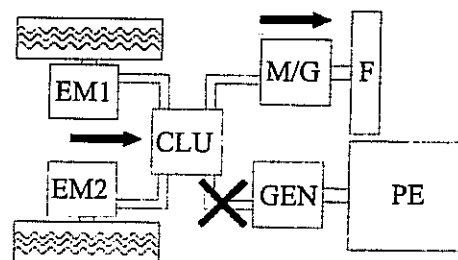
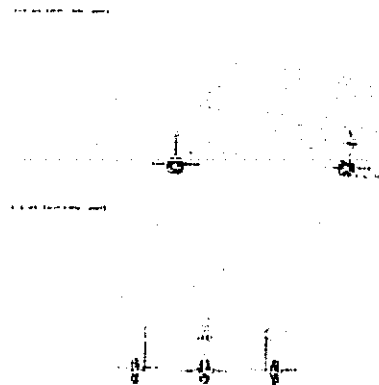
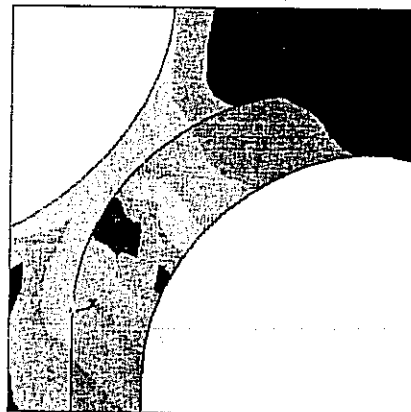
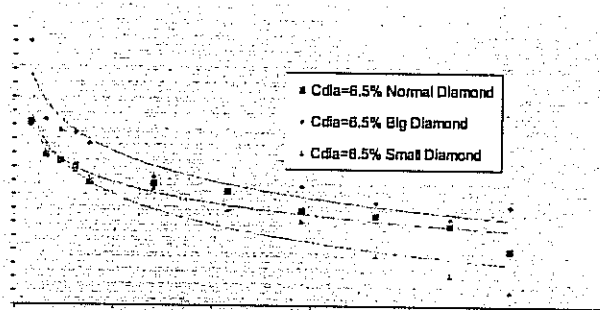
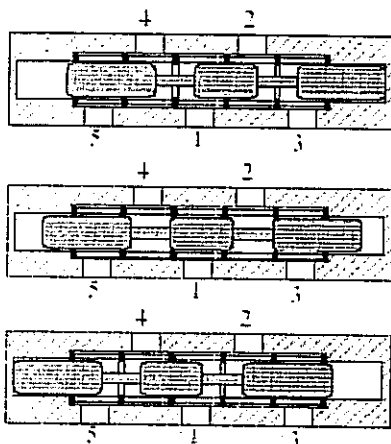


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TRANSIENT COUPLED THEORY OF DRILLING AND WEAR

Alberto Carpinteri and Nicola Pugno

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ABSTRACT

Drilling perforation and tool wear are intimately and mutually connected. To study this interaction phenomenon, we propose an ad hoc developed coupled theory. Describing the two steady state processes in terms of drilling and wear velocities, the theory is able to predict these quantities as functions of classical parameters related to base- and tool-materials. In addition, to extend the results to transient perforation stages, a new approach for tool wear, based on the well-known Malthusian model for population dynamics, is proposed. Theoretical predictions and experimental results seem to agree satisfactorily.

Keywords: Drilling, wear, tool.

1 INTRODUCTION

Drilling [1] and wear [2] phenomena are intimately connected each over each other. In particular, the wear phenomenon is studied in the Tribology science. The word Tribology is derived from the Greek word *tribos*, meaning "rubbing" and it is defined as "the science and technology of interacting surfaces in relative motion and of the practices related thereto". It embraces the scientific investigation of all types of friction, lubrication and wear and also the technical application of tribological knowledge [2].

