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ΜΗΧΑΝΙΚΗ.— **Dectile crack blunting by scanning electron microscopy**, by *P. S. Theocaris**, Fellow of the Academy of Athens.

## 1. INTRODUCTION

The problem of kinking and branching of a ductile crack constitutes one of the most popular problems in linear elastic fracture mechanics (LEFM), whose complete understanding of the causes and the mechanisms of its development still resists a satisfactory clarification and solution. The main reason fer this difficulty is the fact that the problem lies on the border line between micromechanics and continuum mechanics, needing information from both sides of confrontation, which should be in congruency, thus contributing one another for the explanation of this complicated phenomenon **[1]**.

The theoretical approach to the problem was made either by the method of the matched coefficients technique **[2]** or by using Muskhelishvili's potential formulation and conformal mapping of the crack geometry onto the unit circle **[3]**.

Reference [**4**] introduced another more realistic approach, based on the Mellin transform technique. The advantage of the method was its validity all over the stress field independently of the length of the initial crack. The Fredholm integral equation system developed from the application of the

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Mellin transform was asymptotically developed in the close vicinity of the initial crack tip and gave satisfactory results.

All these theoretical studies could not succeed to describe decently and in detail the branching and kinking phenomena in ductile cracks. However, using these preliminary studies on the mode of crack curving and branching in cases of ductile materials, a thorough study was undertaken experimentally in this paper where a typical crack propagation in a ductile material (polycarbonate, PC) was followed up to the complete failure of the cracked plate, where several successive cases of branching appeared during the crack propagation. Interesting results and an insight of the ductile fracture of materials were disclosed.

## 2. THE BLUNTING AND KINKING PHASE OF DUCTILE CRACKS

For the study of the mode of dynamic fracture of ductile materials the polycarbonate of bisphenol A (PCBA) was selected as convenient polymer, since it presents typical properties of an elastic perfectly plastic material [5]. Single edge-notch tensile specimens (SENT) were prepared for testing in the loading device of the scanning electron microscope. The specimens were of the dogbone type with overall lengths between jaws equal to $l=35mm$. Their width was $w=4.9mm$ and their thickness varied between $d_{min}=0.7mm$ and $d_{max}=3mm$. Initial slots of length a varying between $a=0.5mm$ and $a=4.5mm$, were cut-out with a razor blade, up to the tips of the slots, so that the ratios $a/w$ varied between $a/w=0.07$ and $a/w=0.6$. One of the lateral faces of the specimen was coated with a fine aluminum layer by evaporation. The thickness of this layer was of the order of 50Å, which was achieved with the help of a digital film-monitor system of type FTM3 of the Edwards Co. The thin aluminum layers, besides their protective role of the specimens from the high energy of the electron bundle of the microscope, played also the role of sensitive indicators and trackers of the strain concentrations in the substrate, as well as automatic plotters of the slip-line fields around the crack-tips.

The tests were executed in a scanning electron microscope of the type Cambridge S4-10, equipped with a special tensile stage. The strain rates were kept low and equal to $\delta=0.5mm/min$. The photographic recording was executed always on load with a rate of one frame every 5 seconds.

Photographs in the scanning electron microscope have shown that, during the process of initiation and development of the kink the main crack front through its blunting changed continuously the form and order of singularity from a typical one for the crack tip to a weaker double singularity at the corners of the blunted front which, for plane stress conditions in ductile materials, was found experimentally to be of a rounded off polygonal type.

3. RESULTS

The quantitative evaluation of the experiments resulted in the following important observations related with the initiation of propagation of ductile cracks. The phase of the stable crack growth (SCG) starts at a critical loading step, where the blunted crack was already established, and a damaged ligament, in front of the crack tip, is developed and stabilized. This phase may be divided into two successive steps. The first step is characterized by a step-by-step advancement of the blunted crack, by exhausting respective parts of the damaged ligament, so that the overall length of the crack and ligament remains stationary. In this step the crack tip opening angle is increasing and it attains its final value of the order of 55 degrees.

