Cavitation Erosion Qualities for 40Cr10 Steel With and Without Thermal Treatment

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The paper analyses the experimental results obtained in determining the cavitation resistance of 40Cr10 *steel with and without thermal treatment. The experimental research has been carried out in the* T1 *facility of the "Aurel Barglazan" laboratory (Timisoara "Polytechnic" University). The substance losses are evaluated both in mass and volume units. The diagrams containing the characteristic curves are presented in four distinctive shapes: free linear regression, linear regression compulsory passing through the origin, free fourth degree polynomial regression and fourth degree polynomial regression compulsory passing through the origin. From the diagrams results the conclusion that the free linear regression represents a simple and efficient method in determining the cavitation resistance of the tested material. The experimental work was done also for probes submitted to a hardening thermal treatment. Through these analyses resulted that the thermal treatment has highly improved the cavitation resistance.*

Keywords: *cavitation erosion, hydraulic drive system*

1. INTRODUCTION

The resistance against cavitation erosion of different materials is commonly given as diagrams containing the curves $\Delta m = f(t)$ or $\Delta V = f(t)$, as a result of tests carried out in facilities with intense erosion capabilities. The volume evaluation is recommended in the case of comparisons between materials having different specific masses (for instance steel and bronze). In the paper there are presented the characteristic curves for the steel 40Cr10 without thermal treatments, both for mass and volume evaluation.

2. THE TESTED MATERIAL

The steel 40Cr10 is frequently used in manufacturing valves, spools and other important details of the hydraulic systems for control and distribution. The tested material was obtained from the SC Electrotimis SA-Timisoara. The chemical compo-sition of the steel 40Cr10 is: C=0,044%; Si=0.29%; S= 0,008%; Cr=0,97%; the rest being Fe.

The surfaces exposed to cavitation is polished to Ra=0,2-0,4µm, before cavitation, the microscopic examination of the active surfaces revealed no crack, pore or other defectives that can favour the beginning of the erosion. During the tests the mass of the specimen was determined with an analytical balance that allow obtaining six significant digits.

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3. TESTING METHOD

The experimental researches have been carried out in the magnetostrictive facility T1 of the "Aurel Barglazan" laboratory belonging to Timisoara "Polytechnic" University having the following parameters, (Popoviciu, 1995):

- vibration amplitude: A = 47 µm;
- vibration frequency: f = 7000 ± 3% Hz;
- probe diameter: d = 14 mm;
- working liquid: distilled water;
- temperature of working liquid: t = 20 ±1°C;
- pressure at the liquid surface: atmospheric pressure;
- immersion height: h = 3 mm.

Before the beginning of the cavitation erosion, as well as after each testing period the specimen is successively washed in drinking water, distilled water, alcohol and acetone and dried with warm air.

The entire duration of the tests was 165 minutes divided like this: two periods of 5 minutes, two of 10 minutes and 9 of 15 minutes.

After each testing period, the specimen mass was determined by carefully weighing. From this row of measurements the mass loses have been calculated. In order to obtain volume loses the masses are divided through the density of material.

4. EXPERIMENTAL RESULTS FOR SPECIMENS WITHOUT TREATMENT

The mass of untreated specimens is noted with m_1, m_2 and m_3, the material loses with y_1, y_2 and y_3 for the measured specimens and their mean is noted with y. The volume loses are noted with V_1, V_2, V_3 and V.

For all specimens there have been determined the characteristic curves in the following variants:

- free linear regression;
- linear regression compulsory passing through the origin;
- free fourth degree polynomial regression
- fourth degree polynomial regression compulsory passing through the origin.