Focusing our attention on wear, we can distinguish four main forms of wear [2]:

- (1) *Adhesive wear* occurs when two smooth bodies are sliding one over each other, and fragments are pulled off one surface and adhere to the other. It derives from the strong adhesive forces set up whenever atoms come into intimate contact.
- (2) *Abrasive wear* occurs when a rough hard surface, or a soft surface containing hard particles, slides on a softer surface and ploughs a series of grooves on it.

(3) *Corrosive wear* occurs when sliding takes place in a corrosive environment. In the absence of sliding, the products of the corrosion will form a film on the surfaces. This film tends to slow down or even arrest the corrosion. However, the sliding action wears the film away, so that the corrosive attack continues.

(4) *Surface fatigue wear* occurs during repeated sliding or rolling over a track. The repeated loading and unloading cycles to which the materials are exposed may induce the formation of surface or subsurface cracks, which eventually will result in the formation of large fragments, leaving large pits in the surface.

Other forms of wear are the following [2]:

- (5) *Fretting* occurs when contacting surfaces undergo oscillatory tangential displacement of small amplitude.
- (6) *Erosion* is a process in which a particle carried in a fluid medium hits a solid surface and removes material from it (low-speed, high-speed and cavitation erosion).
- (7) *Impact wear* happens when two surfaces collide while having large relative velocities normal to their interface.
- (8) *Brittle fracture wear* occurs during sliding in brittle materials, when a characteristic series of cracks is observed in the wear track. Subsequently, large wear particles tend to be produced during surface breakup.

The examination of a failed sliding member, to determine the type of wear responsible, can be a complex process. For details, the reader is referred to [2-9].

The studies on wear of impregnated diamond core-bits for drilling have been largely concentrated on the diamond wear. The documentation on metal matrix wear and the wear of the entire impregnated diamond tool is rare and substantially experimental [10-12]. Experimental results on

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micro-bit drilling tests indicate that the penetration per revolution is one of the most important factors influencing the wear of impregnated diamond bits. In fact, the bit weight loss per distance drilled increases drastically with an increase of the penetration per revolution. On the other hand, the bit weight loss per distance drilled is found to decrease slightly with an increase in the rotational speed.

Referring to the described wear types, the wear modes due to the drilling process are substantially of brittle fracture, abrasive, adhesive, and erosion. Under ordinary drilling conditions, the brittle fracture wear is the predominant wear mode. This wear mechanism generates sharp diamonds. On the other hand, under very small applied thrust loads, the abrasive wear is the predominant wear mode. This wear mechanism generates excessive wear flats at the diamond cutting edges that often result in a rapid decrease of the penetration rate. Furthermore, under very high penetration rates, the so-called "micro-burn" phenomenon takes place at the cutting surface. Drilling detritus particles adhere to the matrix between diamond grits. They are delaminated under rock abrasion, causing rapid adhesive wear of the impregnated diamond bit. In addition, the flow of drilling detritus constitutes the major abrasive third body against the matrix; in this case, the wear of the bit matrix is a mixed micro-ploughing process of erosion.

In order to achieve the proper wear rate of bit matrix in a steady state of drilling, it is important to maintain an optimal value of penetration per revolution to produce the right amount of drilling detritus under the bit cutting face and a proper diamond cracking for maintaining rock cutting ability. If the penetration per revolution is too large, excessive wear of diamonds and metal matrix takes place, shortening the working life of the diamond bits. On the other hand, if the penetration per revolution is too small, excessive wear flats of diamond cutting edges result in a rapid decrease of the penetration rate.

As previously argued, drilling perforation and tool wear appear as complex phenomena, intimately and mutually connected. In the present paper, we propose a coupled theory, based on statistical concepts [13-17], to describe these phenomena from a global point of view [1].

