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Dynamic Fracture Behavior of Brittle Materials: Microdefects, Crack Propagation, and Fragmentation under Impact Loading

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ABSTRACT

Brittle materials are widely used in structural, protective, and aerospace applications but are highly susceptible to rapid fracture under impact loading and high-speed deformation. This study examined glass, ceramics, concrete, borosilicate glass, and polycrystalline diamond, focusing on microdefects, crack propagation, dynamic strengthening, energy localization, and fragmentation. Fracture was mainly initiated at pores, inclusions, microcracks, and other structural heterogeneities acting as stress concentrators. Increasing loading intensity and strain rate accelerated crack growth and fragmentation, while dynamic strengthening and quasi-brittle behavior could emerge under high-rate conditions. Theoretical analysis using dynamic fracture mechanics, energy criteria, statistical defect models, and fragmentation models showed that fracture behavior depends on microstructure, loading rate, crack velocity, and impact energy, providing a basis for predicting failure under extreme conditions.

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1. INTRODUCTION

The fracture behavior of brittle materials is strongly influenced by microstructural defects, loading rate, impact energy, and crack propagation characteristics. Previous studies have emphasized the importance of micro-mechanical characteristics and microstructural features in determining the mechanical response of brittle materials [1, 2]. Pores, inclusions, and microcracks can act as local stress-concentration sites that promote crack initiation and accelerate fragmentation. Dynamic loading can also produce rate-dependent strengthening and modify the transition from crack initiation to extensive fracture [3]. In concrete and other brittle materials, increasing impact or blast energy generally decreases average fragment size while increasing the number of fragments [4]. Structural discontinuities and geometric features can generate local stress concentrations and influence damage propagation [5]. Localized deformation and shear-zone development can further modify stress redistribution and fracture evolution [6]. In addition, fracture geometry, temperature, and impact velocity have been reported to affect crack propagation and fragmentation behavior [7, 8]. Dynamic fracture models also indicate that loading rate influences crack velocity, branching, energy dissipation, and fragmentation behavior [9, 10].

Despite these developments, many studies have focused on individual materials or specific fracture mechanisms. A broader comparative analysis is still needed to relate microdefect characteristics, crack propagation, dynamic strengthening, energy localization, and fragmentation across different brittle materials under extreme loading conditions.

This study aimed to: (i) examine the fracture behavior of brittle materials under impact and high-speed loading; (ii) analyze the influence of microdefects, defect concentration, and crack propagation velocity on dynamic stability; and (iii) evaluate the relationship between impact energy and fragment-size distribution. The novelty of this study lies in integrating microstructural characteristics, dynamic-loading conditions, fracture mechanisms, and theoretical approaches within a comparative framework for glass, ceramics, concrete, borosilicate glass, and polycrystalline diamond.

2. METHODS

This study employed a comparative analytical approach to investigate the dynamic fracture behavior of brittle materials, including glass, ceramics (corundum and aluminium oxide), concrete, borosilicate glass, and polycrystalline diamond. The analysis focused on plastic deformation, microdefect size and concentration, crack propagation velocity, loading rate, impact energy, and fragmentation behavior. These characteristics were systematically compared to identify common and material-specific responses under impact loading and high-speed deformation.

Dynamic fracture mechanisms were analyzed by considering crack initiation at pores, inclusions, and microcracks, followed by rapid crack propagation, shock-wave interaction, energy localization, and fragmentation [11-13]. High-speed deformation was further examined in relation to dynamic strengthening and strain-rate-dependent fracture. High-rate characterization methods considered in this study included split Hopkinson pressure bar testing, ballistic and explosive loading, and laser shock techniques [14-16]. These methods provide complementary approaches for evaluating material response under rapid loading conditions. Dynamic fracture mechanics was used to describe the relationship between crack velocity and the dynamic stress intensity factor, as expressed in Equation (1) [17]:

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$$K_d = K\sqrt{1-\frac{v}{c_R}} \qquad (1)$$

where K_d is the dynamic stress intensity factor, K is the static stress intensity factor, v is the crack velocity, and c_R is the Rayleigh wave velocity. Critical fracture occurs when $K_d \geq K_{IC}$.

The Griffith energy criterion with a loading-rate correction was considered to evaluate the relationship between crack velocity and critical fracture energy, as expressed in Equation (2) [18]:

$$G_c(v) = G_c^0\left(1+\alpha\frac{v}{c_R}\right) \qquad (2)$$

where $G_c(v)$ is the critical fracture energy at crack velocity v, G_c^0 is the fracture energy under static loading, α is an empirical coefficient accounting for the influence of loading rate, and c_R is the Rayleigh wave velocity. Crack propagation occurs when $G \geq G_c(v)$.