With the view of exemplifying, in Figures 1, 2, 3 and 4 the experimental results for the specimen 3 are presented as well as the four specified types of regression lines, using only mass evaluations. Examining the figures it is easy to see that the dispersion is smaller for the fourth degree polynomial regression, both curves the free and the compulsory passing through the origin are very similar (not only from the point of view of the correlation coefficient but also taking into account the regression equations). Between the two linear regressions, the free one gives the smallest dispersion.

$$y_3 = 0.3051x - 2.088 \quad ; \quad R_3^2 = 0.9925$$

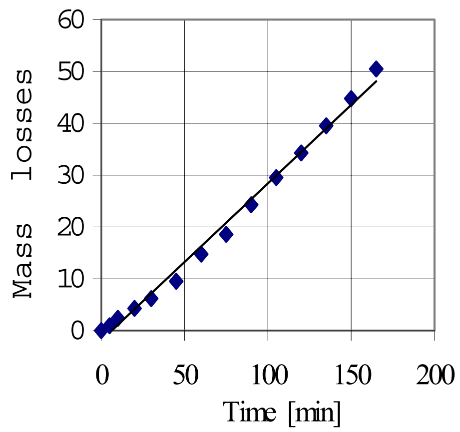

Figure 1: Specimen 3. Free linear regression

$$y_3 = 0,2866\,x \quad ; \quad R_3^2 = 0,9868$$

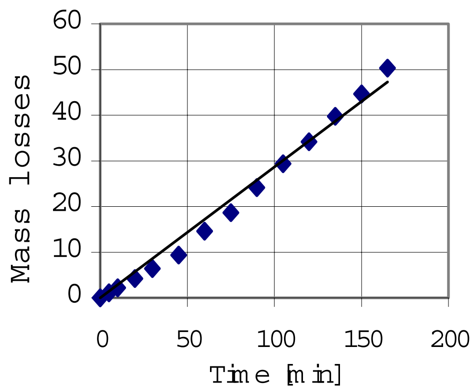

Figure 2: Specimen 3. Compulsory linear regression

$$y_3 = 3\times10^{-10}x^4 - 4\times10^{-6}x^3 + 0.0015x^2 + 0.1574x + 0.2554$$

$$R_3^2 = 0.9997$$

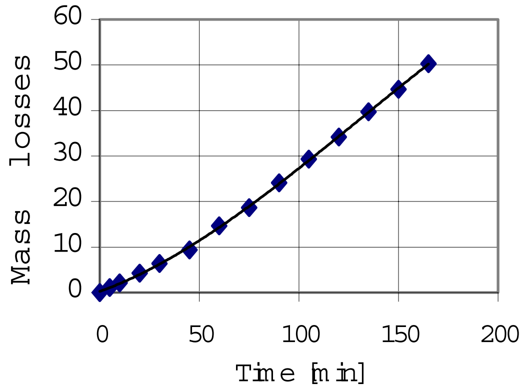

Figure 3: Specimen 3. Free 4 degree polynomial regression

$$y_3 = -1\times10^{-08}x^4 - 3\times10^{-07}x^3 + 0.0011x^2 + 0.178x$$

$$R_3^2 = 0.9997$$

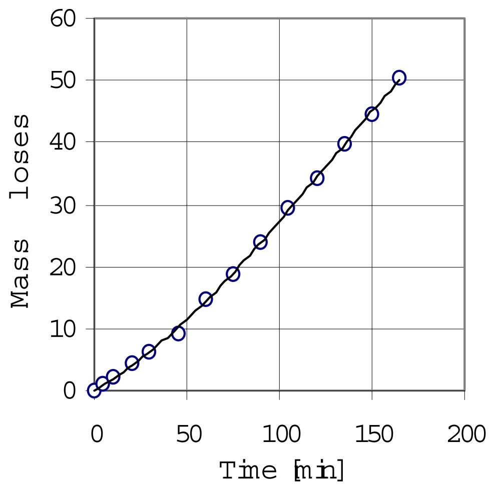

Figure 4: Specimen 3. Compulsory 4 degree polynomial regression

Out of previous researches (Balasoiu, 2002, and Popoviciu, 2001), it is known that for materials with improved cavitation resistance, the polynomial regressions with higher degrees than four do not significantly contribute to diminishing the dispersions. For that reason we restrain the study only to the fourth degree polynomial regression. In some cases, it is possible to use also regression lines with smaller polynomial degrees. Evidently, we have represented the characteristic curves for all four variants and for every specimen, and the conclusion has remained the same.