2 COUPLED LAW FOR DRILLING AND WEAR VELOCITIES

The wear loss w is defined as the volume removed V per unit area A and per unit length x of sliding:

$$w = \frac{V}{xA} = \frac{\dot{V}}{\dot{x}A}. \quad (1)$$

On the other hand, the wear coefficient k is defined as the probability of wear in the portion of the surface which is interacting:

$$w = k \frac{A_{\text{contact}}}{A} = k \frac{F}{AH}, \quad (2)$$

where A_{contact} is the portion of the nominal area A in contact, H is the hardness (of the worn material) and F is the thrust. The main difference between the wear loss w and the wear coefficient k is that the first is not a material property being thrust-dependent. On the other hand, the second, in the classical approach, can be considered as a material property and it is obviously thrust-independent [18].

Assuming that all the friction energy is dissipated in wear, we have:

$$dW = \mu F dx, \quad (3)$$

where μ is the friction coefficient (between the two materials in contact). Eliminating F from eqs. (2) and (3), we obtain:

$$w = \frac{k}{AH\mu} \frac{dW}{dx} = \frac{k}{AH\mu} \frac{\dot{W}}{\dot{x}}. \quad (4)$$

From eq. (1) and from the definition of wear resistance S (or wear strength, ratio between power and removed volume per unit time, [1,19]) we have:

$$w = \frac{\dot{V}}{\dot{x}A} = \frac{1}{\dot{x}A} \frac{\dot{W}}{S}. \quad (5)$$

Combining eqs. (4) and (5), we obtain the wear resistance S as:

$$S = \frac{\mu H}{k}. \quad (6)$$

The developed theory has permitted to obtain the relationship between the classical wear coefficient k and the wear resistance S (of the tool). If eq. (6) were applied to the drilling process, S would represent the drilling strength (of the base-material). The grindability G is defined as the inverse of the drilling strength. As a consequence, wear loss w , wear coefficient k , drilling (or wear) strength S and grindability G are mutually connected. Eq. (6) shows that the wear/drilling strength S is a function of the friction coefficient μ , of the hardness H and of the coefficient k .

It is important to emphasize that relationship (6) is true only for a pure wear process, i.e. we have assumed that the whole power is entirely dissipated in wear. This can not be assumed (by definition) in a coupled theory, for which the definition of eq. (6) must be modified taking into account

that not the whole power is dissipated in wear. According to these considerations, we have:

$$dW_i = \alpha_i \mu F dx, \alpha_i = \frac{\dot{W}_i}{\dot{W}}, i = 1, 2, \quad (7)$$

where α_i is the ratio of the power \dot{W}_i , dissipated in the drilling ($i=1$) or wear ($i=2$) processes, to the total power supplied. As a consequence, eq. (6) becomes:

$$S_i = \alpha_i \frac{\mu H_i}{k_i}, \quad (8)$$

H_i and k_i being the hardness and the wear coefficient for a multiphase material that can be obtained from the usual rules of mixture [18,20]:

$$H_i = \sum_j v_j^{(i)} H_j^{(i)}, \quad (9)$$

$$k_i = \sum_j v_j^{(i)} k_j^{(i)}, \quad (10)$$

$v_j^{(i)}$ being the volumetric percentage of the phase j in the composite material i , and $H_j^{(i)}, k_j^{(i)}$ the corresponding hardness and wear coefficient.

Equation (8) is very important, permitting us to obtain theoretically the ratio between the wear and the drilling velocities (coupled parameter):

$$\frac{\alpha_2}{\alpha_1} = \frac{\dot{W}_2}{\dot{W}_1} = \frac{S_2 A_2 \dot{\delta}_2}{S_1 A_1 \dot{\delta}_1} = \frac{\alpha_2 H_2 k_1 A_2 \dot{\delta}_2}{\alpha_1 H_1 k_2 A_1 \dot{\delta}_1}, \quad (11)$$

from which the Coupled Law becomes:

$$\frac{\dot{\delta}_2}{\dot{\delta}_1} = \frac{H_1 k_2 A_1}{H_2 k_1 A_2} = \alpha, \quad (12)$$

and predicts a linear relationship between wear and drilling velocities, in good agreement with the experimental results presented in Figure 1. The Coupled Law (12) agrees with the experimental results on impregnated diamond drilling tests, showing that the main parameter influencing the wear of the tool is the drilling velocity [10-12].

