INFLUENCES OF HEAT-TREATING PROCESS ON DUCTILE FRACTURE MECHANISM UNDER MIXED MODE LOADINGS[①]

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ABSTRACT The fracture behavior and micro-mechanism of aluminum alloy were investigated experimentally under different mixed mode loadings in different processes of heat-treatment (quenching(LY12- CZ) and annealing (LY12- M)) materials. Under mode Ⅰ loading, the fracture behavior and micro-mechanism of the above two materials coincided with those of typical ductile fracture. Under mode Ⅱ loading or near mode Ⅱ loading, the differences between fracture behavior and micro-mechanism of the two materials were outstanding. The fracture of the material LY12- CZ was initiated and propagated under the control of maximum tensile stress, and that of the material LY12- M was also initiated under the control of maximum tensile stress, but propagated under the control of maximum shear stress. In all mechanical parameters of ductile material, the strain hardening index n is the main factor controlling the transformation of fracture mechanism with the loading condition varied from mode Ⅰ to mode Ⅱ.

Key words mixed mode fracture fracture mechanism shearing yield strain hardening index

1 INTRODUCTION

In engineering practice, a lot of crack problems can be included in different combinations of three basic fracture modes, i. e. mixed mode fracture problem. As one can see, fracture mechanisms and theories of mixed mode fracture have been paid considerable attention in the last 40 years by mechanics and material science engineers. Considering the thorough study on mode Ⅰ fracture and the cracks in brittle material tend to initiation and growth in mode Ⅰ type, the linear elastic mixed mode fracture theory was considerable developed. It can be found from a lot of experiments[1-3] that the fracture is tensile type of brittle fracture under different mixed mode loading conditions and the micro-mechanism of fracture surface is as cleavage or quasi-cleavage fracture. Therefore, the fracture theories have been created successfully in most brittle materials such as glass and some kinds of ceramics. However the fracture mechanisms of most ductile materials used in engineering practice are different with different mixed mode loadings such as moderate strength steel, aluminum alloy, etc. These mixed mode fracture theories cannot be successfully used in ductile materials[4-7]. In mixed mode fracture problems, the influence of mixing degree of mixed mode and the action between material properties and different stress fields on fracture process and mechanism must be considered[8-10]. So the influence of ductile material characteristics on mixed mode fracture cannot be ignored.

In this paper, the problem is restrained in plane strain mixed mode fracture. The fracture

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behavior and micro-mechanism of aluminum alloy under different processes of heat-treatment (quenching for LY12- CZ and annealing for LY12- M) have been investigated by experiments under different mixed mode loadings.

2 EXPERIMENTAL

2.1 Material and specimen selection

To study the different mechanisms of two kinds of ductile materials, two kinds of heat-treatment aluminum alloys were chosen to investigate different mechanisms. Material A is quenched LY12- CZ and material B is annealed LY12- M, their chemical composition is shown in Table 1, and mechanical properties in Table 2.

Table 1 The chemical composition of LY12(%)

Main composition			Impurity no larger than				
Cu	Mg	Mn	Al	Fe	Si	Fe+ Si	Zn
2.8~ 4.9	1.2~ 1.8	0.3~ 0.9	base	0.5	0.5	0.5	0.3

Talbe 2 The mechanical properties of LY12

Material	E /MPa	$\sigma_{0.2}$ /MPa	σ_b /MPa	δ_s /%	ψ /%	n
A	75 000	268	585	10.0	11.9	0.23
B	65 000	136	230	11.5	12.9	0.11

Comparing the yield strength and plastic strain harden index of two kinds of materials, we can find that the yield strength of material B is about half of that of material A. The plastic strain harden index has drastic reduction comparing with material A. Based on this relatively larger difference of mechanical property in the same chemical composition materials, these two kinds of materials were selected to carry out the mixed mode fracture experiment. Several specimen designs have been reported in the literature for determining the mixed fracture of mode Ⅰ-Ⅱ. The modified test specimen based on the compact tension-shear specimen design and loading fixture proposed by Richard and Benitz[11] was employed in this investigation. The specimen designs are illustrated in Fig. 1. The shape of crack tip is pre-created as 0.10 mm curvature radius of blunted crack tip.

