Composite Structures 155 (2016) 145–159

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Interfacial failure modelling of diamond bits made of particulate composites

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A R T I C L E I N F O

Article history:
Received 4 January 2016
Revised 15 July 2016
Accepted 27 July 2016
Available online 29 July 2016

Keywords:
Diamond impregnated bits
Particulate composite materials
Diamond pull out
Interface de-bonding
Cohesive zone modelling
Finite element modelling

A B S T R A C T

The failure analysis of diamond impregnated bits, which are found as particulate composite materials consist of diamond particles randomly distributed within a metal matrix, is conducted to study the pull out behaviour of diamond grits for an assessment of diamond retention capacity of these drilling bits. The finite element technique is used to model the diamond-matrix system where a zero thickness surface based cohesive zone modelling technique is used to simulate the failure at the interface between the matrix and the diamond particle. For the validation of the model, few numerical examples are initially solved and the results produced by the model are compared with the published results which show a good performance of the model. Finally, a parametric study is conducted to show the effects of shapes, orientations and protrusions of diamond particles as well as interface properties on the retention capacity of diamond particles.

1. Introduction

Since the invention of synthetic diamonds dated back to 1950s, these diamonds have been increasingly used as impregnated diamond tools for drilling, grinding, sawing and similar activities of hard materials such as rock, concrete, metal and glass. The popularity of diamond impregnated tools is due to various advantages such as low friction coefficient, high stiffness and thermal conductivity as well as high bulk modulus exhibited by these tools [1,2]. The impregnated diamond bits are commonly used in the mineral exploration industry for drilling hard rocks. A segment of these bits is made with particulate composite material consist of large numbers of diamond particles having a size of the order of 100 μm which are evenly distributed within a metal matrix. The diamond grits are thoroughly mixed with metal powders and the mixture is processed under high temperature and pressure, known as sintering process, to form these solid bit segments. The materials commonly used for this metal matrix are cobalt, copper, tin, tungsten, and nickel due to their optimal mechanical and thermal properties [3–5]. During the drilling operation, when the cutting surface of the bit slides over a rock due to rotation of the bit, the embedded diamond particles near the cutting surface are partially exposed due to gradual wear of the matrix material and these exposed diamonds do the cutting or drilling of the rock. The matrix is expected to hold the freshly exposed sharp diamonds firmly and at the same time, it should wear at a rate compatible with that of diamonds so that the worn diamond can fall out to allow new diamonds to expose continuously [6]. This is one of the major advantages of impregnated diamond bits, which is known as their self-sharpening ability. The de-bonding of diamonds prior to reaching their full service life is one of the most undesirable failure modes of these bits. This premature loss of diamonds greatly impacts the tool's cutting efficiency and increase the cost of drilling operation [7].

In order to study the mechanical properties of particulate composites, Huang et al. [8] conducted an experimental test to evaluate the Elastic Moduli of polyester resin matrix composites with hollow glass spheres inclusions as reinforcements and the results have been compared with the theoretically calculated elastic moduli. Tagliavia et al. [9] have investigated the mechanical properties of syntactic forms reinforced with spherical hollow particles under tensile loading where the effect of particle-matrix de-bonding and particle wall thickness on the elastic modulus of the reinforced foam has been shown. Tagliavia et al. [9] have developed a model which they used along with the finite element analysis to undertake this research. Shams et al. [10] have developed another model and made a study, which is very similar to Tagliavia et al. [9]. However, the behaviour of these particulate composite materials [8–10] will be quite different from the diamond impregnated bits as the most effective particles are partially exposed from the matrix in

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http://dx.doi.org/10.1016/j.compstruct.2016.07.075

the present case whereas these are embedded within the matrix for these materials [8–10].

The retention of diamond grits by the matrix is a complex and system-dependent process which is affected by the properties of the matrix, interfacial materials as well as the size, shape and orientation of diamond particles [11,12]. A poor adhesion at the interface between the matrix and diamond particles leads to premature fall out of diamond grits while resisting the interfacial stresses developed during the operation of the bits. A majority of literature has identified that the premature interface failure is one of the major issues limiting the performance of diamond bits. In some cases, diamonds are mostly hold by the matrix through mechanical interlocking which gives a low interfacial strength. In order to improve the retention capacity of diamonds, many attempts have been made to establish a strong bond between the matrix and diamonds by adding some alloy which reacts with carbons present in diamonds to form chemical bonding in the form of metal-carbide elements at the interface [13,14]. Initially, iron, tungsten and nickel alloys are added into the metal matrix formation which not only helps to improve the strength, toughness and hardness of the matrix but also enhances the interfacial strength as these metals have a strong atomic bonding affinity for carbons. However, it has been proved that a severe diamond surface degradation is often observed by the formation of too thick carbide layers due to adding more chemically reactive materials into the metal matrix powder [7]. Also for an industrial scale of production, it is almost impracticable to prevent the graphitization of diamonds under high temperature which is required when the matrix material includes these reactive alloys. Consequently, the technique of metal-coated diamonds has been invented which not only protects the diamonds from oxidization, but also increases their retention capacity [12]. Tungsten has been widely used as a coating material for diamond grits, and it helps to form a thin film of tungsten carbide at the interface that acts as a strong chemical bond between the matrix and diamonds [7]. Besides using tungsten as coating material, some other metals such as Ti-coating are also used which improves the interfacial bonding strength significantly [4].

