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Optimization of parameters in material selection of tricone drill bit head design

A F Benavides-Serrano[1], A S Peña-Sabogal[1], O M León[1], H G Sánchez-Acevedo[2] and O A González-Estrada[3]
[1] Department of Mechanical Engineering, Universitat Politècnica de València, Valencia, Spain
[2] GIEMA, Universidad Industrial de Santander, Bucaramanga, Colombia
[3] GIC, Universidad Industrial de Santander, Bucaramanga, Colombia

E-mail: agonzale@uis.edu.co

Abstract. The tricone drill bit head is one of the main components in petroleum perforation settings because it makes possible to break the soil to establish a flow path between the reservoir and the wellbore. For this reason, it is a component that requires special analysis. This work investigates the optimization process of the parameters used in the material selection for a tricone drill bit. It includes the material selection for the bit body and the inserts. The stresses to which the drill is subjected during drilling are calculated and conditions to be fulfilled are established according to its function.

1. Introduction
Oil wells drilling is a high-risk activity with a good economic potential. A correct drilling procedure marks the difference between benefits or economic losses [1]. In order to minimise the chances of failing during drilling [2], it is necessary to make selections and previous controls that allow managing as many variables as possible. Among the variables that can affect the perforation are: soil formation [3], types of drill bits needed during drilling [4], bits materials [5,6], drilling speed and bottom temperature [7], weather conditions and pipeline to be installed [8,9].

The tricone drill bit is the main component of rotary drilling tools due to its replacement and repair costs. The direct contact with the rock generates various damage to the surface of the bit during the excavation. According to the observation of drill bits [4], after the perforation, damages appear with different characteristics and mechanisms that can occur in different surfaces of the bit. The mechanisms of wear are varied and complex, but among them, predominate: abrasive [10], chemical [11] adhesive [12], fatigue [13] and erosive wear [10]. Observations showed that cracking, cutting, flattening, breaking, rounding and detachment were common modes of damage [4], where many of the bits suffered damage in more than one part simultaneously.

For the selection of the bit, it must be considered that the dominant concern in the drilling process is the improvement of the drilling performance by increasing the useful life of the bit. Under uncontrolled conditions, the damage leads to a severe decrease in the life expectancy of the drill bit and to a significant increase in the cost of drilling. Many of the failure modes are included during the material selection process, however, it is not possible to try to avoid some of them due to their nature. The purpose of this work is to identify the optimal material for a tricone drill bit under specific conditions.

2. Methods and materials

The drill bit under consideration is designed for deep layers of ground (from 7300ft approximately) where triconic type is usually used [14].

2.1. Working temperature

The bottom hole and contact temperature are the ones that define the value the head operates, given by the Equation 1:

$$T_{total} = T_{contact} + \delta T, \quad (1)$$

where T_{total} is the total temperature at which the head operates, $T_{contact}$ refers to the temperature generated by the friction between the rock and the head, and δT is the temperature gradient produced by the depth, defined as:

$$\delta T = T_{surface} + 0.015H, \quad (2)$$

where $T_{surface}$ is the temperature (°F) at the drilling surface and H denotes the drilling depth. In [7], we can find temperature values based on the speed of rotation of 60RPM and the working time of 60min, from which a value of $T_{contact} = 70°C$ is obtained. The temperature at the drilling surface is set to $T_{surface} = 74.3°F$ [14]. Finally, solving for the total temperature of operation we obtain:

$$\begin{gathered} \delta T = 74.3 + 7300(0.015) \\ \delta T = 183°F = 84°C \\ T_{total} = 154°C \end{gathered} \quad (3)$$

2.2. Boundary conditions

A cutting model that is used for calculating the forces acting on the inserts is proposed in [15]. These values are based on the geometry of a tricone drill bit and the properties of the soil that determine the drilling forces.

In Figure 1, the forces acting on the insert are shown, Fc is the cutting force and Fn is the normal force. Also, two zones are generated during drilling. Those are, the crushed zone and the main chip zone. For the evaluation of Fc and Fn , the relationships used by [15] are considered:

$$F_c = \frac{2\,\sigma_t\, d \sin(\theta + \phi)\cos(\theta)}{1 - \sin(2\theta + \phi)} = 137130\text{N}, \quad (4)$$

$$F_n = \frac{2\,\sigma_t\, d \sin(\theta + \phi)\sin(\theta)}{1 - \sin(2\theta + \phi)} = 36745\text{N}, \quad (5)$$

where $\theta = 15°$, $\phi = 10°$ and $d = 0.0075$m, considering the rock tensile stress $\sigma_t = 8$MPa, [16].

Finite Element Analysis (FEA) has been widely used for assessment of structural integrity [9,17] and optimisation in the energy sector [18]. A FEA is done in Autodesk Nastran v2017 to determine the stress requirements in the drill body. The applied forces of the numerical model are those transmitted by the inserts, because of the work they do during the drilling. From the geometrical model obtained, the shear forces and normal forces are applied to each insert. During drilling, not all inserts are in contact with the ground, thus, 10 inserts are assumed to be working simultaneously. This condition emulates the start of the drilling in an accidental situation (emergency stop) which is the critical condition. Figure 2 shows the boundary conditions, restricting the cone on the surfaces where it is in contact with the bearing with a fixed support. The forces are applied tangential and normal to the inserts. The FEA is performed with 74701 tetrahedral elements, order 1.