2.2 Fracture test

The microscopic tension-shear fracture test was carried out in Instron 1196 testing machine at a constant cross-head rate of 0.5 mm/min. The test temperature was room temperature. The appropriate selection of the loading holes in the loading fixture produced an entire range of mode Ⅰ-Ⅱ loading condition from pure mode Ⅰ to pure mode Ⅱ. The loading (P)-displacement (Δ) curve was recorded. Some specimens were

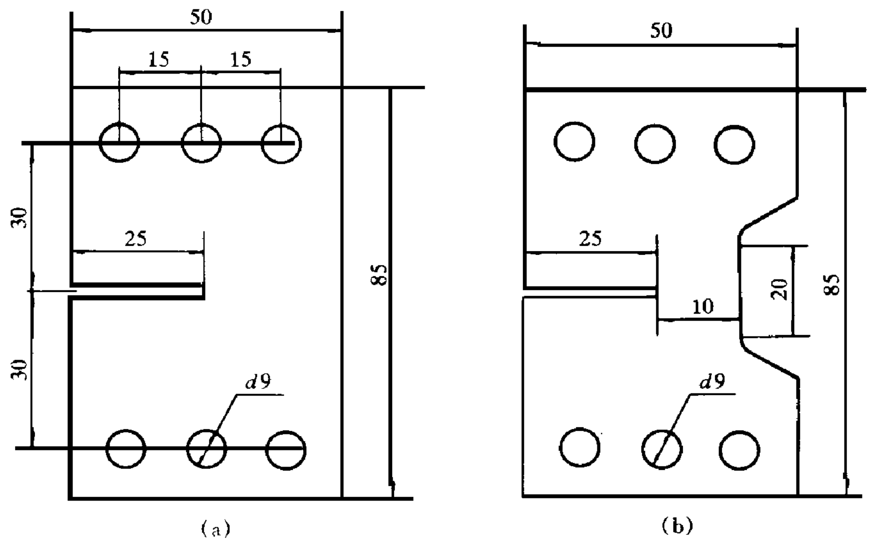

Fig. 1 Specimen shape in test (unit: mm)

loaded up to a series of specified load level to produce different crack initiation and crack propagation, and then unloaded. Some specimens were sectioned into halves at the centre. The samples for fractographs of various grades of crack growth were obtained by selecting the specimens of different unloading points. The shape of the blunted crack tip and the direction of crack propagation were determined by a scanning electron microscope along the cross-sections.

The $P-\Delta$ curve corresponding to six kinds of mixed mode loading condition of material A is shown in Fig. 2. The equivalent crack angle β_{eq} (β_{eq}= arctg $K_{\rm I}/K_{\rm II}$) denotes the mixed mode condition of stress field. β_{eq}= 90° corresponds to the pure mode Ⅰ loading, and β_{eq}= 0° corresponds to the pure mode Ⅱ loading. It can be found from Fig. 2 that there existed regular nonlinear effect of different levels in the initial loading stage. It can be thought to result from the variation of flexibility of the loading system, and the difference of elastic deformation of spcimens in different loading configurations. In our investigation, the characteristics of variation of the curve were coincidence with each other. The fracture load was increased when β_{eq} decreased. In the last part of all curves, a series of different level of vibration can be found on the smoothed curves. As the mixing degree of mixed mode changing, the shape and trend of this vibration in different ($P-\Delta$) curves were changed regularly. In near mode Ⅰ loading condition, the trend of the vibration was sloped up, and the sound emission was slightly arising while crack initiating. This behavior of vibration vanished after the first sudden drop on the ($P-\Delta$) curve in pure mode Ⅱ loading while crack initiating, and then the material was fractured. The amplitude of vibration on ($P-\Delta$) curve was decreased and the trend of rising up increased while the equivalent crack angle β_{eq} increased. For example, as β_{eq} changed from 45° to 30°, the trend of vibration transferred from rising up to sloped down clearly.

We found from the ($P-\Delta$) curves of material B (Fig. 3) that there has no vibration in the last part of each curve. The curves were smooth in the part of crack initiation and crack growth compared with material A. The trend of ($P-\Delta$) curve reached its peak and dropped down gradually in different mixed mode loadings. The increasing of maximal load was smaller than that of material A while the β_{eq} decreased. Just in pure mode Ⅱ and near mode Ⅱ loading, the phenomenon of sound emission could emerge.

