A New Model for the Equation Describing the Cavitation Mean Depth Erosion Rate Curve

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Paper present a new relation describing the curve MDER(t) which mediates the experimentally obtained values of the mean depth erosion rates. These curves are used to characterize the cavitation erosion behavioor of materials tested in the Cavitation Laboratory of Timisoara Polytechnic University. Practically the new relation is an improvement of the analytical model established in 2004 by Bordeasu and coworkers, by introducing a supplementary element, which take into consideration the shape of the zone in where the cavitation erosion rate became stable and has linear variation. These addition allow increasing the approximation of the experimental values and also putting into evidence the tiny differences between different materials (various types of stainless steels, highly alloyed bronzes etc.) which till now were considered with similar resistance. Thus, the supplementary term allow a better differentiation resulting from the chemical composition, the structure and the mechanical properties.

Key words: mean depth erosion rate, mean depths erosion, cavitation erosion characteristic curves, stainless steel, cast iron, bronze, cavitation vibrating laboratory device

The research takes into account the fact that cavitation erosion is a cumulate effect of two distinct phenomena:

- the first, a hydrodynamic one is characterized by the formation and implosion of cavitation bubbles developing high velocity micro jets as well as shock waves [2, 6, 7, 9];
- the second, a mechanical one is given by the solid boundary and his resistance to the repetitive impacts of micro jets and shock waves and depending essentially on the mechanical properties, chemical composition and micro-structure [3-6, 8, 10].

Because the common interaction of these two phenomena, all the experts of the field agreed that the cavitation erosion resistance is given by an energetic mechanism developed during the stresses exposure. The energetic evaluation of the erosion being extremely difficult to be done, in our days all the laboratories analyzes the behavior in time of the material and evaluate the cavitation erosion resistance by comparing the characteristic curves for the losses, in terms of mass m(t), volume V(t), mean depth erosion MDE(t), or their velocities v(t) = Dm(t)/Dt, v(t) = DV(t)/Dt, respective MDER(t) = DMDE(t)/Dt). In figure1 are presented various shapes of the curves MDER(t).

At the beginning, the characteristic curves were constructed only graphically [1, 4]. In time, it arise the problem to determine a mathematical expresion for the curve approximating, as well as posible, the experimental points. Concerns in this area exist in numerous cavitation erosion laboratories from USA, Great Britain, Poland, Italy, India, China, Japan [2, 6, 8, 10]. As a result of such concerns, the present work proposes an improved analytical model for obtaining a curve MDER(t) approximating with minimum scatter the experimental data.

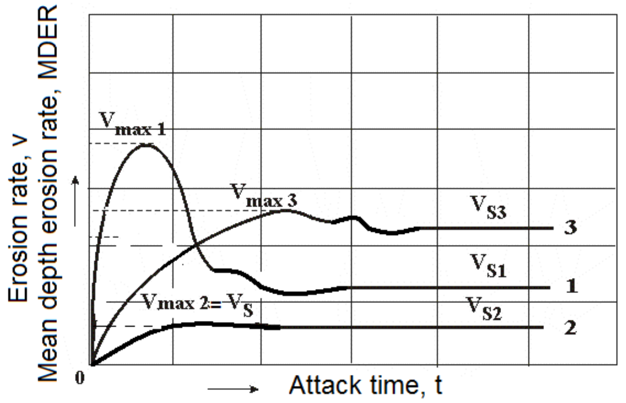

Fig.1 Various types of curves showing the dependence of mean depth erosion rate against cavitation exposure (processed after [2])(v_{max}- maximum value of erosion rate; v_s- value towards which the depth of the erosion rate has the tendency to became stable) 1, 2,3 – types o mediation curves, for materials with various resistance and behavior to cavitation erosion in laboratory devices

Proposed model

Mathematical form of the mean depth erosion rate curve

In the Cavitation Laboratory of Timisoara Polytechnic University, the characteristic curves representing the cavitation erosion process taking place in the vibrating standard device with piezoelectric crystals are constructed with the relations presented by Bordeasu and his collaborators [1, 5], which for the erosion velocity has the following form:

$$MDER(t) = \frac{dMDE(t)}{dt} = A(1 - e^{-Bt}) + ABte^{-Bt} \quad (1)$$

Even if till now, this relation proved satisfaction for the required exigency necessary to cavitation erosion resistance analyze, it has been found that for materials having a very close behavior to cavitation erosion it is relatively difficult to establish which is the better one. For such purposes were applied supplementary microscopic analyzes regarding the eroded structure.