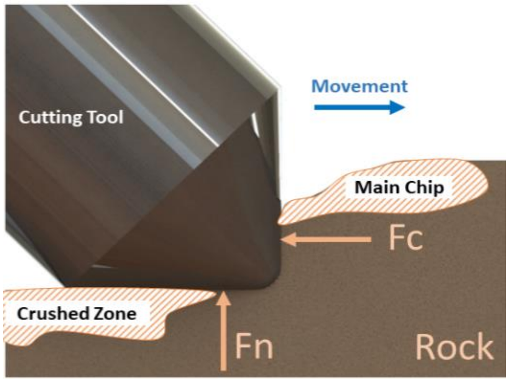

Figure 1. Forces acting and geometry during cutting

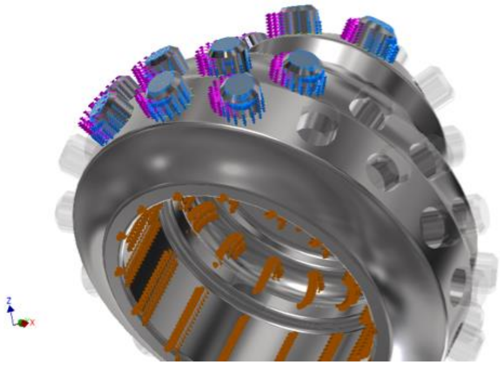

Figure 2. Boundary conditions for the numerical model.

2.3. Material selection

The selection of materials is done using the Ashby methodology [19], which seeks to optimise the most important constraints to which the drill is subjected. The material of the drill differs in two parts: the body and the inserts. The material of the body of the cone is responsible for receiving stress, deformations, and vibrations during drilling, and must also withstand the environmental conditions. The material of the inserts must withstand the high hardness of the rocks to be drilled, the abrasion with the ground, and must have a high resistance to fracture.

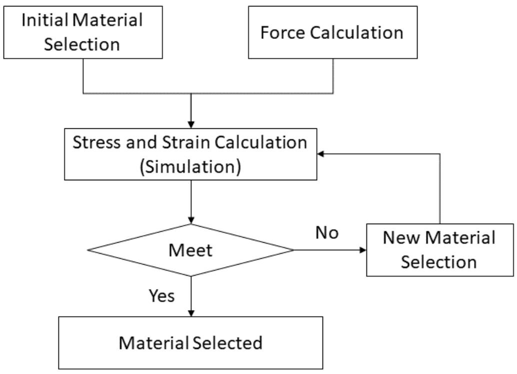

Figure 3. Flowchart of the selection process.

Finally, with the use of the software CES EduPack 2017, the material is selected and compared with the catalogues suggested by the manufacturers. The restrictions of the material selection are: design loads, damage resistance, resistance to erosion and abrasion, support vibration, and temperature.

For parameter optimization of the design of mechanical components, the objective function can be expressed like the product of three main functions [19], functional constraint, geometric constraints, and material properties. In this work, material properties are used as optimization functions. For the selection of these design restrictions, it is necessary to know the components function on a drill bit. The body is responsible for receiving stress, deformations and vibrations during drilling. It must withstand the environmental conditions. Therefore, the following parameters are optimised: yield stress, tolerance to damage, stiffness of the material and resistance to environmental conditions. The yield stress is calculated through the numerical model performed by FEA with the forces calculated before, obtaining a maximum value of 1000MPa for the cone, applying a safety factor of 1.5 and taking as design value 1500MPa. For fracture toughness optimization is necessary to maximise the energy that the component can absorb, to reduce the risk of fracture. For this, we increase the value of the ratio K_{1C}^2/E, where, K_{1C} is fracture toughness and E the Young's modulus of the material.

Regarding the inserts, the main parameter to be considered is the abrasion resistance. Ashby establishes the mathematical expression H^3/E^2, where H is the hardness and E is the Young's modulus, obtained in an empirical way, defining a design function that optimises the abrasion resistance using the material properties, hardness and Young's modulus. Thus, the model optimises the capacity of the material against the wear, seeking to prevent the material from entering the plastic deformation zone.

The material must withstand temperatures equal to or greater than 154°C, depending on the bottom temperature of the well and the temperature generated by contact between surfaces [7]. This condition increases the metal oxidation speed. Therefore, it is necessary that the material has an excellent behaviour to oxidation at high temperatures. In addition, a high resistance to organic solvents was sought, due to the contact with the sludge inside the perforation.

Regarding its manufacture, attributes such as machinability, weldability and ability to receive surface treatments were considered. The external surface that performs the greatest amount of work during drilling must be able to be hardened by thermal spraying to provide higher resistance to abrasion and erosion.