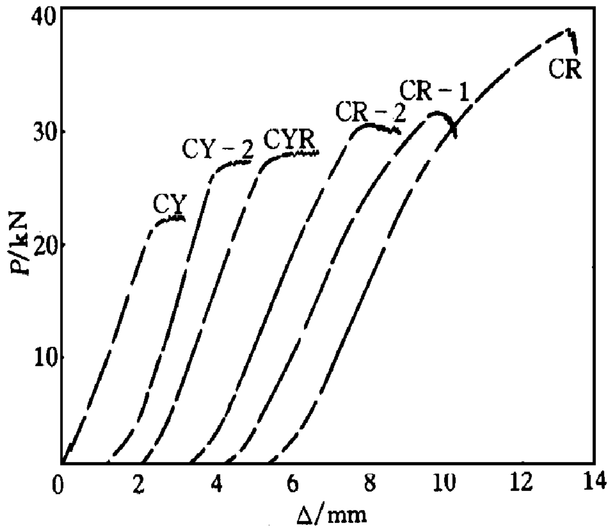

Fig. 2 $P-\Delta$ curve of material A

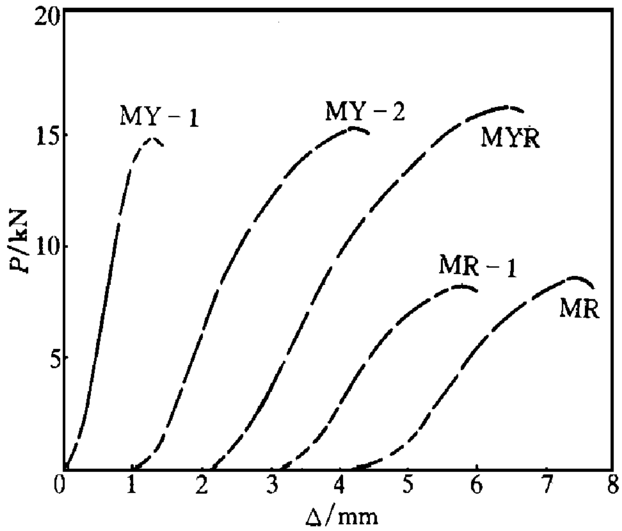

Fig. 3 $P-\Delta$ curve of material B

3 MACROSCOPIC AND MICROSCOPIC INVESTIGATION

3.1 Fracture surface and profile in near mode Ⅰ loading

From the fracture surface of material A, a typical ductile fracture characterization can be found. In the fracture surface near the pre-crack, a triangle fibrous area was observed, a series of radiation characteristic can be found along the direction of crack extension out of this area. The area of shear lip was very small and emerged near the edge of sample surface. From the fracture surface of material B, except the fibrous property existing in the initial crack, no radiation characteristic area can be observed. Outside the fibrous area, a kind of shear type fractures can be observed along the direction of crack propagation. The area of shear lip was larger than that in material A. At the same time, a serious necking produced in the area of crack propagation. It can be seen from the microscopic observation, the fibrous property arranged on the fracture surface of each material. However, the difference is that the void on the fracture surface in material A was larger than that in material B.

It can be noted that the crack initiation point was arranged in the blunted part of crack tip from the microscope analysis of the profile of cross section of specimen. The main process of crack initiation was void nucleation growth and coalescence with crack tip in the area near the crack tip in material A. The void coalescence was due to the ligament where happened shear damage(Fig. 4(a)). The coalescence of larger voids can be found followed the crack tip before the crack initiating. In material B, the coalescence of voids happened due to necking and linking of ligament between smaller voids (Fig. 4 (b)).

The initiation of crack was characterized by nucleation, growth and coalescence of voids in material A and B under mode I and near mode I loading conditions, however the difference in the processes of void coalescences was found.