Then, the progressive crack growth at the expense of the *damaged ligament* is replaced by the proper *steady crack growth,* where the crack advances steadily, under an almost constant external load and under a constant crack tip opening angle (CTOA), up to a limit, where the third phase intervenes, when a catastrophic fracture occurs [5].

The blunted cracks develop a flat front with rounded-off corners and have their flanks deformed in an oblique shape, due to the crack-tip opening angle (CTOA), generated before blunting. The value of the CTOA, which was initially of the order of 55°, after blunting and the development of the flat-crack front is reduced to angles $\delta$ varying between 6° and 12° (see Figs. 1 and 7 and ref. [5]). The SEM micrographs reveal all these interesting and novel phenomena, not as yet recorded and only anticipated.

Figure 1 presents a transverse edge crack at four steps of loading. The crack initially opens under an acute angle (Fig. 1a) and then it is blunted (Fig. 1b). Finally, as the loading is increased, an acute crack branch appears from the blunted front of the crack near to one of its extremities having the form of a feline claw (Figs. 1c and d).

Figure 1(a) indicates a surface pattern derived from an arrangement of the scanning microscope in z-modulation, where the electron bundle is impinging the coated surface of the specimen under an oblique angle. This arrangement has the advantage to present in relief the irregularities of the surface at the neighborhood of the crack. The population of voids and microcavities around the crack tip is obvious, with high precipices along the crack flanks. In this stage the material is getting set to develop some blunting at the crack tip.

The step of fully developed blunted front of a crack is shown in Fig. 1(b). It is evident that the crack flanks have been opened and become slant, whereas the crack front takes a flat shape with rounded-off corners. In the same photo the slip-line field is very distinctly manifested by the crazing of the coating layer of the specimen. It is worthwhile pointing out that families of crazes of the coating start from the rounded corners and the oblique flanks of the blunted crack, which intertwine in front of the crack face. The points of the intersections of the limiting crazes lie at a distance from the crack front equal to the front-width of the blunted cracks, d. Another important observation concerns the tuft of parallel crazes emanating from the straight flanks of the crack branch shown in Fig. 1(c), where the intertwined families of crazes form canonical rhombs with angles of 40° and 140° at their corners respectively. Moreover, in Fig. 1(d) the extent of this plastic enclave emanating from the straight flank of the crack branch is indicated covering the whole width of the specimen.

Figure 2 contains photographs taken in the SEM under z-modulation arrangement for a transverse edge crack in a PCBA-specimen. They show the evolution of the blunting process of the transverse crack ($\beta=90°$) where the blunted crack front is shown in the extreme left parts of the photos. The shape of the blunted crack is again with a flat front and rounded-off corners. The importance of these photographs lies on the impressive appearance of the formation of voids and microdefects in front of the crack face which, at the beginning, occupies an almost circular region in front of the crack (Figs. 2a and b), and then develops two curved arms full of microdefects thus forming a continuous chain (see Fig. 2c). Note again that in front of the flat crack face there is an almost triangular enclave where no defect has developed. Figure 2(d) presents a further step of loading where deep precipices are developed at the circular enclave in front of the crack, as well as along the oblique curved chains of defects.

Figures 3 and 4 present the evolution of blunting in oblique cracks with angles of slantness varying between 63° and 60°. Figure 3 shows the evolution of the blunted front of the crack if the external loading is increased. The initial crack in Fig. 3(a) develops a blunted straight oblique front with rounded-off corners, which later-on disappear changing into sharp corners (see Fig. 3d). Figures 3(c) and (d) indicate the black zones emanating either from the blunted crack front, or from the abdominal flank of the crack. It will be shown later on, by tracing the slip-line field of the case, that these zones are either zones of minimum local straining of the plate (in front of the crack face), or elastic zones of reduced straining.

