Fracture Modes for Self-Fragmentation of Al-Based Quasicrystals Contaminated by Carbon

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Cast ingots of quasicrystal forming composition $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ and $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ were prepared in an inductive melting apparatus using graphite crucible in the aim of investigating the effect of carbon on the stability of the single icosahedral (i) and decagonal (d) quasicrystalline phases, respectively. Owing to this process, the contamination of carbon was expected to occur during melting by diffusion from the crucible into the quasicrystalline ingots. The detected amounts of carbon in the i- and d-phase were 0.15 mass% and 0.88 mass%, respectively. Carbon introduced by this method was first found to disintegrate spontaneously these monolithic i-AlCuFe and d-AlNiCo ingots, *i.e.*, a detrimental effect of self-fragmentation of quasicrystals induced by carbon. Our experimental results indicated that the self-fragmentation occurring in the carbon contaminated i- and d-phases did not appear immediately after solidification, but after a certain incubation time. During the self-fragmentation process, the quasicrystalline samples with an initial size of 20 mm diameter bar ingot were disintegrated to form small fragments of about 200 μm after 50 days. Fractography was carried out to analyze fracture modes in the i- and d-phases. The fracture surfaces of the i-phase exhibited a transgranular cleavage pattern without trace of cleavage steps and river patterns, while the d-phase showed both transgranular cleavage and intergranular fracture. Such unique fracture modes in the i- and d-phases are thought to arise from an internal mechanism of carbon-assisted fracture.

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1. Introduction

Al-Cu-Fe icosahedral quasicrystal phase exists only within a restricted temperature range between 750 and 850°C or at a very sharply defined composition around $\text{Al}_{62}\text{Cu}_{25.5}\text{Fe}_{12.5}$.¹⁻³⁾ As a stable i-phase, interests in this system have arisen mainly to study its quasiperiodic structure, its bulk and surface properties, and the possibility of growing large single quasicrystals.⁴⁻⁷⁾ Recently, starting from the Al-Cu-Fe system, researchers have focused on the effects of non-metallic elemental additions such as oxygen and boron, on the structure and stability of the icosahedral phase.⁸⁻¹⁰⁾ It has been shown that the inclusion of oxygen into the icosahedral phase gave a phason strained i phase, and that the motion of phasons resulted in an irreversible lattice damage giving rise to strain softening.¹¹⁻¹³⁾

Among the decagonal quasicrystal forming alloys, the Al-Ni-Co is considered to be the system that forms single-quasicrystal the most easily by slow-cooling solidification.¹⁴⁾ Of particular interest is that $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ alloy, which was proved to be of a congruent solidification,^{15,16)} can produce single decagonal phase just below its melting temperature. In comparison to the i-phase, little interest has been put on the effect of small atoms on the d-AlNiCo phase. Recently, Song *et al.*¹⁷⁾ studied the effect of Si on the d-AlNiCo phase, and found that the introduction of Si not only changed the solidification path, but also decreased significantly the decaprismatic grain size of the d-phase. However, to the authors' knowledge, no information exists on the effects of metalloid carbon addition on the i- and d-phase forming alloys.

Here, we present an astonishing phenomenon of carbon-assisted fracture in quasicrystals initiated without the application of external force, *i.e.*, carbon-induced self-fragmentation of quasicrystals. In order to get evidence of the self-

fragmentation of quasicrystals induced by the presence of carbon, we have investigated a number of quasicrystalline samples of the Al(-Si)-Cu-Fe and the Al(-Si)-Ni-Co systems. Two different techniques were used for the preparation of these quasicrystalline specimens: an arc furnace and an induction melting apparatus with graphite crucible. In the former method, samples were not affected by the carbon contamination from the crucible material since a water-cooled Cu hearth was used. Whereas in the latter method, samples were let in direct contact with the graphite crucible in order to achieve voluntarily the carbon contamination during melting process. It has been found that samples fabricated by the two different processes exhibited different behavior to natural aging. When exposed to the ambient condition at room temperature for about two months, the arc-melted ingots, without carbon, remained as they were initially in the form of monolith, while the ingots prepared in graphite crucible broke spontaneously into powder. In order to further confirm this carbon-induced self-fragmentation of quasicrystals, a ceramic BN material coated on the interior surface of graphite crucible was used to prevent carbon contamination during melting. As we expected, all the samples prepared in this way do not crumble up, since no carbon contamination occurred, keeping their original geometry in the form of monolithic ingots. This is a direct evidence for the correlation of self-fragmentation of quasicrystals induced by carbon present in Al-based quasicrystalline ingots. Actually, similar self-fragmentation has been observed in aluminum alloy-carbon crystalline composites containing small amounts of aluminum carbide phase.¹⁸⁾ In the present paper, we only report the fracture modes by self-fragmentation of icosahedral and decagonal quasicrystals resulting from the contamination of carbon introduced in i-AlCuFe and d-AlNiCo alloys.