The influence of randomly distributed microstructural defects on fracture probability was evaluated using the Monte Carlo statistical model presented in Equation (3) [19]:

$$P_f = 1-\prod_{i=1}^{N}(1-P_i) \qquad (3)$$

where P_f is the probability of fracture, N is the number of randomly distributed defects within the material volume, and P_i is the probability that an individual defect initiates a crack.

Fragment-size distribution under dynamic fracture conditions was analyzed using the fragmentation model given in Equation (4) [20]:

$$n(s) \sim s^{-\tau}\exp\left(-\frac{s}{s_0}\right) \qquad (4)$$

where $n(s)$ is the number of fragments of size s, τ is a material-dependent exponent, and s_0 is the characteristic fragment size determined by impact energy. Equation (4) was used to describe the relationship between impact energy and the resulting fragment-size distribution.

3. RESULTS AND DISCUSSION

3.1. Characteristics of Brittle Materials

Brittle materials exhibit high strength but very limited plastic deformation, resulting in sudden failure when critical loading conditions are reached. The characteristics of the investigated materials are summarized in **Table 1**. Glass shows plastic deformation of 0-0.2%, microdefect sizes of 1-50 μm, defect concentrations of 0.1-2%, and crack propagation velocities of 1,500-3,000 m/s. Ceramics exhibit plastic deformation of 0-0.5%, microdefect sizes of 1-100 μm, defect concentrations of 0.5-5%, and crack velocities of 1,000-4,000 m/s. Concrete contains larger microdefects of 10-200 μm and exhibits lower crack propagation velocities of 500-1,500 m/s. Borosilicate glass and polycrystalline diamond exhibit crack propagation velocities reaching 4,500 and 5,000 m/s, respectively.

The data in **Table 1** demonstrate that all investigated materials have plastic deformation below 0.5%, confirming their limited ability to redistribute stress through plastic flow.

Microdefect size varies substantially among the materials. Concrete contains the largest defects, reaching 200 μm, whereas polycrystalline diamond contains defects as small as 1-20 μm. Defect concentration also varies from approximately 0.1% to 5%. These differences are important because cracks, pores, inclusions, and other structural heterogeneities act as local stress concentrators and determine where fracture is initiated.

Table 1. Characteristics of brittle materials.

MATERIAL	PLASTIC DEFORMATION	MICRODEFECT SIZE	DEFECT CONCENTRATION	CRACK PROPAGATION VELOCITY
Glass	0-0.2%	1-50 μm	0.1-2%	1,500-3,000 m/s
Ceramics (corundum, aluminium oxide)	0-0.5%	1-100 μm	0.5-5%	1,000-4,000 m/s
Concrete	0-0.5%	10-200 μm	1.0-1.5%	500-1,500 m/s
Borosilicate glass	0-0.3%	1-80 μm	0.2-3%	1,500-4,500 m/s
Polycrystalline diamond	0-0.1%	1-20 μm	0.1-1%	3,000-5,000 m/s

Note: Measurements were taken on standard samples at a controlled temperature of 20°C, humidity of 50%, and a loading rate of up to 10^5 1/s. Data were adopted from reference [21].

The high crack propagation velocities further distinguish brittle fracture from ductile failure. Crack velocities range from 500-1,500 m/s in concrete to 3,000-5,000 m/s in polycrystalline diamond. Once a crack is initiated, its rapid propagation limits the time available for stress redistribution and promotes abrupt failure. Therefore, although all of the investigated materials are classified as brittle, their dynamic responses differ substantially according to microstructure, defect population, and crack propagation characteristics.

Microdefects play a particularly important role in determining fracture initiation. Cracks, pores, inclusions, and structural heterogeneities create localized stress concentrations that can initiate fracture even when the average applied stress remains below the theoretical strength of an ideal homogeneous material [22]. The strength of real brittle materials is therefore strongly controlled by defect characteristics rather than only by the intrinsic strength of the material.

Crack propagation velocity is also critical because rapidly propagating cracks can involve a large volume of material within a very short time. This behavior increases the probability of crack branching, interaction, and coalescence, eventually producing extensive fragmentation [23]. Consequently, the combination of limited plasticity, microstructural defects, and rapid crack growth governs the characteristic failure response of brittle materials.