Figure 4 indicates the evolution of the slip-line field with the plastic zones embracing and enveloping these black enclaves of Fig. 3. Figures 4(b) and (c) present completely evoluted slip-line fields, whereas Fig. 4(d) shows dramatical details of both families of slip-lines at the neighborhood of the crack front and the lower flank of the crack. Finally, Fig. 5 presents the case of a $\beta=48°$ oblique crack developing under loading a blunted form at its tip. Again the shape of its crack front at the beginning of loading was rounded-off as indicated in Fig. 5(b) and afterwards the front of the crack took the shape of a trapeze evoluting into the shape of a bird's bill (see Figs. 5c and 5d).

Figure 6 presents the formation of slip lines developed around the tip of an oblique crack ($\beta=45°$). The plastic enclaves around the tip are already significantly advanced and branches already appear emanating from the acuter corner in the trapezoidal shape of the crack. In Fig. 6(a) two tufts of slip lines radiate from the obtuse corner and from the end of the elastic zone existing along the abdominal flank, whereas a crack branch emenates from the acuter corner. Figs 6(b) and (c) show the evolution of the initial slip line field, whereas Fig. 6(d) indicates clearly and synoptically the critical points at the intense stress concentration zones.

## 4. SLIP-LINE FIELDS IN BLUNTED CRACKS

The typical slip-line fields traced from the experimental evidence with SEM micrographs are based on the usual assumptions valid for tracing these fields by graphical and numerical methods.

Plane stress slip-line fields were traced by theoretical methods only for the symmetric case of mode-I and the antisymmetric one for the pure mode-II deformation of the crack. This is because in these cases particular symmetric conditions are held, facilitating the solution of the problem. However, the establishment of the slip - line field for the general mixed - mode crack presents unsurmountable difficulties, since it necessitates the introduction of an arbitrary assumption which must be physically admissible. The experimental evidence with SEM allows the acceptance of the most plausible condition for the complete definition of the general slip-line field.

The experimental evidence with SEM indicated clearly that the best assumption is to consider the sum of the angles subtended by the elastic zones between the crack flanks and the first hind-field discontinuities, that is the angles (IA′D) and (CB′E) of Fig. 7 to be constant.

Thus Fig. 7 presents the slip-line field of a transverse edge-crack with $\beta=90^{o}$ when the crack is blunted. It is worthwhile indicating the striking resemblance between the slip-line field of Fig. 7 and the field given by the slip-lines represented by crazes of the coating in specimen shown in Fig. 1(a).

Similarly, Fig. 8 presents the slip-line field of an oblique crack under plane-stress conditions. The angle of obliqueness is $\beta=63^{o}$. In this case the exponential spiral zone of the slip-line field (OAKBO) becomes shallower than the field is with crack under mode-I of loading. Moreover, the deformed flanks of the blunted crack present an obliquity of an angle $\delta=4.30^{o}$, whereas angle $\delta$ for mode - I is found to be $\delta_{90^{o}}=6^{o}$. Finally, the blunted oblique crack with $\beta=63^{o}$ has its flank BC subtending an angle of $5^{o}$ with its initial position exactly the same of the angle of obliquity of the respective hind discontinuity line.

## 5. CONCLUSIONS

Based on extensive experimental evidence, by using scanning electron microscope photographs of slowly and intermittently propagating cracks in a typically ductile material, as is the polycarbonate (PCBA), and tensile specimens under plane-stress conditions, the following important results have been derived:

(i) The loaded edge cracks under different angles of obliquity presented at the beginning large openings of their flanks, consisting in the creation of almost flat crack fronts inclined under certain angles, and angular displacements of their flanks. At the first steps of loading each crack front displayed rounded - off corners with the flanks of the crack. This phenomenon resulted in a considerable reduction of the orders of singularities at these corners.

(ii) As the loading was progressed the rounded-off corners became acute, thus increasing again the already reduced values of the respective orders of stress singularities.