This allows to solve the coupled problem. We have in fact:

$$\begin{aligned} \dot{W}_i &= \alpha_i \dot{W} = S_i A_i \dot{\delta}_i = \\ &= \alpha_i \frac{\mu H_i}{k_i} A_i \dot{\delta}_i, \end{aligned} \quad (13)$$

and, eliminating α_i :

$$\dot{\delta}_i = \frac{k_i \dot{W}}{\mu A_i H_i}. \quad (14)$$

It is crucial to emphasize that, in equation (14), \dot{W} is the total (measurable) power and not the unknown power fraction dissipated in the wear or drilling processes. This equation can be used to evaluate both the wear and drilling velocities.

3 FORCE-CONTROLLED PERFORATIONS

Drilling processes are typically power- or force-controlled. In the first case, the perforation is in a steady state condition, the drilling velocity being constant – see eq. (14). On the other hand, if the thrust force is the controlled parameter, the power consumption could change as a consequence of the diamond tool evolution.

To describe the transient stage of perforation, we have to evaluate the evolution of the different percentages of diamonds in the drilling tool. We can assume, as a first approximation, two kinds of diamonds: grains of high or low quality. As a consequence, if the high quality diamonds present a volumetric percentage equal to $v_{DIA}^{(1)} = v$, the volumetric percentage of the low quality diamonds will be $v_{DIA}^{(2)} = 1 - v$.

According to the well-known Malthusian model, we can assume a decrease in the percentage of high quality diamonds, with respect to the drilling depth δ_1 , proportional to the percentage itself. In this hypothesis, the relative variation in the number of high quality diamonds is a constant: the larger the number of diamonds, the larger their mortality. In other words, the Malthusian model assumes the following differential equation for the dynamic evolution of high quality diamonds:

$$\frac{dv}{d\delta_1} = av, \quad (15)$$

where a is a constant depending on the tool self-sharpening. If a is equal to zero, we have an ideal self-sharpening, so that any transient phenomenon vanishes (ideal tool vs. base material coupling). If a is lower than zero, the self-sharpening becomes less efficient and the number of high quality diamonds becomes smaller (real

tool vs. base material coupling). A positive value of α implies an increase in the high quality diamonds during perforation and experimentally is not observed in the usual base materials (virtual tool vs. base material coupling).

The integration of eq. (15) provides the following dynamic evolution:

$$v = v_0 e^{\alpha \delta_1(t)}, \quad (16)$$

as is depicted in Figure 2. If $\alpha < 0$, the model predicts that the high quality diamonds are killed during the transient process.

Putting eq. (16) into eq. (14), we can obtain the transient pseudo-friction coefficient as a function of the drilling depth:

$$\begin{aligned} \mu &= v_{DIA}^{(1)} \mu_1 + v_{DIA}^{(2)} \mu_2 = \\ &= \mu_2 + (\mu_1 - \mu_2) v_0 e^{\alpha \delta_1(t)}, \end{aligned} \quad (17)$$

where μ_1, μ_2 are the pseudo-friction coefficients for a single diamond of, respectively, high or low quality and represent microscopic parameters. The evolution described by eq. (17) is shown in Figure 3 and presents a non-zero value for the horizontal asymptote.

The power consumption during the transient drilling process can be easily obtained from the evolution-law of the global pseudo-friction coefficient:

$$\begin{aligned} \dot{W} &= \mu FR \dot{\phi} = \\ &= FR \dot{\phi} [\mu_2 + (\mu_1 - \mu_2) v_0 e^{\alpha \delta_1(t)}], \end{aligned} \quad (18)$$

where F is the thrust force, R the radius of the tool and $\dot{\phi}$ the rotational speed. This evolution is shown in Figure 4.

