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Progress and Challenges in Fracture Prediction of Die-Cast Lightweight Alloys

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ABSTRACT

Die-cast alloys, such as aluminum, zinc, and magnesium alloys, are widely used in automotive, aerospace, and consumer electronics applications due to their excellent mechanical properties, castability, and cost-effectiveness. Fracture failure, however, remains a critical concern, directly affecting performance and service life. This review summarizes current advances in fracture prediction for die-cast alloys, including common alloy types, fracture mechanisms, failure modes, influencing factors, and predictive models. Key studies are cited to highlight the coupled effects of microstructural defects, stress state, and temperature on fracture behavior, and the applicability and limitations of models such as GISSMO and MMC are discussed. Future research directions are also outlined.

KEYWORDS

Die-cast alloys; Fracture failure; Failure prediction; GISSMO; Mohr-Coulomb (MMC); Tension-compression asymmetry; Finite element analysis

1. INTRODUCTION

With the continuous progress of industrialization, the demand for lightweight and high-performance materials has been steadily increasing. Die-cast alloys have become widely used structural materials due to their excellent fluidity, capability to form complex shapes, high production efficiency, and superior surface quality. The main types of die-cast alloys include aluminum, zinc, magnesium, and copper alloys, among which aluminum, zinc, and magnesium alloys are the most widely applied.

Aluminum die-cast alloys (A380, ADC12, A356, e.g.) are widely used in automotive components, such as engine blocks, transmission housings, and suspension systems, as well as in aerospace applications, due to their good castability, relatively high strength, and lightweight. Zinc die-cast alloys (Zamak 3, Zamak 5, e.g.) are often employed for electronic and electrical housings and precision small components because of their low melting temperature, excellent surface treatment performance, and high-precision casting capability. Magnesium die-cast alloys (AZ91D, AM60, ZK60, e.g.) are favored in automotive lightweight designs, including engine covers and chassis components, and in portable electronic devices due to their extremely low density and favorable mechanical properties.

However, die-cast alloys are prone to fracture failures under practical service conditions, particularly under high stresses and complex loading scenarios. Such failures not only compromise structural safety but may also lead to equipment or system malfunction. Different types of die-cast alloys (Al-Si-based A380 and Mg-Al-based AZ91D, e.g.) exhibit significant variations in microstructure and inherent defects, such as porosity and segregation, which result in different fracture mechanisms and failure modes. Therefore, accurately predicting the fracture behavior of die-cast alloys has become a critical research issue for improving their reliability and service life [1].

2. RACTURE MECHANISMS OF DIE-CAST ALLOYS

The fracture behavior of die-cast alloys is closely related to their microstructure and stress state. Common fracture mechanisms include brittle fracture, ductile fracture, and fatigue fracture. At the microscopic level, fracture in die-cast alloys typically involves processes such as void nucleation and growth, void coalescence, and microcrack propagation.

Due to the die-casting process, complex casting defects such as porosity and inclusions are often introduced, which significantly affect the mechanical properties and fracture behavior of the materials. For example, in aluminum die-cast alloys (A380, e.g.), the morphology and distribution of the silicon phase, or in magnesium alloys (AZ91D, e.g.), the β and α phases, have a decisive influence on crack initiation and propagation paths. Wang et al. [2] reported that in die-cast A380 aluminum alloy, void nucleation primarily occurs at coarse eutectic silicon particles or inclusions, and subsequent plastic deformation leads to void growth and eventual coalescence, forming ductile fracture surfaces. Brittle fracture is mainly caused by cleavage of hard brittle phases or intergranular separation.

Fatigue failure in die-cast components is typically initiated by casting defects near the surface or subsurface, particularly pores. Zhang et al. [3] conducted an in-situ study of the fatigue behavior of die-cast Al-Si-Cu alloys using X-ray computed tomography (XCT) and confirmed that the size of the largest pore, rather than the total porosity volume, is the dominant factor controlling high-cycle fatigue life.

3. FACTORS INFLUENCING FRACTURE FAILURE

The fracture behavior of die-cast alloys is influenced by multiple coupled factors, including composition, microstructure, stress state, and temperature.