3.2. Fracture under Impact Loading

Impact loading produces rapid stress development and energy concentration within a localized region of the material. Stress levels can reach approximately 50-1,500 MPa within fractions of a millisecond, leaving insufficient time for substantial stress redistribution through deformation. Under these conditions, fracture commonly begins at pores, inclusions, microcracks, or other defects that act as preferential sites for crack initiation [11].

The fracture process generally develops through successive stages. The first stage involves crack initiation at stress-concentration sites. These cracks then propagate rapidly through the surrounding material and generate additional microcracks. Interaction and coalescence among these cracks produce a network of internal damage. When the accumulated damage exceeds the material resistance, fragmentation occurs, and the material separates into multiple fragments [12].

Impact energy is also localized in the loading region and generates stress waves that propagate through the material. Alternating compression and unloading zones modify the local stress state and can accelerate crack growth. The interaction between these waves and existing structural defects increases fracture complexity and influences the resulting fragment-size distribution [13]. The sequential development of dynamic fracture under impact loading is schematically illustrated in **Figure 2**.

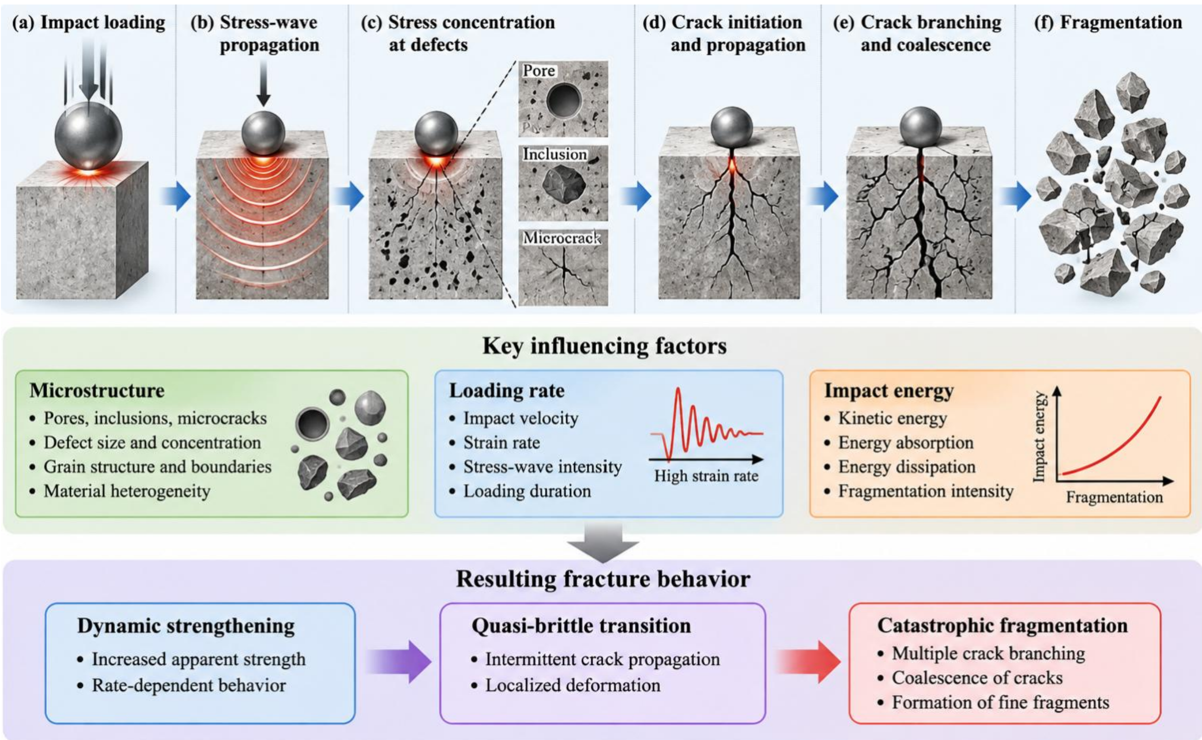

Figure 2. Schematic representation of dynamic fracture evolution in brittle materials under impact loading: (a) application of impact loading to the material; (b) propagation of stress waves generated by the impact; (c) localization of stress around pores, inclusions, microcracks, and other structural defects; (d) initiation and rapid propagation of cracks from stress-concentration sites; (e) crack branching, interaction, and coalescence during continued dynamic loading; and (f) final fragmentation following extensive crack development. The lower sections summarize the roles of microstructure, loading rate, and impact energy in governing dynamic strengthening, quasi-brittle transition, and catastrophic fragmentation.

