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A study on PDC drill bits quality

M. Yahiaoui [a,*], L. Gerbaud [b], J.-Y. Paris [a], J. Denape [a], A. Dourfaye [c]

[a] Laboratoire Génie de Production, Université de Toulouse, Ecole Nationale d'Ingénieurs de Tarbes, 47 avenue d'Azereix 65016 Tarbes, France
[b] Centre de Géosciences, Mines Paritech, France
[c] Varel Europe, France

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ABSTRACT

The quality of innovating PDC (Polycrystalline Diamond Compact) bits materials needs to be determined with accuracy by measuring cutting efficiency and wear rate, both related to the overall mechanical properties. An original approach is developed to encompass cutting efficiency and wear contribution to the overall sample quality. Therefore, a lathe-type test device was used to abrade specific samples from various manufacturers. Post-experiment analyzes are based on models establishing coupled relationships between cutting and friction stresses related to the drag bits excavation mechanism. These models are implemented in order to evaluate cutting efficiency and to estimate wear of the diamond insert. Phase analysis by XRD and finite element simulations were performed to explain the role of physicochemical parameters on the calculated quality factor values. Four main properties of PDC material were studied to explain quality results obtained in this study: cobalt content in samples that characterizes hardness/fracture toughness compromise, undesired phase as tungsten carbide weakening diamond structure, diamond grains sizes and residual stresses distribution affecting abrasion resistance.

1. Introduction

The main tools employed in the drilling industry are roller cone and drag bits. Roller cone bits work by impact excavation and are currently used in hard rock formations because of a convenient wear resistance. Drag bits rather operate by shear mode in softer rock to medium hard formations. Nevertheless, they suffer from thermal abrasive wear and impact damage while drilling interbedded formations. As excavation rate is directly related to the overall cost, the drag bits using PDC (Polycrystalline Diamond Compact) cutters are really attractive compared to roller cone bits. In fact, PDC bits could drill twice faster and longer than roller bits even in hard formations [1]. Petroleum and hydrothermal investigations in deep geological formations lead to manufacturing new bits materials able to drill at higher temperature, in more abrasive and harder geological fields. Such innovating materials, sintering processes and design, recently developed to improve drill bits hardness and fracture toughness, also require new strategies in quality assessment. Drag bits are mostly damaged by abrasion [2] and thus quality can be defined by two main parameters: materials wear rate and excavation performance. Wear rate calculus by Archard's model has been commonly used in several works to describe PDC/rock behavior [3]. Excavation performance depends on cutting efficiency which is initially determined by the sample depth of cut. During friction, cutting efficiency evolves and the change is closely linked to wear flat formation on PDC cutters. Because a long bit life could be related to a poor cutting performance and vice versa, this paper proposes an objective quality criterion to clearly classify PDC cutters. Drilling mechanisms and material analyzes are taken into consideration to interpret the grading of the testing bits.

2. PDC samples

Six cutters coming from various manufacturers (referred from A to F) were selected to represent a large range of properties. Cutters are made of a tungsten carbide cylinder surmounted by a diamond table (Fig. 1a). Material parts have a diameter of 13 mm: the tungsten carbide cylinder has a height of 8 mm and the diamond layer is around 2 mm thick. Diamond tables have a chamfer of $45^\circ \times 0.4$ mm except for sample C where it is $45^\circ \times 0.7$ mm. These cutters were sintered by HPHT (i.e. High Temperature and High Pressure) at a temperature over 1400 °C under a pressure close to 5.5 GPa (Fig. 1b) [4].

Tungsten carbide prismatic grains in a binder cobalt phase form the substrate part (Fig. 2a). The mean grain size of tungsten carbide is around 2 μm with minimum and maximum values observable under

* Corresponding author. Tel.: +33 5624 42700; fax: +33 5624 42708.
E-mail addresses: malik.yahiaoui@enit.fr, yahiaouimalik@gmail.com (M. Yahiaoui).

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Nomenclature

α	back rake angle, deg
ε	intrinsic specific energy, J m^{-3}
η	cutting efficiency
μ	friction coefficient
ρ_x	cobalt mass content at distance x
ζ	cutting coefficient
A_c	cross-sectional area of cut, m^2
A_f	wear flat area, m^2
D	infiltration coefficient, m^2 s^{-1}
E	specific energy, J m^{-3}
E_0	initial specific energy, J m^{-3}
E_m	cutting dissipated energy, J
F^c	cutting force component, N
F^f	friction force component, N
F_N	total normal force, N
F_N^0	initial normal force, N
F_T	total drag force, N
G	grinding ratio
I	sum of maximum peak of present phases
I_{CoC_x}	CoC_x XRD maximum peak intensity
$I_{diamond}$	diamond XRD maximum peak intensity
I_{WC}	WC XRD maximum peak intensity
k	wear rate, m^3 N^{-1} m^{-1}
L	excavation distance, m
L_T	total excavation distance, m
Q	quality factor
R^2	coefficient of determination
t	time of infiltration, s
u	cutting capacity, m
V_C	cutter worn volume, m^3
V_R	cut rock volume, m^3
W_m	cutter mechanical work, J
x_i	infiltration transition position, m

a micrometer and over 10 µm (Table 1). Jeol JSM-7000F field emission scanning electron microscope observations revealed aggregates of micrometric diamond grains also surrounded by cobalt (Fig. 2b). Samples A, E and F have been exposed to a chemical post-treatment called “leaching process” [5]. This treatment removes interstitial cobalt grain boundaries on the diamond layer beyond several tens of micrometers (Fig. 2c).