3.2 **Mixed mode** I - II

In the mixed mode I - II loading condition of material A, the dimple type fracture was observed in a triangle area ahead of the pre-crack tip on the fracture surface. The radiation type and shear lip type can also be found out of the triangle area. The area of shear lip type fracture was a little larger than that in the near mode I loading and appeared non-symmetry. It reveals that the shear damage of the material is sensitive

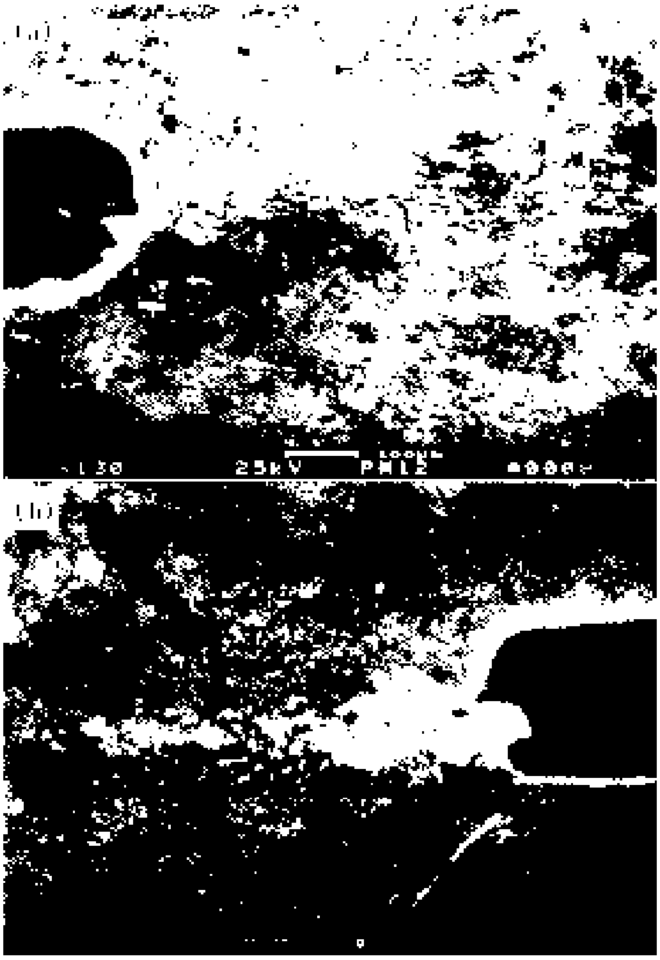

Fig. 4 The initiation of crack under near mode I loading
(a) —Material A; (b) —Material B

to the symmetry of loading system in fracture test. The major characteristic of fracture surface was the non-symmetry shear lip in the part of crack propagation and the different directions of crack propagation happened in different thickness of specimen can be observed in material B, except the fibrous type ahead of pre-crack tip was the same as that in material A.

It can be found from the schematic of the scanning electron microscope fractograph of the crack profile in the cross-section of material A that the crack initiation is the result of the coalesence of voids ahead of crack tip. The path of crack propagation appeared such "Z" type as near mode I loading. The crack initiation in material B is characterized by non-symmetry deformation. A slightly sharpened deformation emerged in one corner of the crack tip. Crack initiation developed in the blunted part in the middle of the crack tip, while a series of nucleated dimple were observed in front of the growing crack tip. The crack propagation was resulted from the void growth and coalescence in local area near crack tip. From the long strip shape of nucleated voids in front of the crack tip, we can conclude that the influence of shear stress on void nucleation was serious and there had nucleated voids coalescences in the same direction before crack initiating on the other hand.

From the above analysis, the initiation of crack in mixed mode I - II loading was as the same as that in mode I loading in material A. Considering the influence of shear stress, the characterize "Z" type crack propagation path was outstanding. It can be thought that the triaxial restrain extent was decreased due to the shear instability resulting from the area of extremely non-symmetry shear lip increasing in material B.

3.3 Mode II and near mode II

In material A, the macroscopic and microscopic property of fracture surface in mode II loading was the same as those in mode I loading. The material fractured as a result of the entire yielding and shear plastic deformation along the ligament as for material B in mode II loading (the width of ligament was selected as 10 mm as shown in Fig. 1). No fibrous and shear lip type was observed on the fracture surface. Only the trace of tear of the two fracture surfaces along the direction of crack propagation can be observed. The direction of elliptical dimples was inclined oppositely on the up and down fracture surfaces.