Analyzing the curve described by the relation (1) it was observed that on the last period of attack, more precisely beginning with the minute 90-105, the evolution has not a linear decrease towards the stabilization period, such as

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results also from the ASTM G32-2010 Standard **[11]**, but is a rather exponential one. Using the graphic model presented in figure 2, we reach to the conclusion that the equation must have a supplementary term to satisfy the shape of the curve in the final period. The new obtained equation has the form:

$$MDER(t) = v(t) = A\times(1-e^{-Bt})+A\times B\times t\times e^{-Bt} - \mathbf{C\times t} \qquad (2)$$

This equation respect the condition that in the origin O (0,0) the value of the erosion velocity must be zero (see the model of the curve in fig. 1). The values of the constants A, B and C, applying the Bordeasu procedure, can be statistically determined from the following conditions:

1-the constant B is a form parameter, which for the stainless steels, regardless of their structure and properties is found in the interval [10]:

$$B \in (0.012 \ldots 0.03) \qquad (3)$$

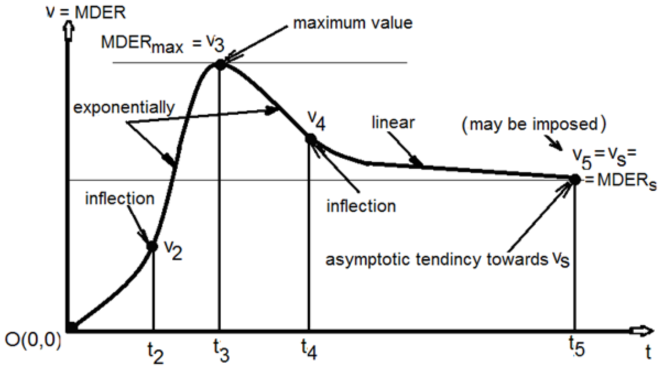

Fig.2.The complex model for an ideal mean depth erosion rate curve

The value of B is arbitrary chosen in this small interval. After founding the constants A and C, by successive iterations, the value of B is modified till the scatter of the measured points reach a minimum.

2- from the experimental data there are found the values for:

time t_3 and the corresponding erosion rate

$$v_3 = v_{max} = MDER_{max} \qquad (4)$$

3- also from the experimental data it is chosen the stable value of the erosion rate $v_s = MDER_s$, at the final period of the cavitation exposure (165 min for the tests realized in our laboratory). We propose for this value the mean of the last four measured points:

$$t_5 = 165 \text{ minutes} \Rightarrow v_s = MDER_s = \sum_{i=9}^{12} \frac{MDER_i}{4} \qquad (5)$$

With this data there can be determined also the values for the constants A and C which depend strictly by those values:

$$A = A(B, v_3, t3, v_s, 165), \text{respective } C = C(B, v_3, t3, v_s, 165) \qquad (6)$$

And have the following expresions:

$$A = \frac{165\cdot v_3 - v_s\cdot t_3}{165\cdot N - t_3\cdot U}; \quad C = \frac{v_3\cdot U - v_s\cdot N}{165\cdot N - t_3\cdot U} \qquad (7)$$

where:

$$U = 1 - e^{-165\cdot B} + 165\cdot B\cdot e^{-165\cdot B} \quad \text{and}$$
$$N = 1 - e^{-t_3\cdot B} + t_3\cdot B\cdot e^{-t_3\cdot B} \qquad (8)$$

After determining the constant values A, B and C, by integrating the relation (2), it can be found also the curve for mean depth erosion:

$$MDE(t) = \int MDER(t)dt = At(1-e^{-Bt}) - Ct^2/2 \qquad (9)$$

Checking the confidence degree

The confidence degree of the proposed relation (2) is presented by the curves from the diagrams of figure 3-8, in which were approximated the experimental values for six metals tested in our Standard Vibratory Device, with piezoelectric crystals. For all the six metals the approximation curve obtained with the relation (2) are compared with those obtained with the relation (1).