Parallel to the study of the forms of blunting of ductile cracks, a study of the slip-line fields in blunted cracks under conditions of plane-stress was originated and typical slip-line fields for blunted cracks with $\beta=90^{o}$ and an arbitrary value of $\beta$ were generated. Since slip-line fields for cracks under mixed mode and plane stress are as yet not completely established, these fields, based on the experimental forms of the blunted cracks, were considered as satisfactory. Furthermore, the trends of the slip lines in typical slip-line fields were checked adequately with the forms of crazes developed around the crack tips in the SEM photographs.

The results of this study indicated the necessity to take into consideration the changes in shape and form of the ductile cracks before fracture, in order to accurately define an appropriate criterion for ductile fracture.

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## ΠΕΡΙΛΗΨΙΣ

**Ἄμβλυνσις ρηγματώσεων εἰς ὄλκιμα μέσα διὰ τοῦ ἠλεκτρονικοῦ μικροσκοπίου**

Εἰς τὴν ἐργασίαν αὐτὴν μελετᾶται ὁ τρόπος ἀμβλύνσεως τῶν αἰχμῶν ρωγμῶν εἰς ρηγματωμένας πλάκας διὰ χρησιμοποιήσεως γραφικῶν καὶ πειραματικῶν μεθόδων. Αἱ συνθῆκαι φορτίσεως τῶν πλακῶν θεωροῦνται ὡς τοιαῦται ἐπιπέδου τάσεως, ὑπὸ τὴν παραδοχὴν ὅτι εἰς τὸ μέτωπον τῆς ρωγμῆς κρατοῦν συνθῆκαι διαρροῆς μικρᾶς ἐκτάσεως. Τὸ ὑλικὸν τῶν πλακῶν θεωρεῖται ὡς ἐλαστικὸν - ἀπολύτως πλαστικὸν καὶ πλαστικῶς ἰσοπαραμόρφωτον. Τέλος θεωροῦνται κεκλιμέναι ἀκραῖαι ρωγμαὶ διαφόρων γωνιῶν β κλίσεως, αἱ ὁποῖαι δημιουργοῦν ἐντατικὰς καταστάσεις μικτοῦ τύπου.

Ἡ πειραματικὴ μελέτη τῶν ἐντατικῶν καταστάσεων εἰς τὴν γειτονίαν τῶν ρωγμῶν ἐγένετο τῇ βοηθείᾳ ἠλεκτρονικοῦ μικροσκοπίου σαρώσεως τύπου Cambridge S4-10 ἐν συνδυασμῷ μὲ σύστημα φορτίσεως τύπου Stereoscan διὰ καταπονήσεις εἰς καθαρὸν ἐφελκυσμόν. Τὰ χρησιμοποιηθέντα δοκίμια κατασκευάσθησαν ἐκ πολυκαρμπονάτου, πολυμεροῦς ὑλικοῦ παρουσιάζοντος μηχανικὴν συμπεριφορὰν προσομοιάζουσαν πρὸς ἐλαστικὰ-ἀπολύτως πλαστικὰ ὑλικὰ καὶ ἰδίως μέταλλα.

Δι᾽ ἐφαρμογῆς προοδευτικῶς αὐξανομένου ἐφελκυστικοῦ φορτίου εἰς τὰ δοκίμια, περιέχοντα ἀρχικῶς λοξὰς ἀκραίας ρωγμὰς διαφόρου γωνίας κλίσεως, κατεγράφοντο καὶ ἐμελετῶντο αἱ διάφοροι βαθμίδες δημιουργίας καὶ ἀναπτύξεως τῆς ἀμβλύνσεως τῶν ρωγμῶν. Αἱ ρωγμαὶ εἰς ὅλα τὰ δοκίμια κατεσκευάσθησαν διὰ κοπῆς μὲ λεπτὸν κοπτικὸν δίσκον πάχους 0.3 χιλιοστῶν καὶ ἐν συνεχείᾳ προεξετάθησαν εἰς φυσικὰς ρωγμὰς διὰ φορτίσεως τῇ βοηθείᾳ λεπτοῦ κοπτικοῦ ἐλάσματος.