From the profile of material A (Fig. 5(a)), it was observed that the deformation was produced before crack initiation was less. The position of initiation point and direction of crack propagation were determined by the position of voids ahead of the blunted part of crack tip. The path of crack propagation was along the boundary of polycrystal. At the stage of crack initiation the material fractured easily along the boundary of polycrystal. However, there was no preferential arientation of material fracturing at the stage of crack propagation. It can be found that the anti-symmetry deformation carried out extremely and the sharpened corner of crack formed was deformed till a sharpened crack formed in the profile (Fig. 5(b)) for material B in mode II loading. On the other hand, the blunted corner of crack tip was deformed as a long trace of crack. It was noted that the initiation point of crack was located at the middle of crack tip and the direction of initiation was the

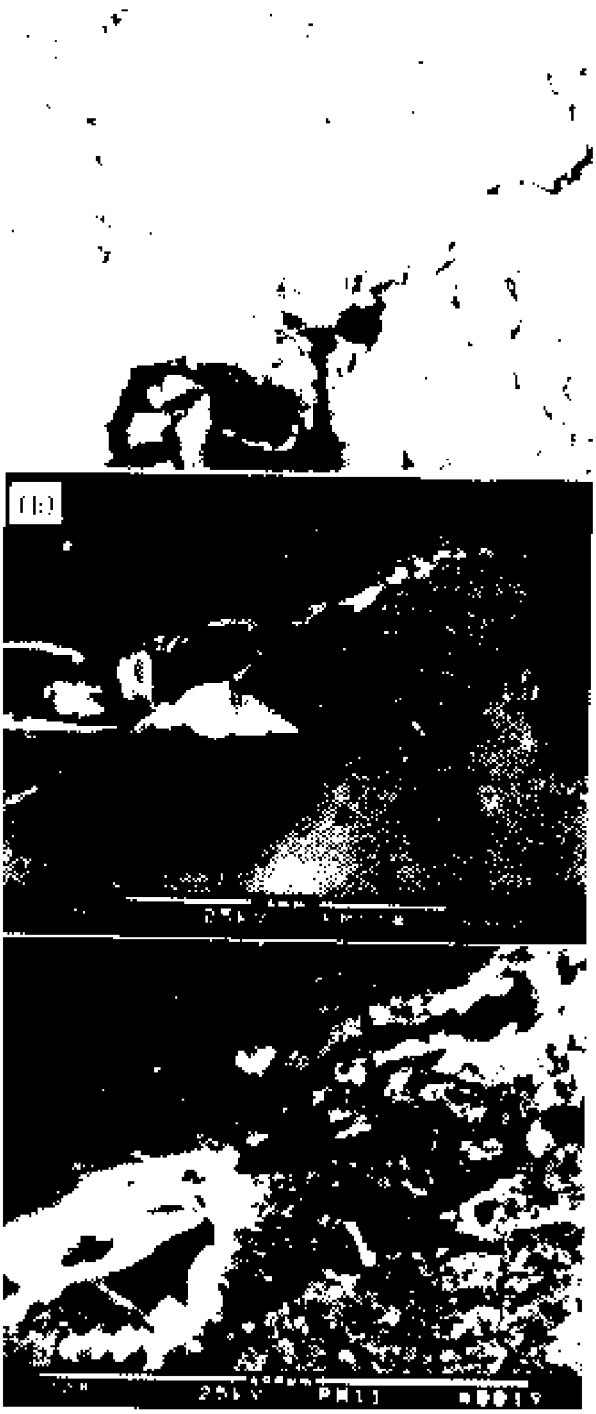

Fig. 5 The profile of specimens in near mode II loading
(a) —Material A(× 800); (b), (c) —Material B

same as that in the stage of crack propagation, where a wider necking strip of material was observed on the profile in the thick of the specimen (Fig. 5(c)). A series of dense irregular voids were observed in the strip. The material yielded and softened because of the linking of large amount of voids in this strip. This plastic deformation accumulation induced the entire departure of the ligament and the crack propagation.

It was resulted from the and microscopic investigation that the mechanism of crack initiation and crack propagation were ductile fracture of dimple type, and influenced by stress state slightly in material A, but obviously in material B. As the shear stress component increased, the fracture type was transferred from the equiaxed dimples fracture in mode Ⅰ loading to elongated dimples shear fracture in mode Ⅱ loading.