In table 1 there are given the values for the maximum/superior deviation (a_s), minimum/inferior deviation (a_i) as well as the standard deviation (s), taking into account only four measured points at the end of the stabilization zone (120-165 min). The deviation is computed for both approximation equations.

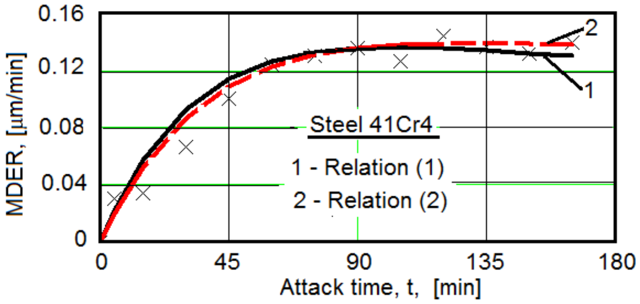

Fig.3 Approximation of the experimental for with the relations (1) and (2) for mean depth erosion rate (41Cr4 Steel)

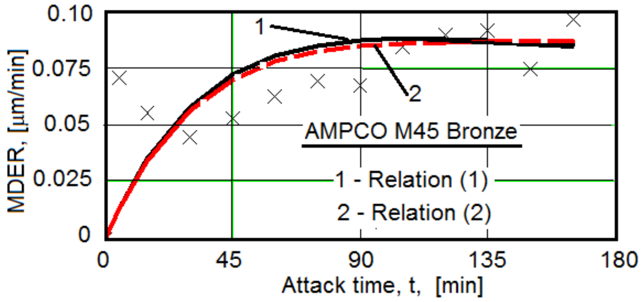

Fig.4. Approximation of the experimental values with the relations (1) and (2) for mean depth erosion rate (AMPCO M45 Bronze)

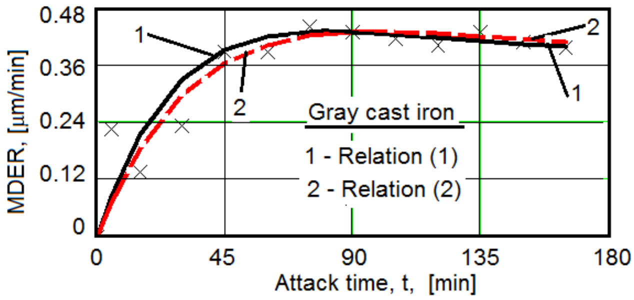

Fig.5. Approximation of the experimental values with the relations (1) and (2) for mean depth erosion rate (Gray cast iron)

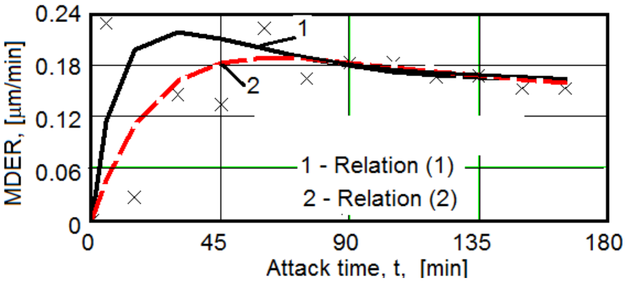

Fig.6. Approximation of the experimental values with the relations (1) and (2) for mean depth erosion rate (Stainless steel OH12NDL)