Among the three tested specimens, for S1 and S3 the experimental results are very close to each other while S2 presents feeble results. That is the reason for which in figure 5 is presented only the comparison for S1 an S2. To give an idea about the manner in which the scatters differ from the linear to the polynomial regression (both free), for S2 it has been chosen linear regression while for S1 the fourth degree polynomial (R2L^2 is the correlation coefficient for the linear regression and R1po^2 is the one for the fourth degree polynomial regression).

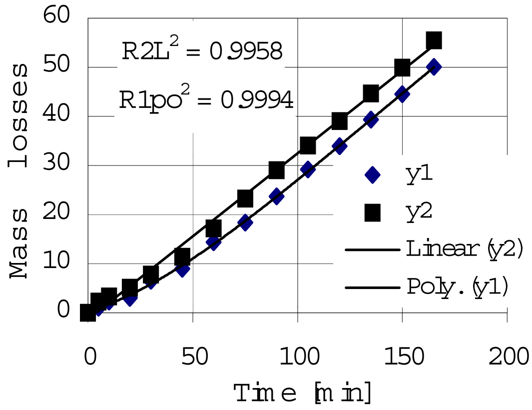

Figure 5: Comparison S1 /S2; Linear/ Polynomial

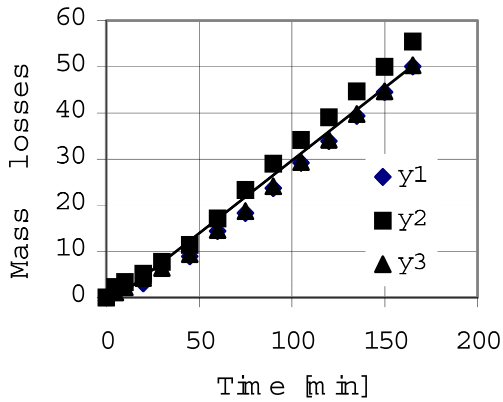

Figure 6: Mass losses. All measurements and the mean line

In figure 6 are presented all the measured points for mass loses and the linear regression line, for the free variant. For comparisons in figure 7 is presented the same type of diagram but with the losses evaluated in volumes. Comparing those two diagrams, it can be seen that no important differences appear between the volume and mass representations of the measured points.

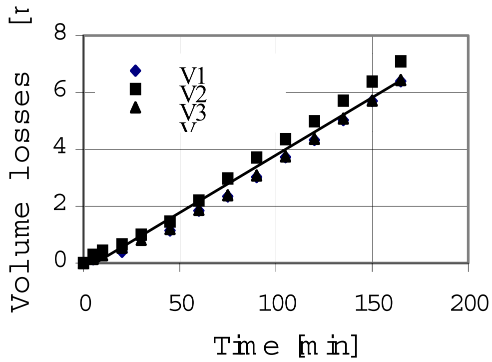

Figure 7: Volume loses. All measurements and the mean line

From both diagrams, it resulted that the measured points for the specimen 1 are extremely difficult to be observed. For this reason in figure 8 is presented a fragment of the diagram with the ordinate enlarged. The fragment is taken from a region where the greatest differences between the results of specimen 1 and 2 are found.

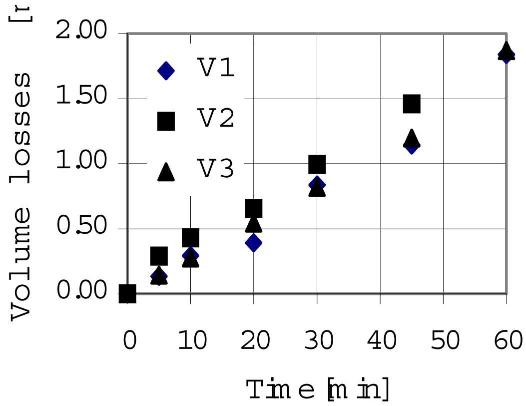

Figure 8: Enlarged fragment of diagram

Examining the figures 6 and 7, it is obvious that no individual regression line can be chosen to represent the material. A representative curve for all the three specimens can be obtained only by computing the mean of the experimental value $y_{i,m}$ for each x_i (this has been done by plotting the diagrams 6 and 7).

