The strength of the ceramic matrix composites under the influence of pore is reviewed

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Abstract. Ceramic matrix composites with strong structural characteristics, is a kind of multiphase materials. Its mechanical properties and the regularity of damage not only depends on the material properties of components, but also depends on the mesoscopic structure characteristics. Past for reinforcement of composite materials, usually by adding inclusions, makes the interface strength is improved. But as a result of the mixed with non-uniformity, and the preparation process to air and other impurities, makes the substrate near the interface of substrate, in particular, inevitable existence of the pore, pore under external load when the crack and then expand, causing material failure. So by studying the material under external load impact, its performance in the damage evolution of mesoscopic level and macro failure, the relationship between material from the mesoscopic level analysis the rule of damage evolution and fracture mechanism, can not only provide theoretical guidance for the preparation of composite materials, but also through the further optimization of material mesoscopic structure to achieve the purpose of design materials. In this paper, the current ceramic matrix composites, has introduced the preparation of defect, defect cause material damage failure occurred, and the research status of the influence of the effective strength of the composites, the composite material related research achievements and disadvantages, on the basis of combining the simulation modeling analysis method for composite material next effective strength problem research was discussed.

1. Introduction
With the development and continuous progress of national defense science and technology, at present, there is hardly a single material or a single component in the weapons and equipment of all services and arms. Composite materials with multiple composite properties are widely used in equipment practice. Composite material is a kind of polyphase material which is made from non-single component materials and combined by composite means. Compared with traditional materials, composite material and structure have the characteristics of designability, identity and dependence on composite technology. However, due to the complex mechanical properties and phenomena of composite materials on the emplacement characteristics, anisotropy and stratification [1]. The material knowledge alone is not enough to judge its properties, so it must be studied with the help of the knowledge of microscopic mechanics. So through research materials subjected to external load, the damage evolution of mesoscopic level and macro failure performance, the relationship between material from the mesoscopic level analysis the rule of damage evolution and fracture mechanism, can not only provide theoretical guidance for the preparation of composite materials, but also through the further optimization of material mesoscopic structure to achieve the purpose of design materials. Due
to its superior performance and special functions, composite ceramics have been playing a more and more prominent role in high-tech frontier fields. Especially in modern high-tech warfare, advanced composite ceramics with characteristics of low density, energy absorption and dynamic effect have become preferred materials for weapons and equipment. Compared with single-phase ceramics, ceramic matrix composites not only improve the hardness and elastic modulus of ceramic materials, but also improve the shortcomings of single-phase ceramics, such as poor fracture toughness and large crack propagation rate [2]. Therefore, they have more advantages in engineering applications.

As the connection part between two phases, defects are easy to appear near the interface and lead to the reduction of bond strength. When the defect begins to be damaged and cracks appear under the action of applied stress, the crack grows under the action of gradually increasing applied stress until the final material failure. Therefore, the study of the mechanical properties of the interface between different phases in composite materials has a significant impact on the design and development of materials and the prediction and evaluation of fracture damage.

2. Research status at home and abroad

2.1. Research status of preparation defects of ceramic matrix composites

In recent years, great progress has been made in improving ceramic performance through advanced preparation technologies such as directional solidification technology and ultra-gravity combustion synthesis technology. The bending strength of Al$_2$O$_3$/ZrO$_2$ eutectic composite ceramics prepared by Professor Zhao Zhongmin can reach 1256MPa [3]. However, due to the material composition and composite ceramic crystallization experienced during the preparation of complex reaction process, and a great deal of temperature changes made will inevitably emerge in the composite ceramic defects, such as free gas, impurity particles residues in the process of the formation of the micro holes and cooling mesosopic composition micro cracks caused by thermal expansion coefficient difference and so on. And these defects often result in a substantial decrease in the effective strength of the material.

Brittle material defect is extremely sensitive. Inglis study found that long and narrow can cause severe stress concentration near the hole, Griffith theory shows that the strength of materials and the crack half-length is inversely proportional to the square root of [4]. In addition, with the increase of content of defects, most of the carbide, cement, the material such as rock physical properties such as the effective strength, stiffness, hardness are obvious downward trend, and high brittleness of the ceramic material is more outstanding [5-7].

