, and (5) Stage II usually follows Stage I, but there are instances where it does not. Despite this variation in behavior, fatigue crack propagation in most materials does occur in two stages, and it is worthwhile to retain the Forsyth terminology. In the case of the nickel-base superalloys, we have described Stage I as occurring on crystallographic slip planes and Stage II as occurring noncrystallographically and normal to the stress axis. These descriptions are appropriate for crack propagation in these materials.

It appears worthwhile to attempt a more general characterization of Stage I and Stage II at this time. Stage I cracking occurs on slip planes on a microscopic scale. Macroscopically, the Stage I fracture area may or may not correspond to a surface of maximum resolved shear stress. For example, it is possible in polycrystalline materials for a crack to propagate in each grain on a slip plane approximately 45 deg to the stress axis and for the macroscopic path to be approximately normal to the stress axis. The same is true in single crystals when slip plane cracking occurs on a number of slip planes of the same family. The important aspect of Stage I cracking is that on a microscopic scale cracking is occurring on only one slip plane in a given region. It is not appropriate to define Stage I in terms of a specific mechanism because more than one mechanism can produce the same results.

Stage II fractures, on the other hand, are always approximately normal to the stress axis on a macroscopic scale and often on a microscopic scale as well. If the latter is true, cracking is noncrystallographic and there is then a clear distinction between Stage I and Stage II.

A number of cases may arise that require somewhat more interpretation. For example, microscopic or submicroscopic cracking may occur in planar slip materials such that cracking in each cycle occurs first on one slip system and then on another, while the macroscopic fracture is normal to the stress axis. We would classify this as Stage II cracking because of the operation of more than one slip plane at the crack tip and the realization that, under conditions of wavy slip, microscopic, noncrystallographic cracking would

[3] Forsyth, P. J. E., "A Two Stage Process of Fatigue Crack Growth," Proceedings, Cranfield Crack Propagation Symposium, Cranfield, Beds., England, Sept. 1961, p. 1.

[4] Stubbington, C. A., *Metallurgia*, METLA, Vol. 68, 1963, pp. 109–121.

[5] Stubbington, C. A. and Forsyth, P. J. E., *Metallurgia*, METLA, Vol. 74, 1966, pp. 15–21.

result. On the other hand, if cracking occurs for a number of cycles on the same slip plane and then deviates onto another slip plane, then this would be considered Stage I cracking. A third example is the microscopic crystallographic cracking observed on {100} planes in Al alloys.[6] The cube planes are not slip planes in these materials, and failure on them is evidence for normal stress mode cracking and should therefore be classified as Stage II.

At present, the number of instances that require special interpretation is small. If this situation changes with the increased study of fatigue crack propagation, especially in body centered cubic and intermetallic materials, then more explicit descriptions of the different stages of cracking in each material will be required.

[6] Forsyth, P. J. E., Stubbington, C. A., and Clark, D., *Journal*, Institute of Metals, JIMEA, Vol. 90, 1961-62, pp. 238–239.