3. Results

Figure 4 shows the von Mises stress for the drill bit head considering the specified boundary conditions. In elements such as corners and holes, in which the inserts are welded, the stresses are increased up to about 1153MPa. In [20], a maximum value of von Mises stress of 470 MPa was obtained, however, in that work, only normal forces were considered and the shear forces were not taken into account since the purpose of the work was the selection of the bearings and, in that case, the tangential forces have no relevance. The obtained results are given as acceptable, as well as the order of magnitude.

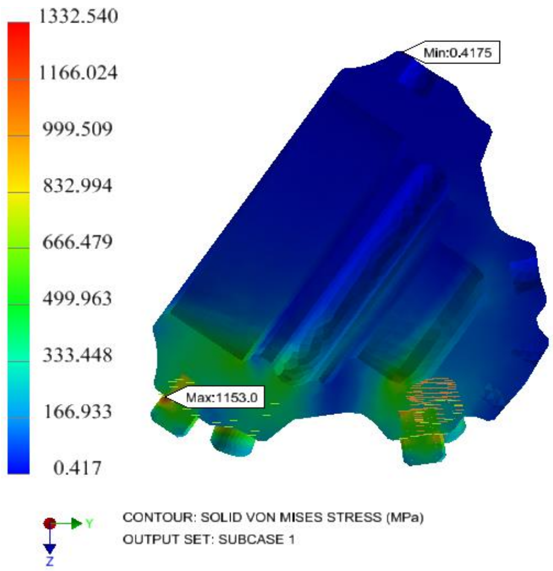

Figure 4. Von Mises stress in the cone.

Figure 5 shows the location in the Ashby chart of the preselected materials for the body in the upper right, exceeding the 1500MPa of the elastic limit and with high resistance to damage. Figure 6 shows the Ashby chart according to the hardness and tolerance to damage of the materials for the insert. The axes represent the optimisation parameters of the material selection, notice that the selected materials are in the upper part. We maximise the yield strength, **Figure 5**, or the hardness Vickers, **Figure 6**. The optimization of these parameters allows to fully comply with the requirements imposed by the function of each component. For the body, we maximise damage tolerance and yield strength using an energy control approach, optimising the body of the drill to support high loads without deforming. For the inserts, we consider the hardness, which reduces the possibility of damage caused by another material.

The main properties of the selected materials are shown in Table 1. Further study could consider the use of metal matrix composites produce by additive manufacturing [21].

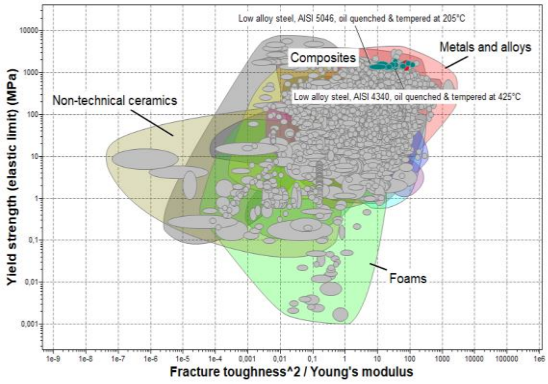

Figure 5. Criteria for body material, low alloy steel AISI 5046. Ashby diagram.

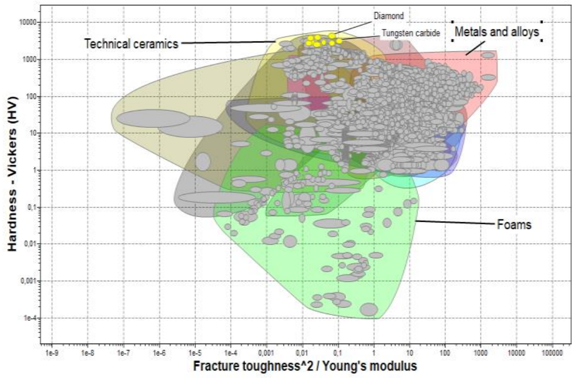

Figure 6. Criteria for insert material, tungsten carbide-cobalt (96). Ashby diagram.

Table 1. Properties of selected materials for the body and inserts.

Part	Insert	Body
Name	Tungsten carbide-cobalt (96)	Low alloy steel AISI 5046
Price	63.5-119EUR/Kg	0.582-0.68EUR/Kg
Hardness	1950-2150HV	430-530HV
Density	1.53E+04	7.8E+03
Young’s modulus	653-686GPa	201-212GPa
Yield strength	1453-1600MPa	1270-1550MPa
Fracture toughness	6.7-7.4MPa.m^0.5	34-62MPa.m^0.5

4. Conclusions

The selection of the material of the drill was made by optimization of the principal parameters used in the manufacture of a tricone drill bit, i.e., yield stress, fracture toughness, bottom hole and contact temperature, abrasion resistance, hardness, and damage tolerance. The parameter optimization allowed to select materials capable of meeting the high standards of operation to which the drills are subjected without the need to greatly affect other aspects such as weight and cost. Composite materials are a viable solution for the high brittleness presented due to the extreme hardness that is needed in the inserts, for which the tungsten carbide-cobalt (96) was the material selected. Low alloy steel, AISI 5046, oil quenched and tempered at 205°C, was selected for the material of the bit body such that possible fracture of an inserts does not propagate to the body, leading to the component failure.

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