The power consumption is the sum of the powers dissipated in drilling the base material and in the tool wear:

$$\dot{W} = S_1 A_1 \dot{\delta}_1 + S_2 A_2 \dot{\delta}_2, \quad (19)$$

where $S_1, \dot{\delta}_1$ are the drilling strength and the drilling velocity for the base material and, analogously, $S_2, \dot{\delta}_2$ are the wear resistance and the wear rate for the tool and A_1, A_2 are the areas of, respectively, the ring-hole in the base material and of the segments in the tool. Fractal [1] and multifractal [21] approaches for the power balance during drilling perforations have been also proposed by the same authors.

In the experiments, the ratio between wear and drilling velocities appears to be approximately constant (typically, for an usual base material like concrete, mortar, sandstone,

limestone, it is around 10^{-4} and around 10^{-3} for reinforced concrete, as suggested by our experiments), also during transient processes (Figure 1):

$$\frac{\dot{\delta}_2}{\dot{\delta}_1} = \alpha \approx \text{constant}. \quad (20)$$

In other words, even if the coefficient α appearing in eq. (12) can be considered to be rigorously a constant only during steady state drilling perforations – when the coefficients k_i are constants – our experiments (see Fig. 1) suggest that it can be approximately considered a constant also during transient perforations – when the coefficients k_i can individually change, although maintaining a constant ratio k_2/k_1 , see eq. (12).

As a consequence, eq. (19) can be rewritten as follows:

$$\dot{W} = (S_1 A_1 + S_2 A_2 \alpha) \dot{\delta}_1. \quad (21)$$

Putting the transient power consumption (18) into eq. (21), we obtain the transient drilling velocity:

$$\begin{aligned} \dot{\delta}_1 &= \frac{FR \dot{\phi}}{S_1 A_1 + S_2 A_2 \alpha} \times \\ &\times [\mu_2 + (\mu_1 - \mu_2) v_0 e^{\alpha \delta_1(t)}] \end{aligned} \quad (22)$$

This evolution is reported in Figure 5a. From eq. (20), we expect the same trend for the wear rate as for the drilling velocity (Figure 5b). The theoretical prediction for the transient drilling velocity (Figure 5a) can be experimentally observed as shown in Figure 6.

4 POWER-CONTROLLED PERFORATIONS

The drilling and wear velocities must satisfy the power balance (19). In power-controlled drilling perforations, the power consumption during the transient process is constant. In addition, since the ratio between drilling and wear velocities is constant – see eq. (20) – the power balance (19) implies that they both are constant:

$$\dot{\delta}_1 = \frac{\dot{\delta}_2}{\alpha} = \frac{\dot{W}}{S_1 A_1 + S_2 A_2 \alpha}. \quad (23)$$

An experimental confirmation is reported in Figure 7.

Putting the expression for the coupled parameter (12) into eq. (21), we finally obtain:

$$\dot{W} = \left(S_1 + S_2 \frac{H_1 k_2}{H_2 k_1} \right) A_1 \dot{\delta}_1 = \quad (24)$$

$$= S_{12} A_1 \dot{\delta}_1$$

It is important to emphasize that, also in this equation, \dot{W} is the total measurable power and not the unknown power fraction dissipated in the drilling process. Eq. (24) is also valid for force-controlled perforations (see eq. (21)), in which the power is variable during drilling. The constants S_{12} represent the drilling-wear coupled strength.

5 CONCLUSIONS

The developed coupled theory has permitted to predict the drilling and wear velocities, as functions of classical parameters related to base- and tool-materials – see eqs. (12), (22), (23). In particular, eq. (12) predicts a constant ratio between drilling and wear velocities as experimentally observed (Fig. 1). Furthermore, eq. (22) predicts a decrease in the drilling velocity during force-controlled transient perforations due to the tool diamond wear (herein described by the Malthusian model); the theoretical trend (Fig. 5a) is experimentally confirmed (Fig. 6). On the other hand, eq. (23) predicts a constant drilling velocity during power-controlled transient perforations; also this trend has been experimentally observed (Fig. 7). Theoretical predictions and experimental results seem to agree satisfactorily.

