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# Role of cobalt of polycrystalline diamond compact (PDC) in drilling process

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ABSTRACT

The contact surface between polycrystalline diamond compact (PDC) and rock was divided into three main areas according to the distinction in heat caused by various frictional forces during drilling process. As temperature rising during drilling, Co played a dominant role in the thermal stability of PDC, however the influence from Co oxidation could be negligible. Usually PDC has a self-sharpening ability with Co removing during drilling, while the injected cooling water (generally mixtures consisting of water and soil) breaks the formed shape. That is because water molecules and soil adhere to the frictional surface thereby forming an absorbed film which prevents direct contact between PDC and rocks, thus the effect from continuous impact forces is enhanced which brings about more unfavorable results. Controlling the content of Co is not only a vital problem existing in PDC industry but an effective way to improve drilling performance.

## 1. Introduction

Polycrystalline diamond compact (PDC) cutter is synthesized through the system in which diamond powder is sintered on the surface of a cemented WC–Co substrate at the temperature of 1400–1700 °C and pressure of 5–7 GPa [1,2]. PCD layer possesses extremely high wear resistance, high hardness and excellent impact fracture toughness, and it has been widely used in many industries such as aviation, manufacturing of precise machining tools, geological drilling especially in oil and gas drilling [2]. As reported before, PDC cutters have been playing an important role in society and owe an increasing share in the drilling bit market, i.e., 2% of all footage drilling in oil fields by 1982, 15% by late 1980s, 45% by late 1990s, 50% in 2003, and 65% in 2010 [3,4].

Usually, PDC cutters are brazed to the bit body directly by induction heating [5], which is of low cost, simple and owns superior properties. However, the heating method normally causes adverse effect on the thermal stability of PDC to a certain degree, which is heavily related with the drilling performance. PDC sintered with Co acting as a catalyst usually has a low thermal stability which has drawn extensive attention in public, and diamond will transform into graphite at the temperature of above 870 °C in oxygen [6]. Wang [7] paid attention on the effect of distribution and shape of cobalt located in the boundaries between diamond particles on the thermal stability of PDC and discussed the means of improving the thermal stability by controlling the distribution and shape of cobalt. Wang [8] announced that the rapid oxidization reaction between diamond and cobalt with oxygen occurred at the elevated temperature, and as a result, microcracks and microholes formed due to the presence of thermal residual stress. Yahiaoui [9] reported that PDC was destroyed under the function of thermal residual stress due to the large mismatch in thermal expansion coefficients between diamond and Co of the PCD layer, and at the same time, he carried out three-dimensional finite element analysis to evaluate the post-sintering residual stresses of PDC samples with different interface designs of the tungsten carbide cement substrate, and found that the interface patterns had great effect on the distribution of the thermal residual stress. Above studies on the thermal stability of PDC have some limits, namely, they used special apparatus to observe the changes of shape and structure in PDC during heating process, while ignoring the influence of stress and heat produced in real exploration drilling. What's more, most studies on the details of Co function mechanism on thermal stability of PDC are narrow, especially during rock cutting. So in this work, we'd like to focus on a comprehensive depiction of these issues associated with the PDC cutter–rock interaction based on the theoretical analysis of mechanisms of Co function on the stability of PDC during the drilling process.

## 2. Materials and methods

PDC samples, donated from Henan Jingrui Superhard Material Co. Ltd., were subjective to a series of evaluation and observation in this study. Scanning electron microscopy (SEM, EVO18, German) was carried out to observe the surface morphology of the table layer of the polycrystalline diamond compact samples. A PDC sample was cut apart along axial direction and the cut surface was further rubbed down and polished, and an X-ray energy dispersive spectrometer affiliated with the SEM instrument was used to detect the distribution of elements

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such as Co, W and C across the interface between the PCD layer and WC–Co substrate. Another PDC sample was treated on an impact test machine (Instron, Dynatup 9200) by continuous impacting under 2 J for each impact until the PCD table was destroyed, and the cracks on the fracture surface were observed by SEM.

## 3. Results and discussion

PDC usually uses its cutting edge to crush virgin rocks under the help of penetrating force, which causes different zones of temperature distribution on the contact surface, and the formation of different temperature areas results from the various forces of friction between the cutting edge and the rocks. According to the heat distribution generated in the cutting process [10] and Gerbaud's new cutter–rock interaction model [11], the cutting edge was divided into three zones namely primary deformation zone, secondary deformation zone, and tertiary deformation zone, as shown in Fig. 1, which was drawn by us based on the abovementioned research work [10,11]. This model offers an effective way to predict the heat distribution in drilling process.

As the temperature rising during drilling, graphitization may occur within the cutter active zone in the presence of Co, and in this case, transition of diamond to graphite is the main failure source of PDC [12]. Cobalt coming from the tungsten carbide substrate is retained inevitably in the boundaries between diamond particles during high-pressure and high-temperature (HPHT) synthetic process. Both different temperature distributions on the contact region and the discrepancy in Co content result in various degrees of graphitization between diamond particles. After graphitization, physical properties of diamond vary drastically in the volume and surface morphology, leading to the deterioration of strength and toughness. When the volume of diamond expands caused by graphitization, it weakens the diamond–diamond (D–D) bonds to some degree and at the meantime the roughness of diamond surface increases. Though diamond has a high thermal conductivity [13], it is not enough to spread out the friction heat in time.