2. Experimental Procedures

Ingots with a nominal composition $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ and $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ were prepared respectively by induction melting a mixture of pure metals Al (99.99%), Cu (99.99%) and Fe (99.98%), and Al (99.99%), Ni (99.99%) and Co (99.98%) under Ar atmosphere using graphite crucibles. These ingots, solidified within graphite crucibles, were *in-situ* annealed at 780°C for 2 hour in a vacuum furnace in order to obtain a single-phase alloy and to enhance the solid state diffusion of carbon into the bulk samples. The amount of carbon in the ingots was detected by LECO CS 444 Analyzer. Microstructural, fractural and phase information of samples before and after fragmentation were obtained by X-ray diffraction (XRD) and scanning electron microscopy (SEM). SEM studies were made using a JSM-6330F scanning electron microscope equipped with an energy-dispersive X-ray spectrometer. XRD patterns were obtained with a Rigaku X-ray diffractometer, using the Cu $K\alpha$ radiation. The volume fraction of aluminum carbide was determined by quantitative metallography. Due to the inherent brittleness of quasicrystals, powdered specimens were used directly for TEM observation. Thin foils prepared by an ion-beam milling method were also observed by TEM (JEOL 200CX, Jeol, Ltd., Tokyo, Japan).

3. Results and Discussion

3.1 Fracture mode in i-AlCuFe phase

The amount of carbon that will diffuse from graphite crucible into the quasicrystalline ingots depends on the melting process such as temperature and time as main parameters. However, other parameters such as the size of the graphite crucible and weight of the ingot also affect the carbon contamination. So far these parameters are not fully controlled. For the specifically processed $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ alloy, the amount of carbon was detected as 0.15 mass%. Experiments revealed that this amount is sufficient to trigger the disintegration of the bulk $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ alloy ingots into pieces due to the action of carbon in the icosahedral quasicrystalline phase, even though we do not know the critical concentration of carbon from which the self-fragmentation occurs in the i-phase ingot. The break-up of bulk ingots is a time-dependent phenomenon, which can lead to the formation of fine powder after exposure to the ambient condition for about one month. Figure 1 compares the X-ray diffraction patterns from powders of samples before and after fragmentation. The X-ray diffraction pattern of the former only shows the peaks of icosahedral quasicrystalline phase, as seen in Fig. 1(a). All indexes corresponding to the d-values as reported by Cahn¹⁹⁾ for the i-phase are present in the diffraction pattern. This indicates that the presence of carbon in the specimens does not shift the composition of the alloys out of the domain of stability of the single i-phase determined by Gayle *et al.*²⁰⁾ Since the X-ray diffraction pattern of the latter Fig. 1(b) is similar to that in Fig. 1(a), it is difficult to affirm by this technique whether a new product phase of cooperative interaction between the carbon and environment may be formed during fragmentation, or minute alterations of the present i-phase are induced by self-fragmentation.

Figure 2(a) shows a typical SEM photograph of the as-

annealed ingot. Except for the black cavities, a well-defined dendritic structure can be found on all the polished cross-sections. These dendrites consist entirely of icosahedral quasicrystals, which is consistent with the result obtained by the XRD technique. Such quasicrystalline dendrite morphology is very similar to that of the icosahedral Al-Li-Cu

Fig. 1 X-ray powder diffraction patterns of an as-annealed ingot of $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ alloy contaminated by carbon: (a) before fragmentation and (b) after fragmentation.