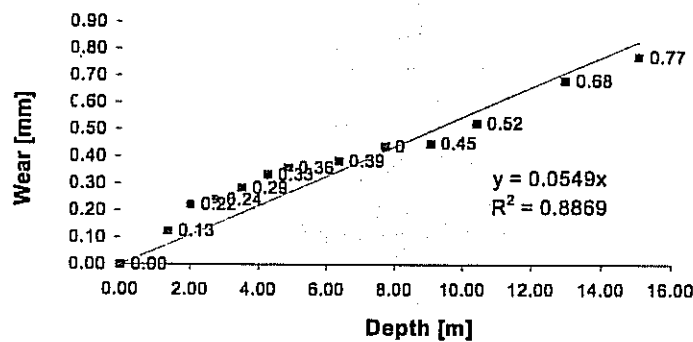


Figure 1 Proportionality between wear loss (δ_2) and drilling depth (δ_1), during transient perforation (concrete; tool diamond content 6.5%).

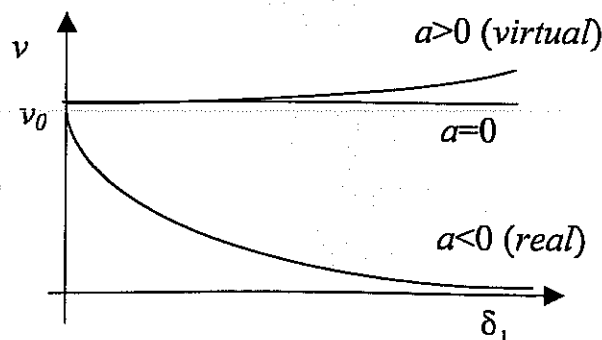


Figure 2 Transient evolution for the percentage of high quality diamonds.

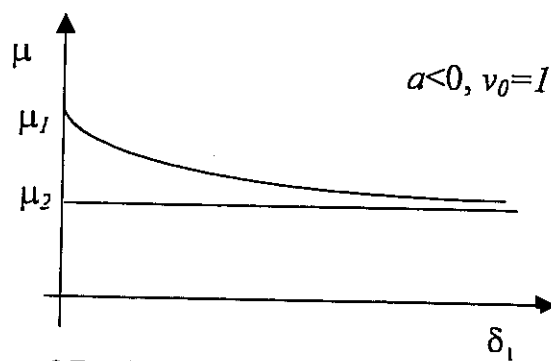


Figure 3 Transient evolution for the pseudo-friction coefficient.

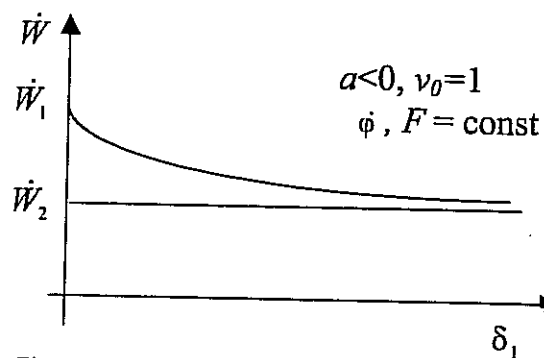


Figure 4 Transient evolution for the power consumption.