The microstructure has a decisive influence on the overall properties of brittle materials. For single phase average of brittle material, because of the energy dissipation mechanism of a single defect once extended often led directly to the material destruction, and the introduction of other phase in the composites, changed the mesoscopic structure and stress field distribution, the introduction of a variety of energy dissipation mechanism, an important role in improving the material tenacity. Toughening enhancement due to a variety of mechanisms, the function of damage and fracture evolution law of composite ceramic is more complex, the researchers of ceramic matrix composites has carried on the thorough research, also had many representative conclusions, but considering the defects, especially porosity role under the influence of mesoscopic properties is relatively less, most research often under the premise of ignoring defect analysis of the mesoscopic composition and structure, which can lead to theoretical results may not accurately reflect the inner connection of mesoscopic characteristic and the strength of materials, there are large deviation between theoretical results and the actual data. Therefore, it is of great significance to fully consider the matrix defects, especially the matrix properties around the pores, to study the defect spreading mechanism in depth, to predict the material performance, to evaluate the reliability of the material, to guide the improvement of the material microstructure, and to reduce the test and production cost.

For ceramic matrix composites, the pore distribution has the following characteristics: one is the defect is mainly distributed in grain and grain area or contact space between the glass phase, in the case of a small number of burnt may appear pore contained in the case of grain, thermal expansion
mismatch effect by the composite components, micro cracks also exists in this area more [8]. Second, in addition to some ceramics used for special purposes, the process means that the defect size of the composite ceramics with good quality can be controlled at the nanometer level, generally smaller than the grain size, and tends to concentrate towards the grain boundary. Therefore, theoretically speaking, the mechanical properties of the medium around the defect need to be studied in detail. Third, pores in general ceramic materials mainly exist in the form of closed pores [9]. For Al₂O₃-ZrO₂ eutectic ceramic matrix composite materials, defects generally appear between rod-shaped eutectic, with different shapes, mainly spherical, tetrahedral, and hexahedral, while the internal eutectic is mostly orthotropic or transverse isotropic due to the homogenous arrangement of micro-inclusion structure. In order to facilitate the research, Fu Yunwei [10] replaced the ellipsoid model in the research process, and also considered the influence of stress concentration at part of the crack tip. At present, there are few simulations and reports on the influence of such defects on the elastic properties, thermal expansion coefficient and strength of composite ceramics.

In order to more intuitive understanding of mesoscopic structure of composite material, as shown in figure 1, in the Al₂O₃ substrate, ZrO₂ as strengthening phase, forming rod-shaped eutectic, several eutectic synthetic array forming similar grain or crystal structure, and multiple rod-shaped eutectic formed area edge usually have not form a eutectic ZrO₂ and other granular or lamellar structure.

2.2. Research status of damage failure of ceramic matrix composites

As one of the most common and most widely used composite materials, ceramic matrix composites have a representative meso-mechanical damage pattern and a certain research value. Matrix cracking as one of the most common failure forms of ceramic matrix composites, the majority of scholars of the crack in the production and the extension that concern for most of the bearing of its material properties-stress strain curve has a very extensive research, the stress and strain distribution to predict the failure of continuous fiber reinforced ceramic matrix composites have quite important significance.

In order to study the influence of crack factors on the damage failure of materials in a more specific and in-depth way, researchers at home and abroad often ignore the inevitable pore influence in the preparation process, resulting in less reports on the failure effect caused by pores. At present, foreign reports on pores are mainly studied from a two-dimensional perspective by using numerical simulation. Kristin A [12] found that pores in composite materials containing oxides could not only reduce the failure strength of the materials but also play a certain toughening role. Hiroki Fujita [13] described the effects of pores on toughening, weakening interface, thermal hardening and mechanical properties. Artz T et al. [14] proposed an oxidization-assisted fracture model based on the framework of continuous damage mechanics, and found that in the process of stretching, the damage first developed slowly in the area around the hole with the highest stress. Over time, damage spreads, cracks form, and fiber bundles rapidly fail. Chateau et al. [15] discussed the effect of porosity on the properties of unidirectional fibre-reinforced SiCf/SiC composites. They showed that the porosity of the composite increased from 4% to 9%, while the lateral stiffness of the composite decreased to about 50%. Shi et al.
[16] used Monte Carlo simulation to study random void elements in the matrix to simulate defect distribution and elastic mechanical properties of materials. Shen[17] compared the two THREE-DIMENSIONAL silicon carbide particles enhanced RVE pore models, and found that the predicted tensile properties of the two RVE models decreased with the increase of porosity, while the smaller tensile modulus was calculated by the RVE model of randomly distributed pore materials, which provided reference for some applications of CVI processing without densification.