Fig. 2 SEM image of an as-annealed ingot of $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ alloy contaminated by carbon: (a) at low magnification and (b) back-scattered image at high magnification.

Fig. 3 SAD patterns from quasicrystals of carbon contaminated i-phase along the prominent zone axis: (a) 5-fold, (b) 3-fold, and (c) 2-fold.

phase observed by Gayle.²¹⁾ Cavities of different sizes could also be observed located at the root of dendrite arms. In some cavities, the faceted growth can be observed along the sides of dendrite arms, and a few quasicrystals grew into the largest shrinkage cavity, revealing typically free faceted surfaces. At a greater magnification, a second-phase that cannot be found at such a low magnification is seen over the whole back-scattered SEM micrograph, as shown in Fig. 2(b). The second-phase is uniformly distributed as flake and forms a continuous network in the microstructure. The size and the volume fraction of the flake phase are on the order of nanoscale and about 5%, respectively. With reference to the identification of Al_4C_3 carbide present in the single d-phase ingots (as discussed below), the second-phase is maybe still in the form of aluminum carbide.

TEM observations were carried out to display the structure of icosahedral quasicrystals composing the dendrite arms at a microscopic level. The selected area diffraction patterns (SAD) observed by TEM were typical of those obtained in other face-centered icosahedral phase alloys. Figure 3 shows representative patterns along the five-fold, three-fold and two-fold. The pattern symmetries and the angle between different axis agree with those required by the icosahedral point group ($m\bar{3}5$). Previous TEM observations on the Ti-based quasicrystalline forming alloys have indicated that the introduction of interstitial oxygen atoms by contamination from the fused silica crucibles did not only influence the formation of the Ti-based i-phases, but also disordered Ti-based quasicrystals showing strong diffused scattering diffraction artifacts.^{22,23)} For the carbon contaminated i (AlCuFe) phase, however, no evidence of strong localized diffuse scattering is found in the present study, suggesting that carbon may not affect the structure of icosahedral quasicrystal phase.

The carbon contamination induced the disintegration of bulk samples placed at the ambient condition. Our experimental results indicated that self-fragmentation does not occur immediately after solidification but it requires a certain incubation time, which is believed to depend on the carbon concentration. In the present case, the incubation time was about 7 days. Then, the fragmentation seems to occur as a continuous process. Figures 4(a) and (b) show the appearance of icosahedral quasicrystalline fragments at a low magnifica-

Fig. 4 SEM images showing appearance of icosahedral quasicrystalline fragments observed after 20 days (a) and 50 days (b) respectively.

tion observed after 20 days and 50 days respectively. The shape of these fragments is highly irregular, and their average size has been decreased from about $400\text{ }\mu\text{m}$ after 20 days to $180\text{ }\mu\text{m}$ after 50 days. The decrease in size with time indicates a continuous refinement occurring in the self-fragmentation process of the i-phase.

Details of the fracture surface of these quasicrystalline fragments are presented in Fig. 5 at a greater magnification.

The fracture path in the single i-phase appears as transgranular mode, and cleavage facets are visible on the whole fracture surface, as seen in Fig. 5(a). This transgranular cleavage pattern indicates the brittle nature of the i-phase contaminated by carbon. The same fracture mode is also observed in Fig. 5(b). With the exception of a large unbroken dodecahedral quasicrystal observed in the largest cavity, one can see that the fracture surface of the fragment exhibits the profile of quasicrystalline dendrite arms. These fractured quasicrystalline surfaces are smooth and flat resembling a cut section, and showing typical feature of transgranular cleavage fracture. However, no traces of cleavage steps and river patterns observed in brittle crystalline materials could be found in quasicrystals contaminated by carbon. Köster *et al.*²⁴⁾ reported the fracture modes of the single-phase Al_2Cu alloy and the quasicrystalline forming $\text{Al}_{65}\text{Cu}_{27}\text{Fe}_8$ alloy. In these uncontaminated crystalline compounds, the fracture surface exhibited cleavage steps and river patterns, while the fracture surface of uncontaminated icosahedral quasicrystalline phase was rough with evidence of quasicleavage patterns. Yokoyama *et al.*²⁵⁾ also reported a river pattern typical for the cleavage fracture mode observed at room temperature in single-quasicrystal $\text{Al}_{70}\text{Pd}_{20}\text{Mn}_{10}$ alloy. The fracture patterns of the carbon contaminated quasicrystalline phase observed in the present study are distinguished from those reported respectively by Köster *et al.*²⁴⁾ and Yokoyama *et al.*,²⁵⁾ suggesting a peculiar carbon-assisted fracture behavior. However, this fracture mechanism is still unclear.

