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Application of aluminide coatings modified with yttrium for protecting corn post-harvest processing equipments against erosion in food industries

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Abstract

Recent studies demonstrate that aluminide coatings are beneficial to wear and erosion resistance and also oxygen-active elements such as yttrium can remarkably improve this resistance. In this research, the micro-hardness of the aluminide coatings with and without yttrium on carbon steel AISI 1045 was investigated using a micro-mechanical probe in post-harvest processing equipments in food industries. Wear of the samples was measured using a pin-on-disk tribometer. The erosion loss of specimens against five varieties of corn was also evaluated using a slurry erosion test machine. Experimental data were analyzed statistically using a 5-factor completely randomized design to study the effect of corn varieties, moisture content at three levels [13, 15, and 17% (wet basis)], and rotation velocity of the slurry erosion machine at three levels (150, 300, and 450 rpm) on erosion resistance. The results showed that the aluminide coatings improved the wear and erosion resistance of substrate carbon steel AISI 1045; yttrium markedly improved the hardness of the aluminide coating and its wear and erosion resistance. The erosion loss of materials was significantly ($P < 0.01$) influenced by the variety of corn, moisture content and rotation velocity. Both aluminide coating without yttrium and aluminide coating with yttrium showed higher wear and erosion resistance than carbon steel AISI 1045 substrate.

Additional key words: carbon steel AISI 1045, corrosion, Indurata, storage bins, transportation, wear.

Resumen

Aplicación en la industria alimentaria de recubrimientos de aluminuro modificados con itrio para proteger a los equipos de procesamiento post-cosecha contra la erosión

Estudios recientes demuestran que los recubrimientos de aluminuro ayudan a resistir el desgaste y la erosión, y también que los elementos con oxígeno activo, tales como el itrio, pueden mejorar notablemente esta resistencia. En este estudio se investigó la micro-dureza de los recubrimientos de aluminuro con y sin itrio sobre acero al carbono AISI 1045 mediante una sonda micro-mecánica en equipos de procesamiento post-cosecha de la industria alimentaria. El desgaste de las muestras se midió utilizando un tribómetro *pin-on-disk*. También se evaluó la erosión en cinco variedades de maíz utilizando una máquina de pruebas de erosión de purines. Los datos experimentales se analizaron mediante un diseño de factor-5 completamente aleatorio para estudiar el efecto de la variedades de maíz, el contenido de humedad a tres niveles [13, 15 y 17% (base húmeda)] y la velocidad de rotación de la máquina de erosión de los purines a tres niveles (150, 300 y 450 rpm) sobre la resistencia a la erosión. Los resultados mostraron que los recubrimientos de aluminuro mejoraron la resistencia al desgaste y a la erosión del sustrato de acero al carbono; el itrio mejoró considerablemente la resistencia del recubrimiento de aluminuro y su resistencia al desgaste y a la erosión. La pérdida de erosión de los materiales se vio influenciada significativamente ($P < 0,01$) por la variedad de maíz, el contenido de humedad y la velocidad de rotación. Los recubrimientos de aluminuro sin itrio y con itrio mostraron una mayor resistencia al desgaste y a la erosión que el sustrato de acero al carbono.

Palabras clave adicionales: acero al carbono AISI 1045, arcas de almacenamiento, corrosión, desgaste, Indurata, transporte.

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Abbreviations used: MC (moisture content), MLR (multiple linear regression), rpm (revolutions per minute), wb (wet basis).

Introduction

Corn kernels are handled mechanically in storage bins and post-harvest processing equipments in food industries by augers and conveyors, airflow, or when it is allowed to flow by gravity. When corn kernels are transported through these equipments, they may impact on the body of equipments and may cause serious erosion damage. When corn is transported through pipelines, previous researches showed that the erosion rate of the bend could be 50 times higher than that of straight pipe (Fan *et al.,* 2001). For this reason improving bend protection against erosion is an urgent task.

Wear of a solid surface by particle erosion has been the subject of many studies. For a similar resistance of the target pipe material and a similar condition of the impacting particles, different approaches can be used to reduce the erosion damage of the pipes such as: a decrease in the momentum of the impacting particles, a decrease in the range of the impact incidence angle (Tabakoff, 1984; Humphrey, 1990; Burakowski and Wierzchon, 1999; Fan *et al*., 2001), fixed ribs on the wall of the inside bend (Song *et al*., 1996; Yao *et al*., 2000; Fan *et al*., 2001), and a finned pipe erosion protection method (Fan *et al*., 1992). Surface damage due to wear and erosion may result in changes of the surface conditions and/or dimension of a mechanical component. As a result, these damages increase the risk of surface breaking, which might cause a disastrous failure of an entire mechanical system. Coating is one of the effective approaches against surface failure. Steel is often used as the core material coated with different materials for applications in the mining, chemical, petrochemical and food processing industries, and in transport pipelines to protect equipment and machinery from wear, corrosion and erosion. Recent studies have shown that wear and corrosive erosion of the aluminide coating can be markedly reduced by adding oxygen-active elements. For instance, yttrium improved the resistance of the aluminide coating to wear, corrosive wear, corrosion, corrosive erosion and dry sand erosion (Zhang *et al*., 1999; Zhang and Li, 2000a,b; Ahmadi and Li, 2002). The objective of this research was to investigate the protection against erosion of corn post-harvest processing equipments in food industries by applying aluminide coatings modified with yttrium.

Material and methods

The substrate material used in this study was commercial carbon steel AISI 1045. The dimension of the specimens was 13,612 mm. All specimens were polished with 600 grit SiC sand paper and cleaned in acetone, and then coated with Al to form an aluminide coating using a pack-cementation process (Soliman and El-Azim, 1999; Xiao and Mei 1999). FeAl (50%Fe-50%Al) alloy powder was used as the aluminium source, NH_4Cl powder as an activator, and Al_2O_3 powder as a filler material. About 3% yttrium powder (–40 mesh) was mixed with the FeAl powder (Ahmadi and Li, 2003).