An approximate method to ascertain the cavitation erosion qualities for a given material, can be obtained by comparing loses after the complete period of testing (in our case 165 minutes). In table 1, these values are given together with the mean value of y and V. For the fourth polynomial regression, both for the evaluation in masses or in volumes do not exist significant differences whether the curve is free or it must pass compulsory through the origin of the axes system. This fact can be observed either directly from the characteristic curves (see figures 3 and 4) or by comparing the correlation coefficient (as in table 2). The small difference between the reciprocal values conducts to the conclusion that plotting both curves should be avoided. We recommend the free polynomial curve.

Table 1: Substance loses after 165 minute of cavitation

Mass loses [mg]			
y_1	y_2	y_3	y
50.05	55.45	50.31	51.94
Volume loses [mm^3]			
V_1	V_2	V_3	V
6.40	7.09	6.43	6.64

For linear regression, the obligation to pass through the origin of the co-ordinate system worsened the scatter of the experimental points around the regression line. This fact results directly from the diagrams (figure 1 and 2) or by comparing the correlation coefficients (as in table 3). From the table 3 it can be seen that the differences are not very great, so both lines can be chosen. Although we recommend the free regression line that gives a better dispersion of measured points around the regression line.

For this alternative, no correlation between the cavitation incubation period and the interception coefficient can be done. The computing program establishes only that interception coefficient which offers the best line approximating the points and no physical interpretation of this fact is possible, especially because the interception coefficient can be either a positive or a negative number, Popoviciu (2001).

Table 2: Correlation coefficients for compulsory and free fourth degree polynomial regression

Mass loses				
	R_1^2	R_2^2	R_3^2	R^2
F	0.9994	0.9993	0.9970	0.9996
C	0.9994	0.9990	0.9970	0.9995
Dif.	0	0.0003	0	0.0001
Volume loses				
	R_1^2	R_2^2	R_3^2	R^2
F	0.9994	0.9993	0.9997	0.9996
C	0.9994	0.9990	0.9997	0.9995
Dif.	0	0.0003	0	0.0001

Table 3: Correlation coefficients for free and compulsory linear regression

Mass losses				
	R_1^2	R_2^2	R_3^2	R^2
F	0.9914	0.9958	0.9925	0.9938
C	0.9843	0.9940	0.9868	0.9894
Dif.	0,0071	0,0018	0,0057	0,0044
Volume losses				
F	0.9914	0.9958	0.9925	0.9938
C	0.9843	0.9940	0.9868	0.9894
Dif.	0.0071	0.0018	0.0057	0.0044

Table 4: Differences between the correlations coefficients of the free regressions, both for linear and fourth degree polynomial

Mass losses				
	R_1^2	R_2^2	R_3^2	R^2
Lin	0.9914	0.9958	0.9925	0.9938
Po4	0.9994	0.993	0.9997	0.9996
Dif %	0.800	0.350	0.720	0.580
Volume losses				
Lin	0.9914	0.9958	0.9925	0.9938
Po4	0.9994	0.9993	0.9997	0.9996
Dif %	0.800	0.350	0.720	0.580

In order to determine the cavitation incubation period it is necessary to accomplish specific researches, generally in facilities with reduced cavitation intensity.

In table 4 there are given the square values of the correlation coefficient for free regression linear and fourth degree polynomial lines. The differences are relatively small (we recall that statistically the regression is acceptable if the correlation coefficient exceeds the value of 0.8). For both situations, the correlation coefficients exceed the value 0.9. Even the percentage differences are not greater than 0,8%. If there are no other motives, we recommend the free linear regression. This type of regression is very simple and by the unique value of the slope gives a clear and convincing image upon the cavitation resistance qualities of the examined material.

5. EXPERIMENTAL RESULTS FOR SPECIMENS WITH THERMAL TREATMENT

The thermal treatment worked out at the SC Electrotimis SA- Timisoara factory consisted in hardening at 1050ºC with a subsequently cooling in oil, followed by reheat at 300ºC, with cooling in air. A simple and convincing possibility concerning the cavitation resistance of a material is given by the final loss of substance after the total exposing time. This numeric value is presented in table 5 both for the probe with and without thermal treatment. Because of the hardening the loss represents only 0.55 till 0.62 from that obtained in the specimens without treatment.