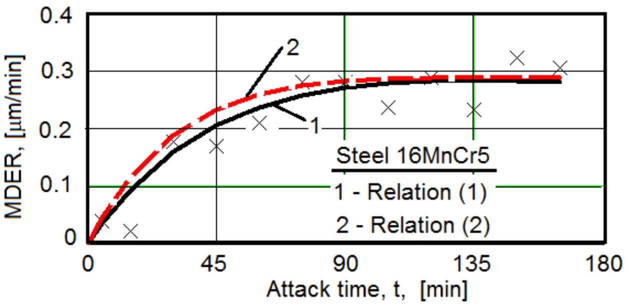

Fig.7. Approximation of the experimental values with the relations (1) and (2) for mean depth erosion rate (16MnCr5 Steel)

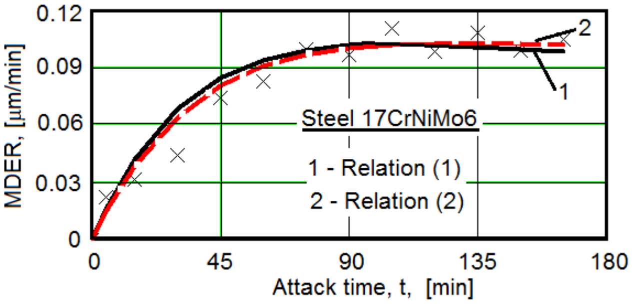

Fig.8. Approximation of the experimental values with the relations (1) and (2) for mean depth erosion rate MDER(t) (17CrNiMo6 Steel)

The relations used for computing the deviations are:

$$a_s(\text{or } a_i) = MDER_j - MDER \tag{10}$$

$$\sigma = \sqrt{\sum_{j-9}^{12} \frac{MDER_j - MDER(t)}{3}} \tag{11}$$

where j is 9, 10, 11, 12 the number of the intermediate period of testing for which was determined experimentally the mean erosion depth. MDER is the value given by the relation (2).

From table 1 it can be seen that the great majority of the values obtained with the relation (2) present smaller deviations from the measures experimental point than those obtained with the old relation (1), regardless of the type of deviation (a_s, a_i or σ). As a result, the new proposed relation (2) brings an increase of the approximation and is recommended for the future experimental researches.

In figure 9-14 are presented the diagrams for the variation of the cumulative mean depth erosion against the exposure time. In those diagrams are given the experimental obtained values as well as the mediation curves MDE(t), given by the relation (9) and (10), established by Bordeasu and coworkers, the derivative of which is the equation (1):

$$MDE(t) = At(1-e^{-Bt}) \tag{12}$$

Table 1

COMPARISONS OF THE STATISTIC PARAMETERS

Steel state	a_s [µm/min]	$\|a_i\|$ [µm/min]	σ [µm/min]
41Cr4 annealed -rel.(1) and (12)	$8.829\cdot10^{-3}$	$2.751\cdot10^{-3}$	$7.334\cdot10^{-3}$
41Cr4 annealed -rel.(2) and (9)	**$1.317\cdot10^{-3}$**	**$1.637\cdot10^{-3}$**	**$5.225\cdot10^{-3}$**
18MoCrNi13 annealed - rel.(1) and (12)	$6.653\cdot10^{-3}$	$3.391\cdot10^{-3}$	$6.125\cdot10^{-3}$
18MoCrNi13 annealed - rel.(2) and (9)	**$5.711\cdot10^{-3}$**	**$2.923\cdot10^{-3}$**	**$4.905\cdot10^{-3}$**
AMPCO M45 annealed - rel.(1) and (12)	0.019	0.011	$9.87\cdot10^{-3}$
AMPCOM45 annealed - rel.(2) and (9)	**0.012**	**$1.505\cdot10^{-3}$**	**$9.679\cdot10^{-3}$**
Gray cast iron-rel.(1) and (12)	0.018	0.015	0.014
Gray cast iron-rel.(2) and (9)	**$9.073\cdot10^{-3}$**	**$0.012\cdot10^{-3}$**	**0.013**
16MnCr5 annealed - rel.(1) and (12)	0.042	0.058	$0.041\cdot10^{-3}$
16MnCr5 annealed - rel.(2) and (9)	**0.018**	**0.056**	**$0.04\cdot10^{-3}$**
OH12NDL annealed - rel.(1) and (12)	0.011	$2.101\cdot10^{-3}$	$9.243\cdot10^{-3}$
OH12NDL annealed - rel.(2) and (9)	**$6.723\cdot10^{-4}$**	**$7.622\cdot10^{-3}$**	**$8.229\cdot10^{-3}$**

