One of the most critical components for oil and gas drilling is the rock bit, which crushes, abrades, or shears the rock in order to move deeper. Figure 1 is a cutaway schematic of a three-cone rock bit. The buttons or inserts on the rock bits are the means by which a bit drills through rock. These buttons or inserts are typically made of tungsten carbide-cobalt (WC-Co).

Over the last fifty years, insert materials for three-cone bits in oil and gas drilling applications have shown little deviation from the original materials. Raw materials and processes have improved, but the buttons still consist of a homogeneous mixture of carbide grains within varying amounts of cobalt. As expected, when a grade is modified to increase wear resistance and hardness, the toughness is reduced. For example, by reducing the cobalt content and/or grain size, hardness is increased.

As a result of this rigid relationship, the drilling industry looked at alternate ways to improve toughness without sacrificing wear resistance or any other critical properties. This article first discusses conventional technology, and then describes some of the newer alternatives, including coarse-grain carbides, double-cemented carbides, and diamond-enhanced inserts.

Tungsten carbide-cobalt
Tungsten carbide-cobalt (WC-Co) hard materials first emerged following Schrotter’s invention in 1923. The first application was for hot-drawing dies for production of tungsten wire in 1926. Since then, this material has become the standard for cutting tools and wear-resistant tools, because of its excellent combination of wear resistance, strength, and toughness.

Tungsten carbide-cobalt is the primary cutting element in three-cone rock bits, with an estimated market size of $40 to $50 million for 2002. These estimates do not include non-rock bit products for other mining applications, which in fact require significantly greater amounts of carbide material.

Conventional carbide grades in bits are fine-grain single crystals of WC mixed with cobalt ranging from 6 to 16 wt%. The mean carbide grain sizes generally range from one to three micrometers.

The old philosophy was to select grades based on well-established wear-toughness relationships. As an example, if an application showed insert breakage, a designer would resolve the problem by moving down the hardness line, compromising wear for higher toughness. However, in the last ten years, different approaches have been taken to address insert breakage or wear resistance, based on the development of new insert materials.

The paradigm shift in materials selection was to develop technologies that enable the engineer to move away from the restrictive wear-toughness-hardness of only one material, and generate new materials with enhanced toughness without sacrificing abrasion resistance. These technologies have resulted in materials such as coarse carbides and carbide composites, including double-cemented (DC) carbide, diamond-enhanced (DE) inserts, and Cellular materials.

Coarse-grain carbide grades
Coarse-grain carbide is not new to the carbide industry, but this represents a dramatic change in oil and gas drilling applications. High-purity coarse grain WC powders enabled development of a new family of WC-Co grades with properties off the conventional property relationship. Their primary applications are components in which the typical insert failure mode is caused by heat checking and breakage rather than wear.

The advantages of coarse carbide grades are as follows:
- Higher thermal conductivity is available at the same hardness.
- Higher-purity crystals are produced by a carburization process rather than by the thermite process.
- Coarser carbide grains with lower cobalt content can lower the coefficient of thermal expansion.
- Higher toughness and better wear resistance are provided at the same hardness. The mean sizes of WC crystals in coarse carbide grades are significantly larger than those of conventional carbides.

As discussed earlier, these grades were developed to combat heat-checking failure, which is damage resulting from cyclical loading and frictional heat. Heat-checking signifies shallow orthogonal cracks on the surface, similar to thermal shock in ceramics, and it results in insert breakage with little or no apparent wear. Coarse carbide grades in such applications provide superior thermal fatigue resistance, \( R \), as defined by:

\[
R \approx k + \frac{k_h}{E \cdot \alpha}
\]

Where \( k \) is thermal conductivity, \( k_h \) is
plane strain toughness, $\alpha$ is thermal expansion, and $E$ is modulus. Data on field performance is found in the literature.

**DC carbide inserts**

Double-cemented (DC) carbide is another means of achieving high toughness while maintaining wear resistance. In this material, granules of WC-Co are dispersed in a matrix of cobalt alloy by means of pressure-assisted sintering technology, which ensures that the microstructure of the granules is maintained during the densification process. The DC carbide structure is shown in Fig. 2 next to conventional carbide with similar matrix loading. High toughness was achieved by the longer mean free path in comparison to conventional carbide.

**Diamond-enhanced inserts**

Diamond-enhanced inserts, known as DEI, were first developed by Smith Bits in 1987 and tested in percussion hammer bits for a petroleum application. DEI is a composite insert with multilayer coating on the surface of cemented carbide. It was developed to improve bit performance based on its tremendous wear resistance, over a hundred times higher than the hardest carbide today. Currently, a third of the bits sold by Smith International contain diamond in three-cone bits, typically ensuring that hole diameter is held to specification.

The main failure mode of DEI for three-cone product is spalling of the diamond layer, which eventually leads to carbide substrate failure. Hence, resources were committed to combat spalling through the choice of new materials for the diamond layer, and/or new substrate geometry.

The result was the Smith Cellular diamond insert, composed of repeating units of honeycomb composite material of polycrystalline diamond (PCD) and WC-Co material. Polycrystalline diamond material constitutes the wear-resistant core of the unit cell, while WC-Co makes up the tough web of the cell boundaries.

The size of the cell and cell boundary thickness can be controlled. The honeycomb structure is visible on the surface of the part, while it appears as a columnar form in the plane perpendicular to the surface. Figures 3a and 3b show a typical microstructure of cellular diamond material compared with that of the standard DEI product.

The cell size is approximately 200 micrometers, and the thickness of the cell boundaries is approximately 50 micrometers. Mean grain size of the diamond crystal is around 8 micrometers, and the WC crystal is approximately 1 to 2 micrometers. More information on Cellular diamond inserts can be found in the literature.

Many field tests have confirmed the spalling resistance improvement of Cellular diamond inserts over conventional diamond-enhanced inserts, including field tests in the North Sea, Alaska, and Middle East. For example, a six-inch bit with and without Cellular inserts is shown in Fig. 4a and 4b.

In addition, the comparative run data is shown in Fig. 5. The data was taken from six-inch (hole diameter) bits run in the Kenai peninsula in Alaska. The standard bit ran for 11 hours, while the enhanced bit ran for 29 hours. These bits were drilling rock at approximately 12,000 ft, where changing a bit (due to bit destruction or changed rock formation) can take over 20 hours. Hence, drilling costs can be lower if bit performance can be enhanced.

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