Table 5: Substance losses after 165 minutes of cavitation

Mass losses [mg]				
Without	y_1	y_2	y_3	y
TT	50.05	55.45	50.31	51.94
With	y_4	y_5	y_6	y
TT	31.24	31.29	2.58	30.37
Rate	0,6241	0,5643	0,5681	0,5924
Volume losses [mm^3]				
Without	V_1	V_2	V_3	V
TT	6.40	7.09	6.43	6.64
With	V_4	V_5	V_6	V
TT	3.99	4.00	3.65	3.88
Rate	0.6234	0.5642	0.5677	0.5843

With the view of differentiate the hardened materials from the other ones, the masses of the non-hardened specimens are designated with m1, m2 and m3, while the masses of the treated ones are designated with m4, m5 and m6. In the same way the mass losses are noted with y_1, y_2, y_3 respectively y_4, y_5, y_6 for the measured specimens but the mean in each situation is noted with y. Using the material specific gravity it was possible to determine the volume loss, noted with V_1, V_2, V_3, V respectively V_4, V_5, V_6 and V. For all specimens, the characteristic curves were determined in the following variants:

- free linear regression;
- linear regression compulsory passing through the origin;
- free fourth degree polynomial regression;
- fourth degree polynomial regression compulsory passing through the origin.

The diagrams have been plotted for all the four variants and for each specimen.

It is necessary to make the mention that for the condition of “Aurel Barglazan” laboratory it is not possible to reuse the tested specimens for the thermal treatment. Therefore, the treated specimens are completely distinct as regard to the non-treated ones but were taken from the same rod. In order to present information upon the behavior of treated 40Cr10 steel at cavitation erosion, in figures 9, 10, 11 and 12 are given the characteristic curves of the specimen number 6 for different types of regressions.

There are also given the equations for the regression lines and the square of the correlation coefficient. From the diagrams, it is seen that for all the four methods adopted, the obtained lines approximate very well the points.

$$V_6 = 0.0225x + 0.1162 \quad ; \quad R_6^2 = 0.9878$$

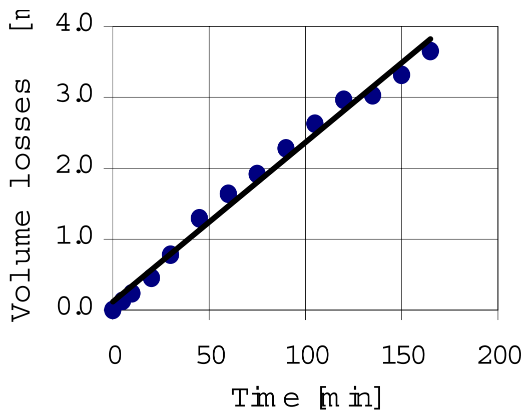

Figure 9: Specimen 6. Free linear regression. Evaluation in volumes

$$V_6 = 0.0235x \quad ; \quad R_6^2 = 0.9846$$

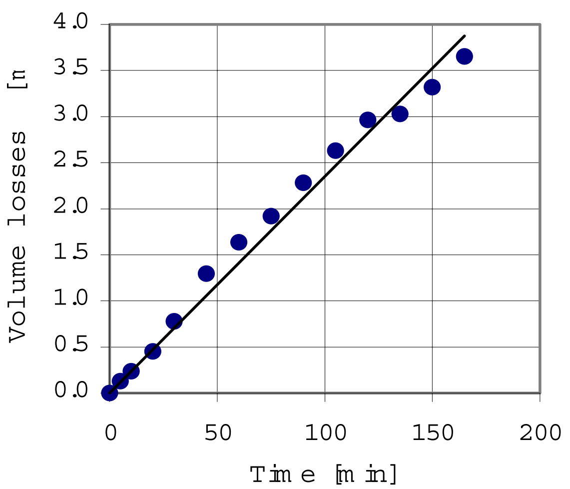

Figure 10: Specimen 6. Compulsory linear regression. Evaluation in volumes

Comparing the polynomial regression with those without treatment it is seen that for the same material the shapes of the line differ. This fact cannot be explained by the evaluation method (mass or volume) because in Figure 13 the shape of the line remains close to that in Figure 12 though the evaluation method is different. So that, taking the specimen from the same rod but from a different part the shape of the polynomial regression is modified principally because of the dispersion of the measured points. Therefore, we think that a linear regression line is more appropriate. It reveals clearly that we are in a zone where the cavitation qualities are better (or worse) and it is not necessary to look for an explanation of the curve shape, which is circumstantially and do not take into account the complusory dispersions between the regression line and the experimental points.