In **Figure 2(a)**, an external impact applies a concentrated dynamic load to the brittle material. The resulting disturbance propagates through the material as stress waves, as illustrated in **Figure 2(b)**. When these waves encounter pores, inclusions, microcracks, and other structural heterogeneities, local stress concentration occurs around the defects (**Figure 2(c)**). Once the local stress reaches the fracture condition, cracks initiate at these weakened regions and rapidly propagate through the material (**Figure 2(d)**). Continued loading promotes crack branching and interaction among neighboring cracks, eventually resulting in crack coalescence (**Figure 2(e)**). At sufficiently severe loading conditions, the interconnected crack network causes extensive loss of structural integrity and fragmentation into multiple pieces (**Figure 2(f)**).

As also summarized in **Figure 2**, the progression of these stages is influenced by microstructural characteristics, loading rate, and impact energy. Microstructure determines the type, size, concentration, and distribution of potential fracture-initiation sites, whereas loading rate influences stress-wave intensity and the time available for stress redistribution. Impact energy controls the severity of crack propagation and fragmentation. Their combined effects can result in dynamic strengthening at high loading rates, a transition toward quasi-brittle behavior involving localized deformation and intermittent crack propagation, or catastrophic fragmentation when extensive crack branching and coalescence occur. Therefore, dynamic fracture should be understood as an interconnected sequence of stress-wave propagation, defect-controlled crack initiation, crack evolution, and fragmentation rather than as a single instantaneous failure event.

3.3. High-Speed Deformation and Dynamic Strengthening

High-speed deformation produces mechanical responses that differ from those observed under static or low-rate loading. At strain rates in the range of 1,000-1,000,000 1/s, dynamic strengthening can occur, causing the apparent resistance of the material to increase with loading rate [24]. This phenomenon demonstrates that fracture strength cannot be treated as a constant material parameter under extreme dynamic conditions.

A transition from purely brittle to quasi-brittle behavior may also occur under high-rate loading. Localized deformation and shear zones can partially redistribute stress, influence crack trajectories, and alter fragmentation behavior. These mechanisms can temporarily delay unstable crack propagation, although catastrophic fracture may still occur once critical loading conditions are exceeded.

Split Hopkinson pressure bar testing is commonly used to generate controlled high-rate loading and evaluate wave propagation, stress development, and fracture behavior. Such systems can operate at high strain rates and allow dynamic response to be quantified [14]. Ballistic and explosive loading provide higher-energy conditions that more closely represent severe impact and blast environments. Ballistic loading can reach kinetic energies of approximately 5-20 kJ, whereas explosive loading can produce stress amplitudes of 10^4-10^5 MPa over durations of approximately 10-50 μs [15].

Laser shock methods provide highly localized and controlled loading. Laser pulses with energies of approximately 0.1-5 J and durations of 10-100 ns can initiate localized dynamic fracture and allow microstructural fracture mechanisms to be investigated [16]. Together, these methods demonstrate that strain rate, loading duration, energy input, and stress-wave characteristics substantially influence brittle-material failure.

3.4. Fracture Mechanisms

Different fracture mechanisms become dominant under different combinations of stress and strain rate, as summarized in **Table 2**. Crack formation occurs at stress levels of approximately 50-500 MPa and strain rates of 1,000-10,000 1/s. At higher stresses and strain rates, intermittent crack propagation becomes increasingly important. This mechanism is associated with unstable crack advance and rapid formation of additional microcracks. Surface erosion and spalling can occur at lower localized stresses and progressively damage material surfaces. At stresses exceeding approximately 1,000 MPa and strain rates above 100,000 1/s, explosive fracture may occur, resulting in almost instantaneous fragmentation.

Table 2. Fracture mechanisms and numerical ranges. Data were adopted from reference [25].

MECHANISM	STRESS LEVEL (MPa)	STRAIN RATE (1/s)
Crack formation	50-500	1,000-10,000
Intermittent propagation	200-1,500	1,000-100,000
Surface erosion	10-100	-
Explosive fracture	>1,000	> 100,000

These mechanisms should not be considered completely independent. Crack initiation can develop into intermittent propagation, followed by crack branching, surface damage, and ultimately extensive fragmentation as the applied energy increases. The transition among these mechanisms depends on material microstructure, defect distribution, loading rate, and stress amplitude.

3.5. Impact Energy and Fragmentation

Fragmentation provides an important quantitative indicator of dynamic fracture severity. The relationship between impact energy, average fragment size, and the number of fragments is presented in **Figure 1**.