The cobalt phase in the diamond part is due to the infiltration of cobalt from the tungsten carbide substrate during sintering. Commonly, cobalt proportion can represent 6–18 wt.% in tungsten carbide substrate and 2–8 wt.% in the diamond part. The cobalt distribution in samples follows a law that can be expressed as a solution [6] of differential equations from Fick’s laws (Eq. (1)).

$$\rho(x)=(\rho_0-\rho_{10})\frac{\operatorname{erfc}\left[\frac{1}{2\sqrt{D\cdot t}}(x-x_i)\right]}{\operatorname{erfc}\left[-\frac{1}{2\sqrt{D\cdot t}}x_i\right]}+\rho_{10} \tag{1}$$

In this equation, $\rho(x)$ represents axial cobalt mass content from diamond face (where $\rho(x)=\rho_0$) to the bottom of the tungsten carbide part (where $\rho(x)=\rho_{10}$). D is the infiltration coefficient, t is the time of infiltration and x_i expresses infiltration transition position between PDC and WC-Co materials. The cobalt

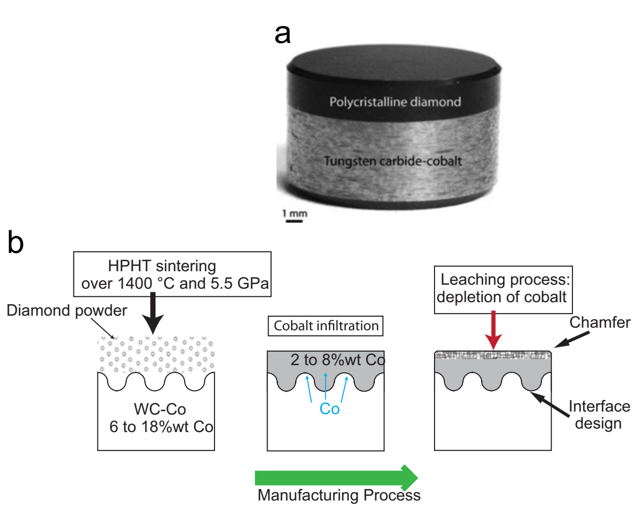

Fig. 1. PDC cutter: (a) photography of a cutter; (b) manufacturing process of a cutter.

distribution was measured on the samples (Fig. 3) using energy dispersive X-ray spectrometry (EDX) analyzes with Bruker XFlash 4010 detector. To perform semi-quantitative measurements, the detector was calibrated with copper located close to samples before each observation campaign. For these measurements, the six samples were longitudinally cut by electroerosion, polished and metalized with palladium. The SEM was adjusted at 15 kV with a working distance of 15 mm. The electron beam intensity was set around 100 counts per second to enable a high speed analysis. The cobalt mass content distribution was evaluated with a step of 500 µm along a line on sections.

EDX characterizations showed that all samples have similar cobalt content (ρ_0) around 3 wt.% in the diamond material whereas cobalt content of tungsten carbide (ρ_{10}) part can vary from 8 to 17 wt.% (Table 2). The square root of $D\cdot t$ permits to evaluate dispersion of the inflection i.e. metal ability to spread from tungsten carbide to diamond. D depends on diamond/WC grains size and on sintering temperature. At sintering temperature, molten cobalt moves by capillarity through voids between diamond grains. Larger voids are directly associated with larger grain size which favors displacement of cobalt [7]. Moreover, metal infiltration in diamond structures increases with temperature as viscosity of molten cobalt decreases.

SEM observations only permit the measurement of diamond aggregates (see Table 1). The aggregates size does not represent the diamond grain size distribution in the sample and cannot be directly related to the mechanical behavior of PDC materials. Considering that t is almost equal for the six samples, $\sqrt{D\cdot t}$ parameter permits to qualitatively evaluate diamond grain sizes rather than of aggregate ones. Here, B and C displays $\sqrt{D\cdot t}$ values two times higher than those of samples A, D, E and F. Theses results may be due to higher diamond grain sizes in samples B and C than in the others.

3. Experimental study

A vertical lathe-type device was used to simulate drilling conditions. Cutters brazed on sample holders were adjusted downward on the lathe shaft. Ring-stone counter-faces were made of a manufactured mortar rock (1 m in external diameter, 0.5 m in internal diameter and 0.6 m thick with a density of 2210 kg m^{-3}). This mortar ensures homogeneous chemical composition (silica content of 80 wt.%) and mechanical properties