The Domestic Zhang Junyan [18] studied the effect of porous material failure under different conditions of open-hole and closed-hole. Liao Mingshun [19] used numerical analysis to discuss the mechanical properties of foam with high porosity and made some progress. Duan Jinchao et al. [20] used RFPA to simulate and analyze the uniaxial compression failure mechanism and hole size effect of periodically arranged porous brittle materials.

According to the meso damage theory, the microcracks grow stably in the continuous damage zone of the crack tip, and then the microcracks enter the damage localization zone with stress drop and continue to grow. Figure 2 shows the elasto - brittle sudden damage model with residual strength when external loads are applied. Section OB is the linear stage before the applied load reaches the failure threshold. Considering the influence of damage, the single tensile stress-strain relation is

$$\sigma = \begin{cases} E\varepsilon & (0 \leq \varepsilon \leq \varepsilon_c = \sigma_c / E) \\ f(\varepsilon) & (\varepsilon \geq \varepsilon_c) \end{cases}$$

(1)

Where, is the elastic modulus of OB section, and is the maximum tensile stress sustained is the strain corresponding to the corresponding tensile stress [21].

![Figure 2](image.png)

**Figure 2.** The elasto-brittle sudden damage model with residual intensity.

2.3. **Research status of strength of ceramic matrix composites**

As an important mechanical index, strength has been used to guide the design and practical preparation of materials since the 19th century. Corresponding to the concept of strength, the researchers proposed a more intuitive hypothesis - critical applied stress -- which became the basis of the first theory of fracture. 1920, Griffith, based on the theory of classical mechanics and thermodynamics energy, the crack propagation criterion was deduced. After Griffith, energy balance after thoughts become a breakthrough point, many scholars research such as Irwin - Orowan has carried on the promotion of Griffith theory, considering the other energy dissipation mechanism of the crack tip, Barenblatt the cohesive zone model is put forward and so on, these studies have shown that: the intrinsic separation process did occur on the atomic scale, which generates the nano mechanics of mesoscopic mechanics and the research methods [4]. The above recognition improves the accuracy of fracture failure problem and strength model research, but at the same time increases the complexity of mathematical calculation sharply, and convergence becomes a problem that needs to be paid close attention to. With the deepening of the research, more and more people realize the importance of mesoscopic structural parameters to the fracture development of materials, so the research focus of composite material fracture naturally transferred to the mesoscopic level.

The earliest mesoscopic strength model of composite materials can be considered as the strength
statistical model. Phoenix et al. [22] estimated the interface shear strength of the bearing process of single fiber reinforced composite materials based on the strength statistical model and attempted to extend it to the research problem of multi-fiber materials. However, due to the noncontinuity, nonuniformity and complexity of failure modes of composite materials, it is difficult to establish the strength statistical fracture theory, which limits the development and application of this model.

For porous materials, studies have shown that there is an empirical formula between their compression strength and total porosity, namely the Ryske with equation [23]:

\[ \sigma = \sigma_0 e^{-\beta P} \]

Where P is porosity, constant C takes into account the influence of pore shape, size and connectivity, etc. Empirical formula has important value in engineering application, but this kind of research did not involve the influence of porosity on the material strength mesoscopic mechanism, therefore needs to be based on mesoscopic mechanics fully considering mesoscopic structure defects and defect of interaction between mechanical model and evolution model, can according to the specific material to make more accurate explanation and forecast.

Defects can be considered as a kind of damage in materials. The theory of damage mechanics is applied to explain the development and evolution of defects in materials, and great progress has been made in studying the macroscopic equivalent properties of materials. Zhou Jianping [24] studied the anisotropy of surface friction with contact microcracks under tensile and compressive loading, and Kachanov [25] summarized and commented the damage theory of microcracks and made certain research results in damage analysis and research.