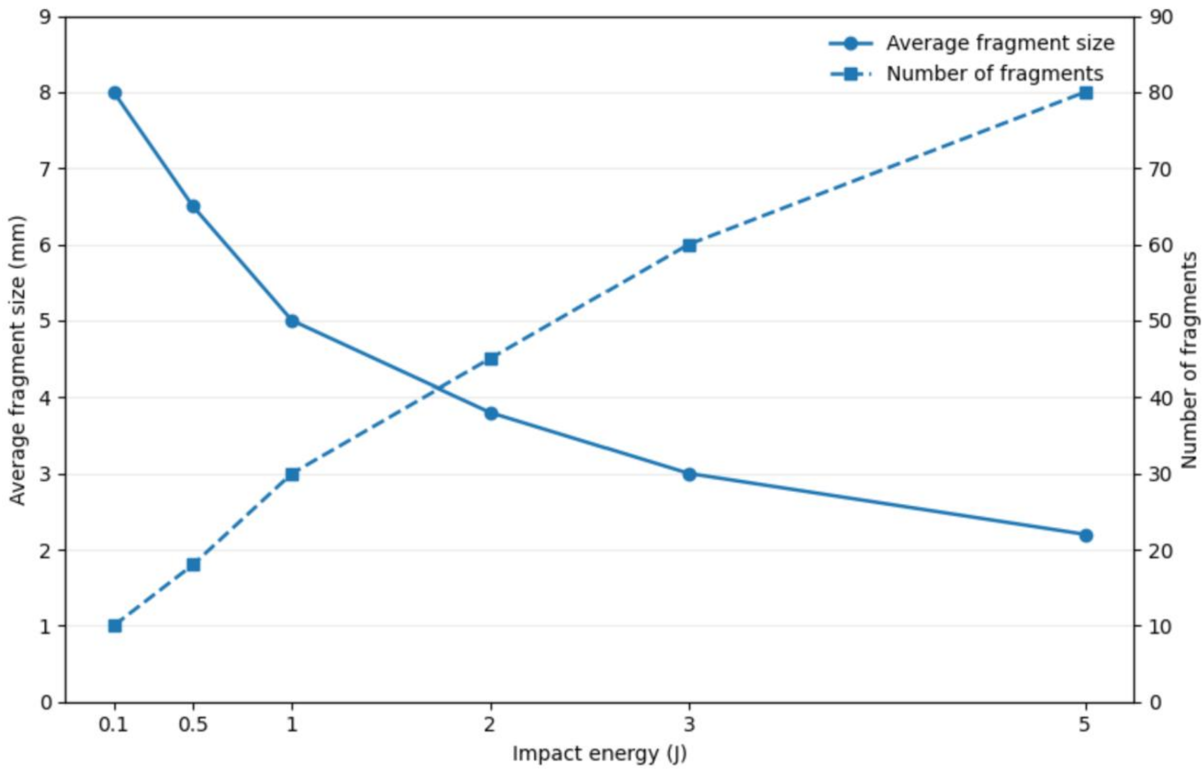

Figure 1. Dependence of average glass fragment size on impact energy. Data were adopted from reference [26].

Increasing impact energy results in smaller average fragments and a larger number of fragments. At an impact energy of 0.1 J, the average fragment size is approximately 8 mm, and the number of fragments is approximately 10. At 5 J, the average fragment size decreases to approximately 2.2 mm while the number of fragments increases to approximately 80. This behavior indicates that additional impact energy promotes the formation and propagation of a greater number of cracks, thereby increasing fragmentation intensity.

Intermittent crack propagation further contributes to dynamic fragmentation. Under rapid loading, crack growth can occur abruptly because stress cannot be redistributed sufficiently quickly through the material. Localized energy release promotes the formation of additional cracks and increases instability [27]. Surface erosion and spalling can occur simultaneously, producing local chipping and microcracking, particularly in materials with high brittleness and very limited plasticity [28].

Under extreme loading conditions, these processes may develop into severe fragmentation as crack initiation, crack branching, intermittent propagation, and localized damage interact within the material. The micromechanical response of brittle particles can also be influenced by microstructural characteristics such as crystallite size, which affect local mechanical properties and resistance to deformation [29]. The progressive reduction in fragment size with increasing impact energy therefore reflects the combined influence of energy input, crack development, and material microstructure.