Comparing the Figures 11 and 12, it results that between the free fourth degree polynomial line and that obliged to pass through the origin there are not visible differences. Even examining the line equations, it can be seen that the difference between the free terms is very small which show that the line passes very close to the origin; the other terms are also very similar and the correlation coefficient is equal. The differences between

$$V_6 = 8 \cdot 10^{-9} x^4 - 3 \cdot 10^{-6} x^3 + 0.0002x^2 + 0.022x - 0.0015$$

$$R_6^2 = 0.9984$$

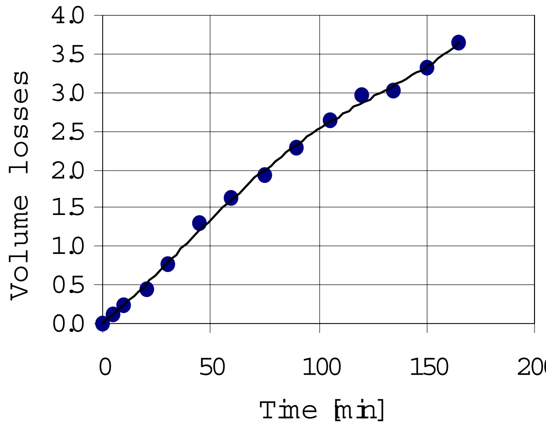

Figure 11: Specimen 6 Free 4 degree polynomial regression. Evaluation in volumes

$$V_6 = 8 \cdot 10^{-9} x^4 - 3 \cdot 10^{-6} x^3 + 0.0002x^2 + 0.0219x \ ; \ R_6^2 = 0.9984$$

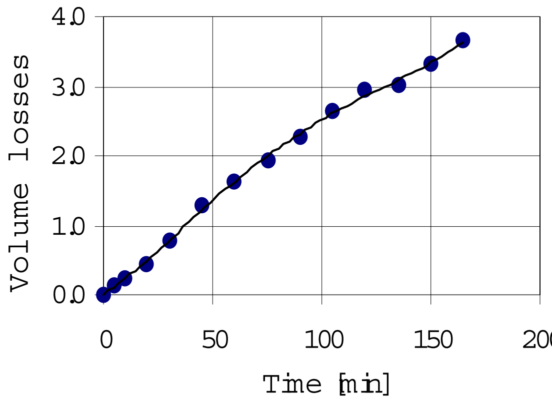

Figure 12: Specimen 6. Compulsory polynomial regression. Evaluation in volumes

$$y_6 = 6 \cdot 10^{-8} x^4 - 2 \cdot 10^{-5} x^3 + 0.0016x^2 + 0.1713x \ ; \ R_6^2 = 0.9984$$

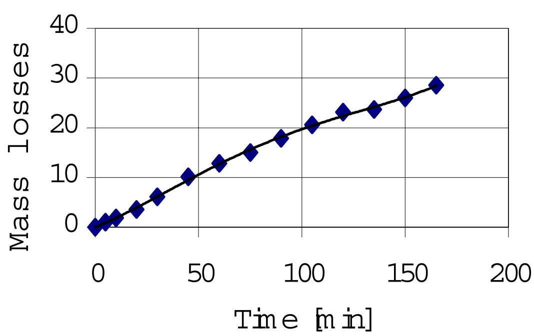

Figure 13: Specimen 6; compulsory fourth degree polynomial regression. Mass evaluation

the linear and polynomial regression can be estimated in figure 14 for the specimen 6 (the differences are similar also for the other specimens). In Figure 15 it is presented the mean regression line and all the experimental results in volume evaluation while in Figure 16, for comparison, the same types of data are presented in mass evaluation. From these Figures it can be seen also the experimental points scatter from the mean regression line.