With the development of computer software, finite element method has been widely used in strength model research and has made great progress in strength analysis of composite materials. T. Sadowski [26] et al. analyzed the stress distribution of discontinuous polycrystalline ceramics containing metal particle phase under uniaxial tensile condition with cracks inside the grains by finite element method. Emin Ergund et al. [27] used the finite element method to simulate the influence of cracks at different positions of particle-reinforced metal-matrix composite ceramic materials, and found that the stress intensity factor was related to the loading conditions and greatly affected by the ratio of elastic modulus of particles and matrix, and the relationship between the elastic properties of particles and matrix had a great influence on the crack orientation. Xing Hailong [28] analyzed the influence of external loads in different directions on material strength by studying the stress-strain curves of C/SiC composites in transverse tensile and longitudinal tensile fracture processes and adopting the finite element simulation method. Xu Jianxin et al. [29] simulated the principal direction Angle of the material by using finite element method, and obtained the S-N curve of the material. The positive correlation between the crack growth rate and the number of cycles is obtained. At the same time, the increase of STRESS intensity factor is accelerated with the increase of material principal direction Angle.

In addition, the rapid development of simulation software also promotes the research on the strength prediction of composite materials. I.B.C.M. Ocha [30] USES Mesomodel to collect highly customized training data from multiple integration points and injected single micromodels representing the strain history to generate hyper-reduced or neural network models. It can effectively solve the problem of sampling in the maximum possible strain combination space, and greatly improve the computational efficiency by modeling a given mesoscopic structure without running the full order FE2 model. TabiaiI [31] provides accurate full experimental displacement field measurement of interface debonding and damage initiation near the fiber or fiber bundle, so as to better predict the damage initiation, growth and strength determination of the fiber under transverse load.

3. Summary and prospect
This paper defects of ceramic matrix composite materials preparation, research status and the strength damage failure, found that the current research strength of composite materials, aiming at the effects of
material composition and its interaction, mostly, the defects in the inclusion and interface, especially for matrix porosity tend to ignore, and thus makes the theoretical derivation and experimental verification, and the simulation analysis results between fitting degree is not ideal enough, the physical properties of a mesoscopic level didn't also can bind to the strength of the macro performance and lead to the conclusion there are some room to improve.

In addition, it is found that during the modeling process of previous studies, due to the continuous development of composite materials, the types and ratios of doped elements are also constantly adjusted and improved. In order to maximize the enhancement of doped matrix materials, the internal structure of materials becomes more and more complex. At present, some don't consider interaction as fully combined interface processing mesoscopic mechanics model, for the general case, doped fiber and matrix combined with relatively uniform, properties of interface, and a relatively stable structure model, on the strength of the composite material is derived, by experimental verification, the fitting degree of ideal, but when doped fiber and matrix combined with the situation is more complicated, and not only on the defects in the matrix, the interface properties of different situation, also can't through a unified model is analyzed, also need to further the mechanism of the model based on damage mechanics, An in-depth analysis of the inherent defects and the mode of crack development. Therefore from the macro research Angle to material, on the one hand, on the current material preparation process, the different elements of doping ratio, doping and experiment preparation process was optimized, at the same time, it can, in theory, a new strength prediction model is established, the theoretically predicted material performance, not real materials design for reference. At the same time, the research on the strength prediction of composite materials depends on the realization of simulation software, so the progress of simulation method and computer technology is needed.

In the recent past some of the model in the computer simulation verified the finite element software, I found that in addition to basic model parameters influence the same model in the simulation analysis and theoretical derivation results under different scales has certain error, on the one hand, as a result of the simulation software in meshing and near the interface of connection form for attaining and theoretical model of the effect exist discrepancy, on the other hand is a computer software for small micro level, nano level, especially because of the scale is too small, can't draw the corresponding scale of RVE model, When the scale is enlarged in the same proportion, the order of magnitude of the scale changes again. At the same time, because the grid division is too detailed, greatly improve the calculation time, if the rough grid division, it is easy to cause the calculation results do not converge. Moreover, because the strength model envisaged includes pores, interfacial debonding, and dynamic elastic moduli, the divided elements are liable to have both debonding and cracking in the same element, resulting in uncomputable results. Therefore, in the next step of using ANSYS simulation software for verification, it is essential to use the life and death unit model and APDL parametric finite element analysis technology [32], which is undoubtedly a major innovation and breakthrough point in the next step of research.

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