The faceted appearance of brittle fracture surfaces of quasicrystals is the evidence that the fracture occurs preferentially on certain cleavage planes. For the $\text{Al}_{70}\text{Pd}_{20}\text{Mn}_{10}$ single icosahedral quasicrystal studied by Gayle *et al.*,²⁰⁾ under applied load the cleavage fracture was observed to occur along the two-fold planes. This is indicative of relatively poor atomic bonds between the two-fold planes of the quasicrystals. With the aid of this finding, it is presumed that carbon atoms may accommodate certain interstitial positions of the lattice structure of quasicrystals and by some mechanisms induced the separation of bonding between two adjacent planes more easily, as of the two-fold planes. Currently, further investigations are needed for a thorough identification of the cleavage planes in carbon contaminated i-AlCuFe phase.

3.2 Fracture mode in d-AlNiCo phase

The amount of carbon detected in the carbon contaminated $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ alloy ingot was 0.88 mass%, higher than that in the carbon contaminated $\text{Al}_{62}\text{Cu}_{26}\text{Fe}_{12}$ ingots. It was observed that this amount could induce the spontaneous disintegration of the bulk d-phase ingots placed in air. With this large amount of carbon, the incubation time required for the first break-up of the bulk ingots was 4.5 days, shorter than that observed for the i-phase ingots. Figure 6 compares X-ray patterns from powders of the as-annealed $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ ingots before and after self-fragmentation. The pattern of the former (Fig. 6(a)) only shows reflections of the d-phase commonly observed in the uncontaminated $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ alloy obtained in an arc furnace²⁶⁾ except for the split of the major (00002) reflection as seen in the present pattern of XRD. This reflection split suggests that carbon atoms may be accommodated within the d-phase lattice. Since the X-ray diffraction pat-

Fig. 5 SEM fractographs showing transgranular cleavage fracture of (a) icosahedral particles and (b) quasicrystalline dendrite arms marked by arrows, respectively.

Fig. 6 X-ray powder diffraction patterns of an as-annealed ingot of $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ alloy contaminated by carbon: (a) before fragmentation and (b) after fragmentation.

tern of the latter (Fig. 6(b)) is similar to that in Fig. 6(a), we cannot find evidence of the formation of any chemical product phase. In other words, it is difficult to confirm whether the self-fragmentation in the d-phase can be associated with a chemical phase transformation that might generate residual stresses.

Within the sensitivity limits of the XRD technique, no other

Fig. 7 Back-scattered SEM images of an as-annealed ingot of $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ alloy contaminated by carbon: (a) at low magnification and (b) at high magnification

phases were detected in addition to the d-phase. But back-scattered SEM, as shown in Fig. 7, revealed a second-phase in the same ingots. The second-phase embedded in the d-phase matrix has a plate-like shape appearance and is uniformly distributed. Furthermore, a few large cracks were observed, as shown in Fig. 7(a). With a larger magnification, it can be seen that the second-phase possesses a faceted lathy shape with a size of about $2\text{ }\mu\text{m}$ in width and $20\text{ }\mu\text{m}$ in length (Fig. 7(b)). To get further information on the second-phase, SEM image and elemental EDS X-ray scans of the cross-section of the as-annealed sample before self-fragmentation are presented in Fig. 8. A plate of the faceted second-phase adjoining a blank cavity, clearly seen in the upper left-hand side image, was used for EDS X-ray analysis. It is shown that the plate-shaped phase is an Al-rich phase depleted in Ni- and Co-elements, as evidenced by the X-ray mappings of Al (bottom of the left-hand side), Ni and Co elements (right-hand side) respectively. Owing to the compositional-sensitivity and the resolution of the EDS equipment, elemental EDS X-ray mappings only gave the distribution of the three major constituents Al, Ni, and Co in the alloy. However, based on the presence of carbon in this alloy and the existence of only one aluminum carbide (Al_4C_3) in Al-C binary system,²⁷⁾ the Al-rich phase seems to be an Al_4C_3 compound. Its volume fraction accounted for about 2% in the d-phase matrix. It is known that carbon can