Initially, some experimental studies [6,15,16] on impregnated diamond bits were conducted where the wear mechanisms of these bits were investigated. Also, the wear modes have also been classified into four distinct types where the pull out of diamonds is one of these failure modes, which has an importance influence on the efficiency of these bits. However, no one made any attempt to quantify these failure mechanisms in terms of displacements, forces or some other mechanical parameters so far. The first attempt towards modelling the behaviour of these diamond bits is due to Zhou et al. [17] who conducted stress analysis of a single diamond particle along with a portion of the surrounding matrix as a representative part of these bits using a 2-dimensional finite element model without considering any failure or damage at the interface between the matrix and diamonds. This may be defined as a micro-mechanical modelling of the bits where the diamond is subjected to a horizontal cutting force only at its cutting tip. Zhou et al. [17] plotted the variation of normal stress along the interface for different levels of matrix wear and these stress distributions were taken as the measure of interface de-bonding failure. Suh et al. [18] conducted a similar study on diamond impregnated grinding wheel where they calculated the von Mises stress along the interface where they also studied the effect of unsymmetrical matrix wear with respect to the diamond particle. In a slightly different study, Li et al. [19] tried to predict the plastic deformation and residual stresses within the matrix near the diamond particle which are produced due to the sintering process where a 3-dimensional finite element simulation of the micro-mechanical model were used. It is interesting to note that no one has paid any attention so far on the modelling of interface failure of this system which can predict the diamond pull out process more realistically. This is a problem of interfacial crack propagation which is a complex process but a proper modelling of this process is necessary for a better understand of these diamond tools and their design.

A satisfactory solution of the above problem can be achieved by using the concept of fracture mechanics which can be implemented through finite element modelling. In this context, the Virtual Crack Closure Technique (VCCT) [20] became quite popular which is based on Linear Elastic Fracture Mechanics (LEFM). Although valuable information related to onset and stability of a crack can be obtained by using this technique (VCCT), it is not convenient for modelling crack propagation as VCCT requires re-meshing to advance the crack front when the energy release rate reaches its critical value [21]. Moreover, the VCCT requires the information of a pre-defined initial crack. These problems can be eliminated by using the cohesive zone modelling (CZM) technique which is becoming very popular in recent years for modelling automatic crack propagation in many engineering problems. However, this technique needs the information of the crack propagation direction in advance. Incidentally this is predefined in the present problem which is simply the interface between the matrix and diamonds. Similarly, there are many other problems such as delamination in multi-layered composite laminates, bond failure of reinforcing bars or externally bonded plates in concrete structures, delamination in adhesively bonded joints, matrix-inclusions de-bonding in any composite materials and similar situations where the direction of crack propagation is known [22–24].

Actually, the delamination problem in multilayered composite structures has drawn a significant attention in recent past which has helped to develop this modelling technique (CZM) so well that it can be used with full confidence. The fundamental idea of the CZM technique is based on the concept of fracture process zone which is characterise by the cohesive law or traction separation law for the de-cohesion of atomic lattices as proposed by Barenblatt [25]. According to this model, the traction across the interface between the two materials is increased elastically at the beginning with the separation of these two materials until the traction reaches its critical value. This traction is then decreased with further increase of the separation and eventually disappears according to some principles of damage mechanics.

The CZM technique, which has been successfully applied to various problems, should to be most suitable for the present problem but it has not been exploited so far. Thus the matrix-diamond interface failure is modelled by finite element and CZM techniques in combination for the first time in this study. This will help to understand the wear mechanism of impregnated diamond bits due to diamond pull out more accurately that can benefit the design of these bits. Moreover, there is a need for investigating the effect of different parameters such as protrusions, shapes and orientations of the diamond particle on its retention capacity which is undertaken in this research as this has not been studied previously.

2. Numerical model

2.1. Geometry of the model and its finite element meshing

Similar to the previous investigations [17,18], the failure of diamond impregnated bits is modelled by taking a single diamond particle which is partially embedded within the matrix and cuts the rock with its exposed part during the drilling operation (Fig. 1a). The model also includes a portion of the surrounding matrix that holds the diamond particle (Fig. 1a) where the dimension of this portion of matrix (within the dotted lines) is adequate