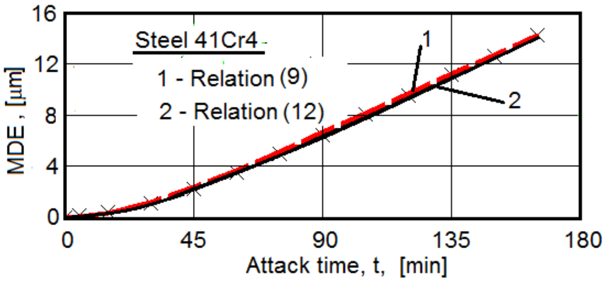

Fig. 9. Approximations of the experimental value with the relations (9) and (12) for mean depth erosion MDE(t) (41Cr4 Steel)

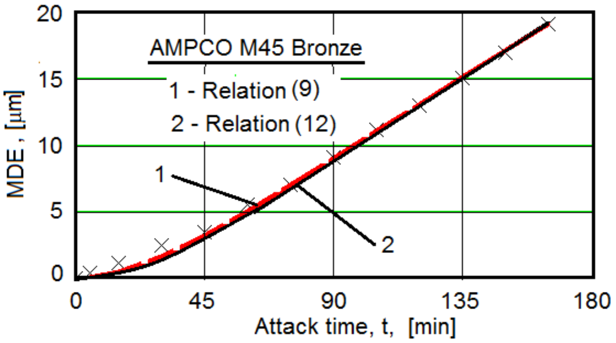

Fig. 10. Approximations of the experimental value with the relations (9) and (12) for mean depth erosion MDE(t) (AMPCO M45 Bronze)

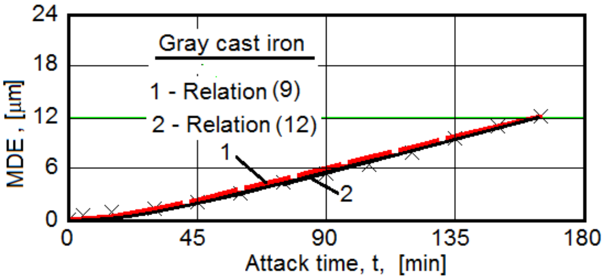

Fig. 11 Approximations of the experimental value with the relations (9) and (12) for mean depth erosion MDE(t) (Gray cast iron)

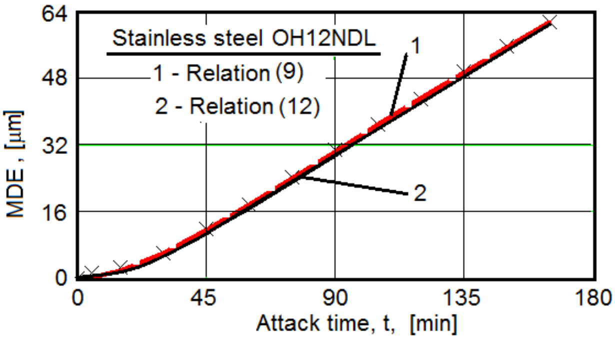

Fig. 12 Approximations of the experimental value with the relations (9) and (12) for mean depth erosion MDE(t) (OH12NDL Stainless Steel)

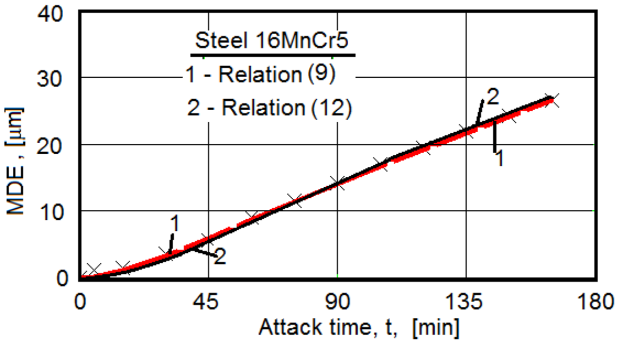

Fig. 13 Approximations of the experimental value with the relations (9) and (12) for mean depth erosion MDE(t) (16MnCr5 Steel)