The fracture response of die-cast alloys is closely related to their composition and microstructure. Different alloy systems exhibit distinct characteristics. For example, in A380 (Al-Si-Cu) aluminum alloy, the morphology, size, and distribution of eutectic silicon in the microstructure are critical factors affecting fracture. The microstructure of Zamak 3 (Zn-Al-Cu) zinc alloy mainly consists of Zn-rich α phase and Al-rich β phase. In AZ91D (Mg-Al-Zn) magnesium alloy, the α-Mg matrix and the β-Mg/Al eutectic phase along grain boundaries are key structural features. Miyazaki et al. further reported that rapid cooling (high-pressure die casting, e.g.) can refine the grains and produce a dispersed, discontinuous β phase, significantly enhancing the elongation and fracture resistance of AZ91D [4].

Casting defects such as porosity, shrinkage cavities, and inclusions are major contributors to fracture failure. Shabani et al. [5] demonstrated that porosity defects in die-cast A380 alloy significantly reduce its fatigue strength.The figure1 shows the results of a uniaxial tensile test on the heat-treatment-free die-cast ADC12 alloy. The specimen fractured outside the gauge section, indicating that the result was dominated by casting defects.

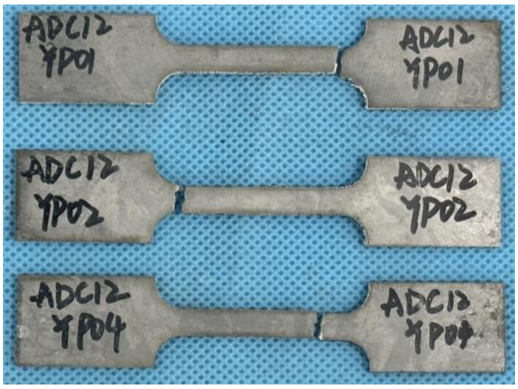

Figure 1. ADC12 Uniaxial Tensile Fracture Diagram

The difference in the stress-strain curves of the samples in the figure2 is caused by the voids within the material.

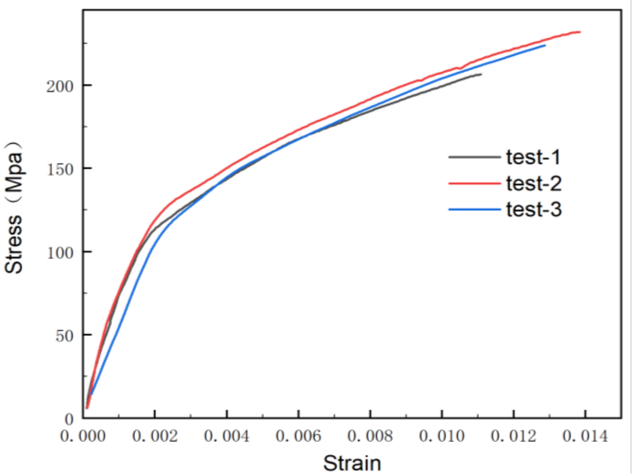

Figure 2. ADC12 Uniaxial Tensile stress-strain curves

Stress state plays a critical role in fracture behavior. Die-cast alloys are typically subjected to complex multiaxial stresses. The triaxiality (η) and Lode parameter (θ)-based fracture criteria proposed by Bao [6] have been widely recognized in the academic community. Liang et al. [7] calibrated the fracture strain of die-cast AM60 magnesium alloy under different stress triaxialities through tensile tests on round bars with V-shaped notches. The results confirmed that fracture strain (ductility) decreases significantly as triaxiality increases (from shear to tension). In addition, the asymmetry between tensile and compressive responses is also a critical factor. Yang et al. [8] investigated A356-T6 cast aluminum alloy and found that, although the yield behavior under tension and compression was similar, the plastic deformation capacity differed greatly: the tensile elongation was only 15%, whereas the compressive strain could exceed 1.2 (120%). This tension-compression asymmetry imposes higher requirements on fracture prediction models, especially when simulating complex stress states involving bending or collision.

Temperature is another key factor affecting the fracture behavior of die-cast alloys. Hu et al. [9] reported that the yield and tensile strength of A380 aluminum alloy decrease significantly at elevated temperatures (150-200 °C, e.g.) due to grain boundary softening and creep effects. For Zamak 3 zinc alloy, Gomez et al. [10] indicated that its ductile-to-brittle transition temperature (DBTT) is near 0 °C, and the material exhibits pronounced brittleness below this temperature.