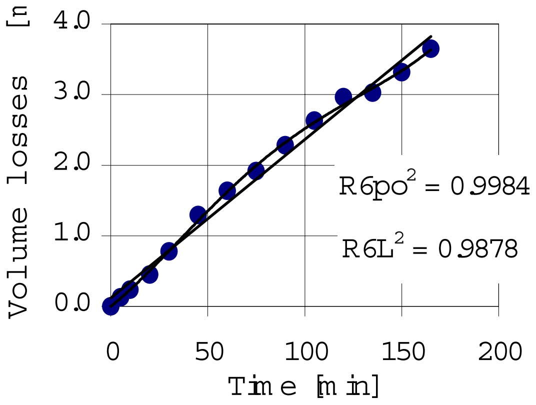

Figure 14: Specimen 6. Differences linear/polynomial

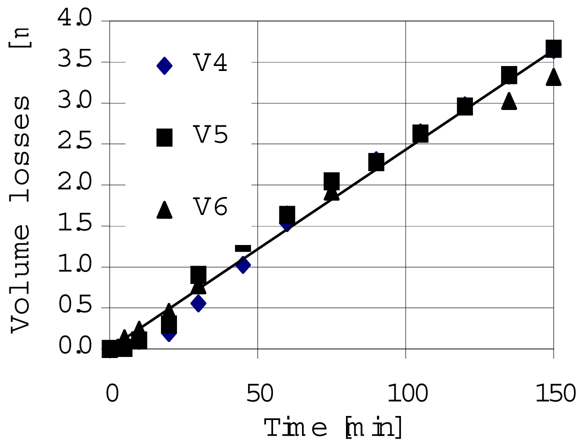

Figure 15: All measurements and the mean line

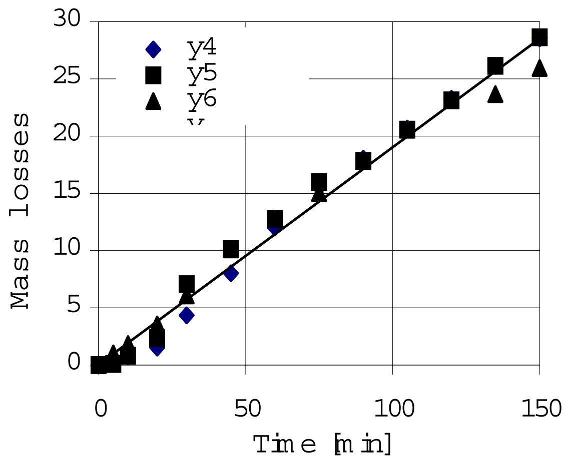

Figure 16: Mass losses. All the measurements and the mean line

6. CONCLUSIONS

1. For the steel 40Cr10 no individual regression line can be chosen to be representative for the material. The characteristic curve must be computed by determining the mean y for every abscissa x_i. From here, arise the necessity to represent also the mean curve.

2. For the fourth degree polynomial regression, it is recommended to avoid that which compulsory passes through the origin of the co-ordinate system. The differences with the free curves are out of significance.

3. In the case of linear regressions, forcing the line to pass through the origin of the co-ordinate system worsens the dispersion. It is recommended to use free regression line. The interception coefficient cannot be considered equivalent with the cavitation incubation period (in this period appear only deformations of the exposed area without any loss of substance).

4. Because the differences between the free linear regression and the polynomial one are very small, we recommend choosing the first one as representative for the material. The polynomial regression has as advantage only the smaller dispersion of points around the regression line. The free linear regression is very simple and by the unique value of the slope gives a clear and convincing image upon the cavitation resistance qualities of the examined material.

5. For the steel 40Cr10, the thermal treatment has an important role in reducing the cavitation erosion. As a result of the hardening the substance loss is reduced to 55…62%.

6. Most of the other conclusions obtained with the non-treated material are valid also for the treated specimens.

7. As characteristic curve, it is recommended the free linear regression line. Only in exceptional cases another regression line can be chosen.

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