The expansion of metallic phase of Co also occurs simultaneously as heat is generated, and it also creates pressure on the D–D bonds combined with the continuously dynamic impact. Co that was in the extruding conditions (Fig. 2) was likely pulled out by the shear traction stresses from rocks and then adhered to the wear surface [14], promoting the occurrence of graphitization. The distribution and shape of Co affected the thermal stability of PDC as well. Wang [7] classified them into three shapes including spherical Co, island-like Co and leaf-like Co, and furthermore pointed out that the leaf-like Co affected the thermal stability of PDC cutter most significantly. It was very easy to find the high concentration area of Co distribution (Fig. 3) near the interface between PCD layer and WC–Co substrate, which was because during HPHT process, Co within the tungsten carbide substrate melted and infiltrated through the whole PCD layer, and the redundant Co gathered near the interface due to the interconnection among diamond particles. Generally the such-gathered metal Co is the main reason of the occurrence of delamination phenomenon and other abnormal failures of PDC cutters.

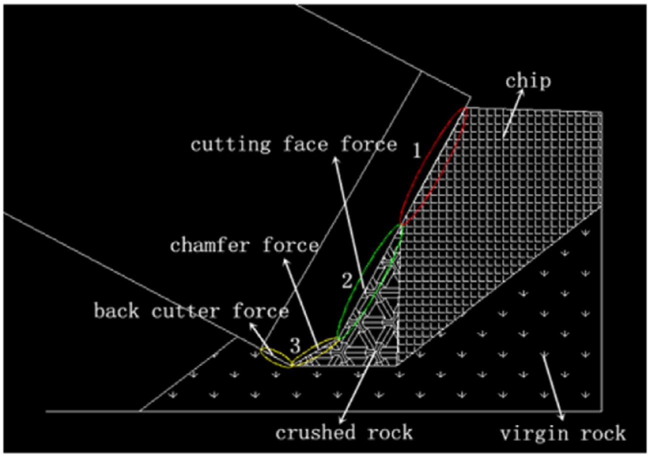

**Fig. 1.** Heat distribution zones on cutting edge generated in drilling process. 1, Secondary deformation zone generated by back cutter force and chamfer force; 2, primary deformation zone generated by sticking–sliding friction; 3, tertiary deformation zone generated by cutting force load, respectively.

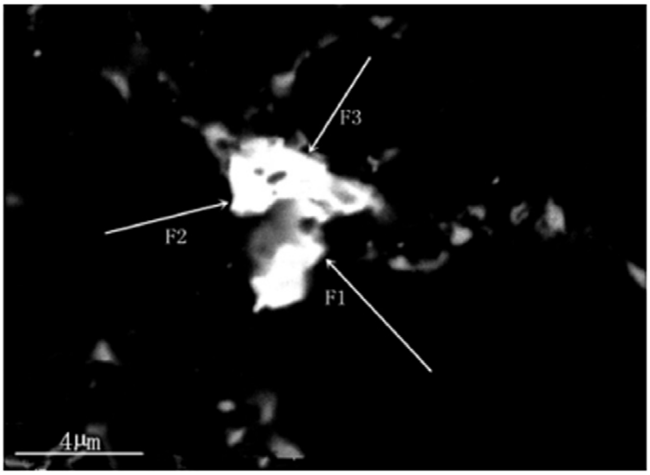

**Fig. 2.** Picture of Co forces from diamond particles in the PCD layer.

It is well recognized that the residual stress is regarded as one of the important factors to evaluate the quality of PDC cutters, and the inhomogeneous distribution of residual stress will induce cracking, tipping even delamination which deteriorates the excavation performance of PDC, especially when the exaggerated tungsten carbide grains exist near the diamond–substrate interface, the destruction from thermal residual stress will be more significant. From a practical standpoint of improving cutting efficiency, it is necessary to reserve a certain residual stress. Generally it is regarded that thermal residual stress is mainly caused by the mismatch of thermal expansion coefficients between diamond, WC and Co (thermal expansion coefficients of diamond is $1.4 \times 10^{-6}$/°C, Co is $12.5 \times 10^{-6}$/°C, WC is $3.84 \times 10^{-6}$/°C, respectively). At the end of sintering process, WC–Co substrate and PCD layer start to shrink simultaneously from nonuniform pressure relief and cooling, however the degree of WC–Co substrate shrinkage is much larger than that of PCD layer, and the whole PCD layer suffers from compressive stress generated from substrate. At the same time in PCD layer the diamond particles have less degree of shrinkage comparing with Co and get similar compressive stress from Co. As a result, the residual stress mainly caused by heat is reserved in PDC [9], which indicates that an overall cap-like radial stress distribution is formed with compression in the PCD table and traction in the substrate, and the stress distribution is consistent with cap type cracks in several microsections observed by electroerosion. The continuous compressive stress along

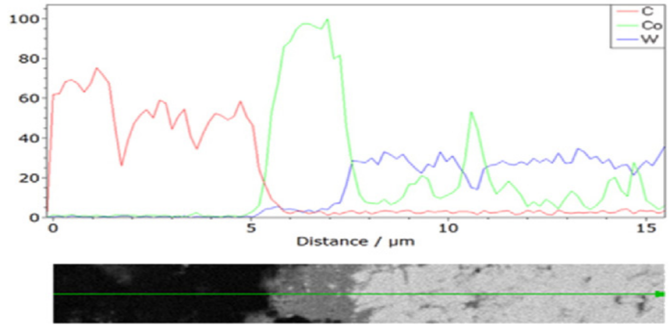

**Fig. 3.** Images of energy dispersive spectrometry at a PDC interface.