Τὰ πειραματικὰ ἀποτελέσματα ἐπεβεβαίωσαν τὰ συμπεράσματα τὰ ὁποῖα ἐπετεύχθησαν διὰ χαράξεως τῶν ἀντιστοίχων πεδίων γραμμῶν ὀλισθήσεως διὰ διαφόρους γωνίας κλίσεως τῆς ρωγμῆς καὶ διὰ συνθήκας ἐπιπέδου ἐντατικῆς καταστάσεως εἰς τὴν γειτονίαν τῶν ρωγμῶν. Τὰ πειραματικὰ ἀποτελέσματα συνετέλεσαν εἰς τὴν ἀκριβῆ διαμόρφωσιν τοῦ πεδίου τῶν γραμμῶν ὀλισθήσεως δι᾽ ἀμβλυμένας ρωγμάς, τῶν ὁποίων ἡ μαθηματικὴ περιγραφὴ εἶναι ἐλλιπὴς καὶ χρήζει καθορισμοῦ ὡρισμένων μεταβλητῶν. Ἐκ τῶν πειραμάτων κατεδείχθη ὅτι ἡ μορφὴ τῶν ἀμβλύνσεων τῶν μετώπων τῶν ρωγμῶν διὰ ἐντατικὴν κατάστασιν ἐπιπέδου ἐντάσεως εἶναι διάφορος τῆς μορφῆς τῆς ὀνομαζομένης ὡς «Ἰαπωνικοῦ Ξίφους», ἐμφανιζομένης εἰς τὴν περίπτωσιν ρωγμῶν εἰς ἐπίπεδον παραμορφωτικὴν κατάστασιν.

Αἱ μορφαὶ τῶν πλαστικῶς παραμορφωμένων ρωγμῶν εἰς τὰς αἰχμάς των καταδεικνύουν τὴν δημιουργίαν γωνιῶν, γεγονὸς ποὺ ἐπιβεβαιώνει προηγουμένας παραδοχὰς ταχυτάτης μεταβολῆς τῶν ἀκτινικῶν τάσεων, προσομοιαζούσης μὲ τασικὰ «ἅλματα».

Περαιτέρω ἀπεδείχθη ὅτι αἱ θέσεις τῶν ἁλμάτων εἰς τὰς ἀκτινικὰς τάσεις συνέπιπταν μὲ τὰ παραμορφωμένα χείλη τῶν ἀμβλυμένων ρωγμῶν, ὥστε νὰ ἑρμηνεύουν πλήρως καὶ λογικῶς τὴν δημιουργίαν αὐτῶν τῶν ἁλμάτων, τὰ ὁποῖα κατ' αὐτὸν τὸν τρόπον ἐμφανίζονται εἰς τὰ σύνορα τῶν παραμορφωμένων ρωγμῶν καὶ ἑπομένως εἶναι συμβιβαστὰ μὲ τὴν ἀρχὴν τῆς συνεχείας τῶν τάσεων.

Σημειοῦται ὅτι ἐνδελεχὴς μελέτη τοῦ τασικοῦ πεδίου ἀμβλυμένων ρωγμῶν ὀλκίμου φύσεως καὶ δι' ἐντατικὰς καταστάσεις μεικτοῦ τύπου παρουσιάζεται διὰ πρώτην φοράν, ἑρμηνεύουσα πλήρως ὅλας τὰς ἀμφιβολίας περὶ τοῦ τασικοῦ πεδίου περὶ τὰς ρωγμὰς ἐπιπέδου ἐντατικῆς καταστάσεως (λεπταὶ πλάκες) καὶ δίδουσα ἀκριβῆ εἰκόνα τοῦ πεδίου τῶν γραμμῶν ὀλισθήσεως εἰς τὰ ἐνδιαφέροντα αὐτὰ προβλήματα τῆς πράξεως.