form strong covalent bonds with the constituents in the alloys and cause the formation of crystalline interstitial compounds with high melting temperature.²⁸⁾ Al has a much larger negative free energy of formation²⁹⁾ with C than that of other constituents. This means that Al and C have the largest driving force for this reaction, $4\text{Al} + 3\text{C} \rightarrow \text{Al}_4\text{C}_3$, at high temperature. Thus, the reaction of Al and C is favored, readily leading to a uniform dispersion of selective Al_4C_3 precipitates. The crystalline Al_4C_3 carbide is formed from the interfacial reaction between graphite crucible and molten Al during melting. Considering the measured C content of 0.88 mass% in Al-Ni-Co specimen, simple calculation by using mass balance indicated that about half of the total C atoms reacted chemically with Al and participated to form about 2 volume percent of aluminum carbide, and that the remaining C atoms are accommodated in the d-phase lattice, which is in agreement with the observed split of the (00002) reflection of the d-phase as shown in Fig. 6.

Figures 9(a) and (b) exhibit SAD patterns obtained respectively along the ten-fold and two-fold symmetries of the decagonal phase in the carbon-contaminated sample. The ten-fold pattern in Fig. 9(a) shows that the d-phase is present in a type S1 superstructural modification as reported by Ristch *et al.*³⁰⁾ In addition, we tried to observe by TEM the second-phase present in the d-phase matrix so as to confirm the structure of this carbide. However, due to its small amount, no carbide could be observed by TEM. In the carbon contaminated d (AlNiCo) phase, there was still not evidence of strong localized diffuse scattering, suggesting a mechanism identical to the one described above on the role of carbon in icosahedral quasicrystalline phase.

The disintegration of bulk samples placed at the ambient condition firstly appeared after about 4 days, and then occurred as a continuous fragmentation mode. Figures 10(a) and (b) show at a low magnification the appearance of decagonal quasicrystalline fragments observed after 20 days and 50 days respectively. The shape of these fragments is highly irregular with sharp edges. Their average size has decreased from about $400\text{ }\mu\text{m}$ after 20 days to $200\text{ }\mu\text{m}$ after 50 days. This indicates that carbon can facilitate the continuous refinement of quasicrystalline fragments.

Figure 11 shows details of fracture surface of these quasicrystalline fragments at a greater magnification. The grain-boundary split was found to occur along the tenfold growth direction, as evidenced by in Fig. 11(a), exhibiting an intergranular fracture mode. This low-energy fracture mode should be related to the impact of carbon along the faceted columnar grain boundaries. Cleavage fracture is the most brittle fracture form. Such fracture mode is also observed in the d-phase, as shown in Fig. 11(b). Except for small voids formed at decaprismatic grain boundaries, or intergranular voids, one can see that the fracture surfaces of fragments exhibit the characteristic flat surface appearance within each decaprismatic grain. This suggests that the d-phase undergoes transgranular cleavage along a specific crystallographic plane in a similar way as described in the i-phase. For the d-phase, the cleavage plane seems to be perpendicular to the tenfold growth direction. For the two types of fracture modes observed in the d-phase, the intergranular fracture may precede the transgranular fracture on the basis that the intergranular

Fig. 8 SEM image of an as-annealed ingot of $\text{Al}_{72}\text{Ni}_{12}\text{Co}_{16}$ alloy contaminated by carbon and elemental EDS X-ray mappings.

fracture is a low-energy fracture mode. In addition, a step formed by secondary cleavage can be seen within a grain, and the cleavage step seems to be parallel to the tenfold growth direction. However, a large number of cleavage steps forming a multiple step could not be found in this study.