3.6. Relationship between Microstructure and Dynamic Fracture

The results demonstrate that microstructure plays a central role in determining dynamic fracture behavior. In glass, pores, microbubbles, residual stresses, and variations in atomic arrangement can act as stress concentrators and reduce dynamic strength [30]. In ceramics, cracks, pores, grain boundaries, and other crystal defects similarly influence crack initiation and propagation [31]. Control of these microstructural features is therefore important for improving resistance to dynamic loading.

Under impact loading, stress localization and shock-wave propagation cause fracture to develop preferentially around weak microstructural regions. Concrete subjected to impulsive loading can exhibit rapid stress development, microcracking, and spalling, while its response remains strongly dependent on loading rate and the ability of the structure to dissipate impact energy [32]. Ceramics similarly exhibit uneven energy distribution, with fracture commonly initiating around defects and interfaces where local stresses are amplified [33].

Dynamic strengthening does not eliminate the influence of microstructural defects. In glass, increased apparent strength can occur under high-rate loading, but catastrophic fracture may still develop when critical impact energy is exceeded [34]. Polycrystalline diamond can exhibit quasi-brittle behavior through crack deflection and branching along grain boundaries, which can slow crack propagation and increase fracture resistance [35]. These observations demonstrate that grain boundaries, defects, and residual stresses can substantially alter the transition between stable and catastrophic fracture.

Intermittent crack propagation is particularly important in ceramic materials because structural non-uniformity and weak regions can temporarily arrest a crack before further propagation occurs when the local stress again reaches a critical value [36]. Under more extreme shock or thermal loading, rapid microcrack generation, erosion, and explosive fragmentation can occur [37]. Thus, reducing microstructural weak zones and controlling defect characteristics remain important strategies for improving dynamic fracture resistance.

3.7. Interpretation Using Fracture Models

The experimental and reported fracture behaviors can be interpreted using the theoretical approaches described in Equations (1)-(4). Dynamic fracture mechanics in Equation (1) relates the dynamic stress intensity factor to crack velocity and provides a framework for assessing crack stability under rapid loading [17]. As crack velocity approaches a substantial fraction of the Rayleigh wave velocity, dynamic effects become increasingly important and static fracture assumptions become insufficient.

The energy-based approach in Equation (2) considers the influence of crack velocity on critical fracture energy [18]. This relationship is consistent with the observed dependence of fracture behavior on loading rate and demonstrates that the energy required for crack propagation can vary under dynamic conditions.

Equation (3) represents fracture probability as a function of multiple randomly distributed defects [19]. This statistical description is particularly relevant to brittle materials because fracture initiation is strongly influenced by the presence, concentration, and distribution of microstructural defects. Materials containing larger or more numerous critical defects consequently have a greater probability of premature fracture.

The fragmentation relationship in Equation (4) provides a connection between dynamic loading and fragment-size distribution [20]. This interpretation is consistent with **Figure 1**, in which increasing impact energy leads to progressively smaller fragments and a larger number of fragments. Dynamic, energy-based, statistical, and fragmentation approaches therefore describe complementary aspects of brittle-material failure rather than competing mechanisms.

Dynamic fracture models can incorporate inertial effects, stress-wave propagation, and defect interactions and can therefore improve prediction of crack initiation and propagation under rapid loading [38]. Statistical approaches provide additional capability for representing heterogeneous defect populations, while energy-based approaches describe the balance between stored energy, crack formation, and fragmentation [39]. The combined application of these approaches provides a more comprehensive representation of brittle-material behavior under extreme loading.

No single parameter or theoretical model is sufficient to describe dynamic brittle fracture. Material response emerges from the interaction among microstructural defects, crack propagation velocity, strain rate, stress level, impact energy, and energy redistribution. Integrating these factors provides a stronger basis for predicting sudden failure and fragmentation and for developing brittle materials and engineering structures with improved resistance to impact and high-speed deformation.

5. CONCLUSION

Brittle materials exhibit rapid and complex fracture under impact loading and high-speed deformation. The results showed that fracture behavior is strongly influenced by microdefect size and concentration, crack propagation velocity, stress level, strain rate, and impact energy. Increasing loading intensity promotes crack initiation, branching, and fragmentation, while high strain rates can produce dynamic strengthening and quasi-brittle behavior. The relationships described by dynamic fracture mechanics, the modified Griffith criterion, statistical defect analysis, and fragmentation modeling provide complementary interpretations of these phenomena. Increasing impact energy also reduces average fragment size while increasing fragment number. These findings provide a framework for predicting dynamic failure and supporting the design of brittle materials and engineering structures with improved resistance to extreme loading.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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