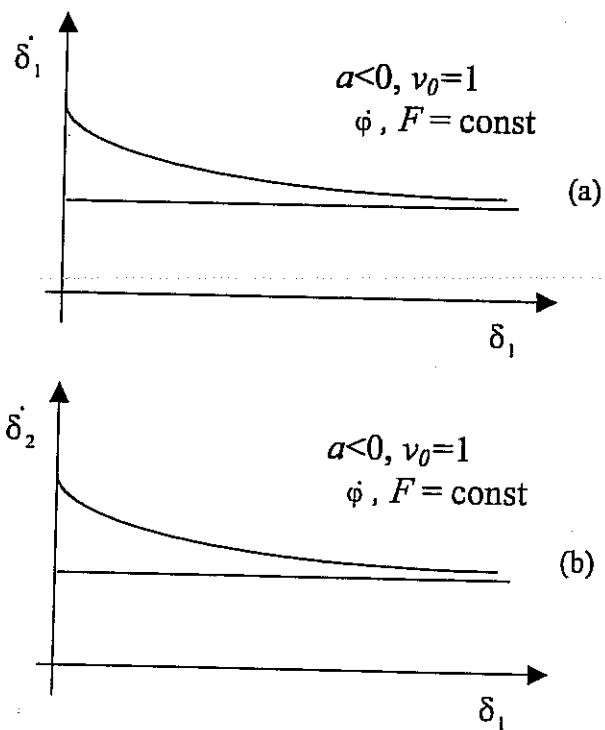


Figure 5 Transient evolution for the drilling (a) and wear (b) velocities during force-controlled perforations.

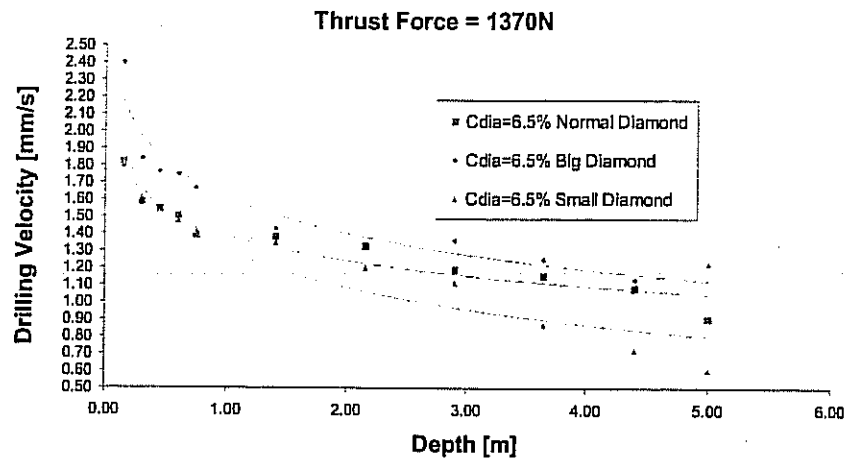


Figure 6 Experimental transient evolution for the drilling velocity during force-controlled tests on concrete (tool diamond content 6.5%; different diamond sizes: small 300 μ m; normal 400 μ m; large 500 μ m).

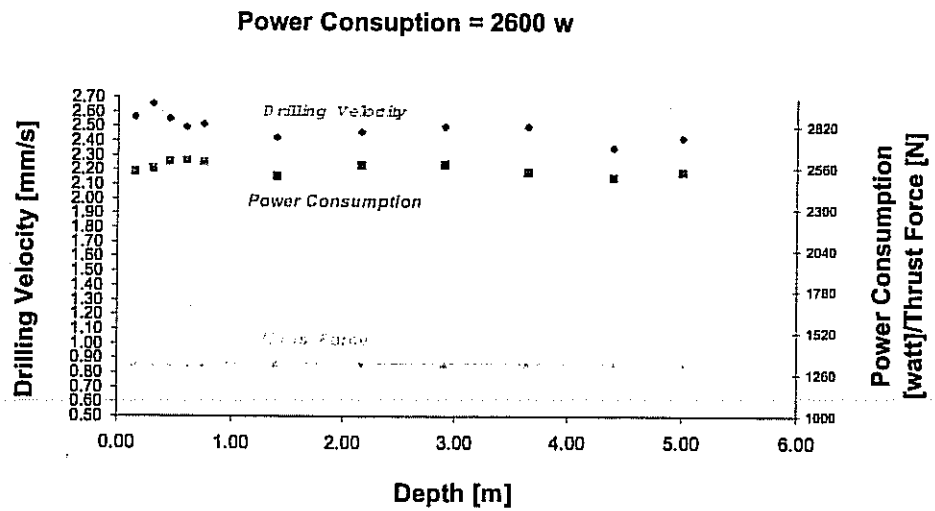


Figure 7 Experimental transient evolution for the drilling velocity during power-controlled tests on concrete (tool diamond content 6.5%; normal diamond size).

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