3.3 Comparison of fracture modes in the i- and d-phases

The lower carbon content in the i-phase in comparison with the d-phase should be attributed to nonequivalent temperature and time used for the preparation of the specimens. However, a structural effect can also be expected. Due to the carbon content in the i-phase lower than that in the d-phase, the incubation time required for the i-phase' break-up is larger than that for the d-phase. However, following the incubation time, the spontaneous break-up in both the i- and d-phase occurs as a continuous process. The i-phase fragments showed rough and misty appearance, while the d-phase fragments showed sharp and bright appearance. But their shape irregularity was a common feature that both phases exhibited after spontaneous rupture. In the polyquasicrystalline i-phase, the fracture path propagated through quasicrystalline grains, thus forming a unique transgranular cleavage structure without cleavage steps. In the polyquasicrystalline d-phase, a transgranular cleavage was observed but the fracture could follow the grain boundaries. It was noted that the transgranular fracture path propagated for the most part through the decapismatic grains just as the fracture in the i-phase, although a large cleavage step was also observed in one grain. In other words, such a process did not give rise to the forma-

tion of visible steps when a cleavage crack spread into adjacent grains. In common, their fracture process involved the separation of adjacent planes in quasicrystals, showing the distinctive bonding characteristics by cleavage, dominated by the same carbon-assisted fracture mechanism.

The carbon-assisted fracture mechanism should be associated with the presence of carbon in Al-based quasicrystals and the distribution of Al_4C_3 phase. Carbon atoms that can be accommodated in Al-based quasicrystals may weaken the bonding between two adjacent planes in quasicrystals. As for the distribution of Al_4C_3 in quasicrystalline phase, since the aluminum carbide with a higher melting point was formed in the liquid at high temperature before the formation of Al-based quasicrystalline phase, the carbides are expected to exist inside the grains or at grain boundaries. From this, it is inferred that a chemical reaction between the carbides and moisture (for example, water in air)¹⁸⁾ may produce residual stress by phase transformation, which could be responsible for crack initiation and growth inside the grains or at grain boundaries, thus leading to the occurrence of two types of fracture modes (intergranular and transgranular) in the carbon-contaminated quasicrystals.

Carbon is definitely a nuisance in Al-based i- or d-phase alloys. When used for bulk property test, the bulk Al-based quasicrystalline ingots containing even small amounts of carbon should be carefully examined due to the negative effect of carbon on self-fragmentation of quasicrystals.

Fig. 9 SAD patterns from quasicrystals of carbon contaminated i-phase along (a) 10-fold and (b) 2-fold symmetry axis.

Fig. 10 SEM images showing appearance of decagonal quasicrystalline fragments observed after 20 days (a) and 50 days (b) respectively.

4. Conclusions

In this investigation, the self-fragmentation of quasicrystals was observed when carbon atoms diffused into the qua-

Fig. 11 SEM fractographs showing (a) intergranular fracture and (b) transgranular cleavage fracture with a secondary-cleavage step within a grain marked by arrow, respectively.

sicrystalline samples. As a result, carbon atoms led to the disintegration of the bulk i- and d-phase ingots. Their self-fragmentation needed a certain incubation time, and then took place as a continuous, slow process. In the self-fragmentation

process of the quasicrystalline samples, quasicrystalline fragments continued to fracture and to split apart into smaller size fragments at ambient condition.

After rupture, the fracture surfaces of the i-phase exhibited a transgranular cleavage structure without trace of cleavage steps and river patterns, while the d-phase showed both transgranular cleavage and intergranular fracture. For the transgranular cleavage mode, the almost entirely faceted appearance of brittle fracture surfaces of quasicrystals was attributed to an easy separation of two adjacent crystallographic planes in quasicrystals. Such unique fracture modes in the i- and d-phases are thought to arise from an internal mechanism of carbon-assisted fracture in quasicrystals. The carbon-assisted fracture mechanism might be associated with the presence of carbon accommodated in Al-based quasilattice and the distribution of Al_4C_3 in Al-based quasicrystalline matrix. At present, the exact mechanism of quasicrystalline break-up is not clearly understood, and stands in need of a thorough investigation.

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