4 DISCUSSION

4.1 Effect of inherent parameter of material

Comparing the transformations of fracture mechanism of the two kinds of materials, the size of shear lip on fracture surface in material B was larger than that in material A. Because the presentation of shear lip was due to the large plastic deformation near the edge of specimen in plane stress state, the plastic zone in material B was increased. Comparing the strain harden index of the two materials in (P-Δ) curve, $n_A = 0.23$ and $n_B = 0.11$, it can be thought that as the n_B (in material B) decreasing, the area of plastic deformation and the possibility of shear fracture increase.

4.2 Path of crack extension

From the vibration in the last part of P-Δ curve in material A and the microscopic observation of fracture surface and profile in the thick of the specimen, it can be considered that the severe degree of voids growth was in direct proportion to the increasing of mode Ⅰ stress component. The crack propagation was the result of the linking between the crack tip and the nearest voids one by one. With the stress state transferring from mode Ⅰ to mode Ⅱ, the influence of this linking on the load-bearing capacity was slight. When the accumulation of this effect reached a certain level (for example, the peak of curve), it could induce the entire load-bearing capacity being decreased.

As for mixed mode loading, the severely degree of voids growth was reduced when the distance between crack tip and these voids decreased because of shear stress and the reduction of triaxial stress state. So the large amount of voids coalescences could emerge in material far away from crack tip, then, a series of larger and sheet-like voids emerged ahead of crack tip before the crack initiation. Once the crack initiated, a large amount of stress was released and resulted in the load-bearing capacity decreasing seriously. With the shear component increasing, the number of linked voids in material far away from crack tip increased continuously before crack initiation. It led to increasing the amplitude of vibration and the trend of vibration being changed gradually. With pure mode Ⅱ loading, the initiation of crack was due to the linking between the crack tip and the largest amount of linked voids. So the vibration stage in (P-Δ) curve was changed to a sloping down line, that is, no vibration can be found.

4.3 Change of direction of crack initiation

The direction changes of crack initiation of two kind materials are shown in Fig. 6. It can be found that the direction of crack initiation of two materials was the same in near mode Ⅰ loading, the angle between the initiation direction and original crack line (α) increased gradually with the shear component increasing. In pure mode Ⅱ loading, this angle reached about 67°, almost as the same as that in linear elastic mixed mode fracture test. However, it is different in mixed mode loading, the curve of material A is near a line in Fig. 6, but the curve of material B changes with the loading condition varying. This indicated that the micro-mechanism of fracture was chagned with loading condition.

5 CONCLUSIONS

From the above discussion, we obtained the following conclusions:

(1) The mechanism of initiation and propa-

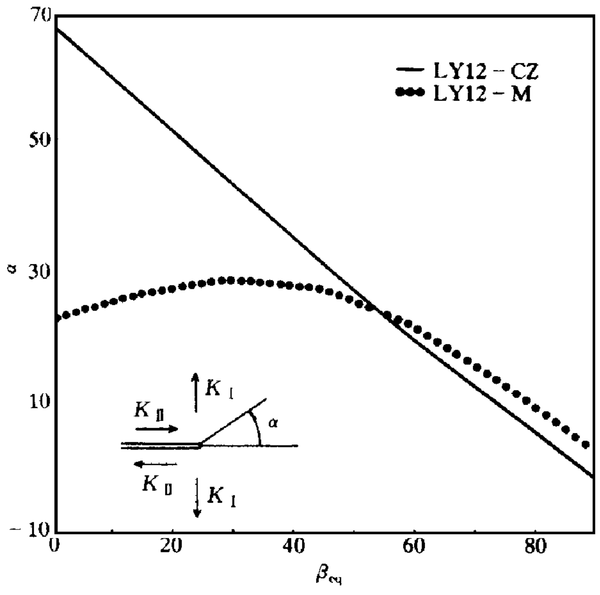

Fig. 6 The direction of inition of materials

gation of crack in material A (quenched) was unchanged, but in material B (annealed), it changed with the loading condition. This changing of mechanism denotes that the two kinds of fracture types were competing each other in the process of fracturing in material B.

(2) Different mechanisms of fracture induce different characteristics and directions of fracture. The phenomenon in material B can not be explained by any of mixed mode fracture theory received till now.

(3) The initiation of blunted crack tip is mainly controlled by tensile stress in material, no matter how the difference of fracture mechanism, the influence of shear stress is very slight relatively.

(4) The plastic strain harden index can be considered as a characteristic parameter of material in investigation of mixed mode fracture in different materials.

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