4. FRACTURE FAILURE PREDICTION METHODS

Various methods have been proposed for predicting fracture failure in die-cast alloys.

Ductile Fracture Criteria (DFC) are models that predict fracture based on plastic deformation and damage evolution. The GTN model was first proposed by Gurson (1977) and later modified by Tvergaard and Needleman (1984) [11, 12]. This model, based on void evolution, effectively describes the damage process of ductile metals. Han et al. (2020) successfully applied the GTN model to fracture simulations of A380 aluminum alloy; by incorporating void nucleation and coalescence parameters calibrated according to porosity, they accurately predicted the fracture initiation locations in notched specimens [13].

The Johnson-Cook (JC) failure model, proposed by Johnson and Cook (1985), is widely used in high-speed impact simulations such as automotive crash analyses due to its simplicity and ability to couple strain rate and temperature effects [14]. The Generalized Incremental Stress-State dependent damage MOdel (GISSMO) is a phenomenological damage model extensively applied in industry, especially in automotive crash simulations, as it accurately captures the influence of stress state on damage accumulation and failure. Most studies on metal plasticity and fracture models focus on shells and fine hexahedral elements. However, generating high-quality hexahedral meshes for complex die-cast components is extremely challenging. To address this issue, Ge et al. [15] investigated the application of the GISSMO fracture model on tetrahedral elements for three thin-walled cast aluminum alloys (A356, A383, and C611), extending the applicability of the model to complex geometries.

The Mohr-Coulomb (MMC) criterion and its variants (e.g., modified MMC) perform well in describing shear-dominated and tension-compression asymmetric fracture, making them particularly suitable for simulating materials with tension-compression asymmetry, as observed by Yang et al. [24]. Zhang et al. [16] conducted monotonic loading tests on A356 die-cast aluminum alloy and fitted an MMC fracture model for solid elements, validating the model through compression and bending tests. Lee et al. [17] further performed tensile, shear, and compressive tests on cast aluminum alloys used in automotive suspension systems, and combined the isotropic Hershey-Hosford yield criterion (for plasticity) with the Mohr-Coulomb fracture criterion to construct ductile fracture trajectories covering a wide range of stress triaxialities and Lode angles, accurately characterizing the material's plastic deformation and fracture initiation.

The predictive accuracy of DFC models heavily depends on accurate parameter calibration. Traditional calibration methods rely on extensive physical testing under multiple stress states (e.g., notched tension, shear) and numerous "trial-and-error" simulations. To improve calibration efficiency and accuracy, Xiao et al. [18] proposed an extended iterative finite element method (FEM) for obtaining GISSMO model parameters. Their study tested four alloys, including ADC12 aluminum alloy and ZK60 magnesium alloy, under positive stress triaxiality conditions. The results demonstrated that the iterative method can accurately estimate fracture behavior, outperforming conventional calibration approaches.

Finite Element Analysis (FEA) serves as the primary platform for implementing these predictive methods. By embedding DFC or fracture mechanics models into FEA, failure predictions for complex components can be achieved. Zhao et al. [19] constructed micro-FEA models of die-cast aluminum alloys incorporating real porosity defects based on XCT scans. The simulations showed that interactions among pores in local stress concentration regions are the main contributors to final failure, while homogenized macroscopic models cannot capture this localized failure behavior. Furthermore, the type of finite element affects prediction accuracy. As mentioned, Ge et al. [15] addressed the challenges of applying the GISSMO model to tetrahedral elements, while Zhang et al. [16] verified the effectiveness of the MMC model in solid elements. These studies are of great significance for fracture simulations of complex die-cast components, which are difficult to discretize into high-quality hexahedral meshes.

5. RESEARCH PROGRESS AND CHALLENGES

Despite significant progress in fracture prediction of die-cast alloys, several challenges remain:

Randomness and characterization of microscopic defects: The size, morphology, and spatial distribution of casting defects, such as porosity and shrinkage cavities, are highly random. Effectively incorporating the statistical information of these random defects into macroscopic FEA models remains a significant research challenge.

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