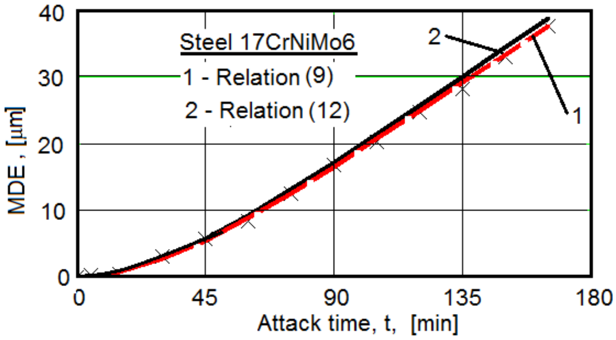

Fig.14 Approximations of the experimental value with the relations (9) and (12) for mean depth erosion MDE(t) (17CrNiMo Steel)

Table 2

CHARACTERISTIC PARAMETER VALUES FOR CAVITATION MEAN DEPTH EROSION AND EROSION RATE

Steel/steel state	MDER_s [µm/min]	MDER_{max} [µm/min]	MDE_{max} [µm] (rel. (9))	$\mathrm{MDE}_{max\text{-}measured}$ [µm]
41Cr4 annealed -rel.(1) and (12)	0.13	0.136	19.03	19.03
41Cr4 annealed-rel.(2) and (9)	**0.138**	**0.138**	**19.1**	
18MoCrNi13 annealed -rel.(1) and (12)	0.098	0.102	14.204	14.204
18MoCrNi13 annealed-rel.(2) and (9)	**0.102**	**0.102**	**14.033**	
AMPCO M45 annealed-rel.(1) and (12)	0.086	0.089	11.806	11.964
AMPCOM45 annealed-rel.(2)	**0.087**	**0.087**	**12.03**	
Gray cast iron -rel.(1) and (12)	0.401	0.431	61.583	61.583
Gray cast iron -rel.(2) and (9) and (9)	**0.41**	**0.43**	**61.179**	
16MnCr5 annealed-rel.(1) and (12)	0.281	0.284	37.622	37.622
16MnCr5 annealed -rel.(2) and (9)	**0,289**	**0,289**	**37,768**	
OH12NDL annealedt-rel.(1) and (12)	0.163	0,218	26.314	26.514
OH12NDL annealed-rel.(2) and (9)	**0,16**	**0.189**	**26.79**	

The diagrams in figures 9-14 show that there are not significant differences between the curves realize with the relation (9) and (10), such as appear for the mean depth erosion rates (fig. 3-8). In table (2) are given the values of the parameters, defined by the mediation curves, recommended by ASTM G32-2010 Standard and used by all the specialists in the evaluation of the resistance of materials to cavitation erosion.

The data in table 2 put into evidence some small differences appearing between the three used parameters, as a result of the introduction of the supplementary term. These differences are favorable for the selection, when the behavior of the materials is very close.

Conclusions

Due to the difficulties encountered in characterizing the energetic behavior of a material at cavitation erosion, respective to the evaluation of his resistance at the cavitation erosion attack, using the characteristic curves and the parameters defined by them, in conformity with the Standard ASTM G-2010, remain the best solution for describing both the behavior and the resistance to cavitation erosion.

The introduction of a supplementary term in the mathematical model proposed by Bordeasu and coworkers for the cavitation erosion velocity, with the hypothesis that the erosion rate, after the attenuation period, is a linear decreasing one towards the stabilization erosion velocity bring a better degree of approximation of the experimental points, such as can be seen table 1, and allow the differentiations between the parameters MDER_{max} and MDERs for the materials with very close behavior as the result of the cumulative effect of the structure, mechanical properties and chemical composition.

The relation (9) assures an excellent approximation of the values obtained for the cumulative losses.

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