Nitrogen gas was used to protect the specimens from oxidation. The coated specimens were mechanically polished using SiC sand papers and, finally, polished using 0.05-micron alumina. The specimens were cleaned in acetone. Micro-hardness of the specimens was determined using a micromechanical probe (Ahmadi and Li, 2003).

In order to evaluate wear resistance of the aluminide coated steel, specimens were also tested using a pin-on-disk tribometer. Volume loss of samples after 1,000 laps was measured. The sliding speed and applied normal load were 10 mm s^{-1} and 3 N, respectively. The diameter of the silicon carbide ball pin was 6 mm. The width of the wear track (W) on the target specimen and diameter of the worn area of the ball pin (w) were measured using an optical-microscope. The cross-section area of a wear track on the target material was the trapezoidal shape area as shown in Figure 1. The volume loss of the material per unit length of the wear track is thus the trapezoidal shape area multiplied by a unit length.

Different varieties of corn were selected for the trials, from hard and soft quality classes. The moisture content of corn kernels (MC_{wb}, % w.b.) was measured using the following formula:

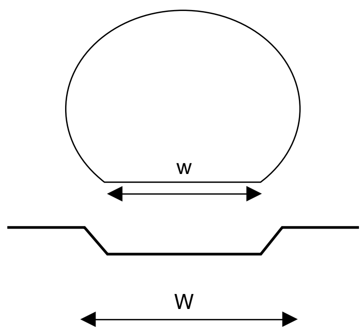

Figure 1. Schematic view of the wear track cross-section area (trapezoidal shape are). W: width of the wear track on a target specimen. w: diameter of the worn area of the ball pin.

$$MC_{wb} = \frac{M_b - M_a}{M_b} \times 100 \quad [1]$$

where M_b = mass of kernels before drying; and M_a = mass of kernels after drying. The sphericity percentage (S, %) of corn kernels was evaluated using the following formula:

$$S = \frac{(abc)^{1/3}}{a} \times 100 \quad [2]$$

where a = length of kernel, mm; b = width of kernel, mm and c = height of kernel, mm. The erosion loss of specimens against five varieties of corn (Amyalcea, Everta, Indentata, Indurata, Sacchatata) was evaluated using a slurry erosion test machine. The volume loss was estimated using the following formula:

$$V = \frac{\Delta W}{\rho A t} \quad [3]$$

where V = erosion rate, cm^3 m^{-2} hr^{-1}; ΔW = weight loss, g; ρ = specimen density, gcm^{-3}; A = eroded area, m^2 and t= testing time, hr.

The erosion loss of Y-containing coating specimens against different varieties of corn was evaluated using a slurry erosion test machine. The rotation velocities of slurry erosion test machine were 150, 300, and 450 rpm. The moisture contents were 13, 15, and 17% (wet basis).

Trials were carried out according to a 5-factor completely randomized design to study the effect on the erosion resistance of the five varieties of corn, moisture contents at three levels [13, 15, and 17 % (wet basis)], and the rotation velocity of the slurry erosion machine at three levels (150, 300, and 450 rpm). Five measurements were done for each test and results were analyzed and compared using the analysis of variance (F-test) and multiple linear regression (MLR).

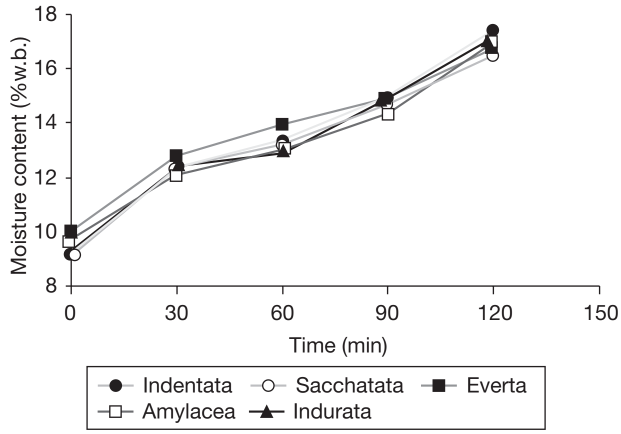

Figure 2. Corn-absorption diagram for five varieties of corn.

Results and discussion

Diagram of water absorption

To prepare the sample at different moisture levels (13, 15, and 17% wb), corn kernels were soaked in water for 5 to 120 min and then their moisture contents were determined by standard air oven method at 103°C for 24 hr. In order to determine the time needed to achieve these moisture contents for each corn variety, a previous experiment was conducted. This action was done four times for each variety and average of them was plotted in Figure 2 as corn-absorption diagram for five varieties of corn. Table 1 gives some physical properties of five varieties of corn that were used for the tests.

Micro-hardness properties

Figure 3 shows the hardness values of the Y-containing and Y-free aluminide coatings, at different loads from 25 to 750 mN. The results demonstrated that the hardness of the Y-free and Y-containing aluminide

Table 1. Physical properties of corn kernels

	Indurata	Sacchatata	Everta	Amyalcea	Indentata
Initial moisture content (% w.b.)	9.3	9.1	10	9.5	9.6
Kernel dimensions (mm)					
a	10.5	9.9	12.1	11.9	11.0
b	4.6	6.9	8.6	6.9	6.8
c	4.0	4.7	5.2	4	5.3
Thousand kernels weight (g)	240	214	202	260	236
Sphericity (%)	55.1	69.3	67.3	58.1	66.8

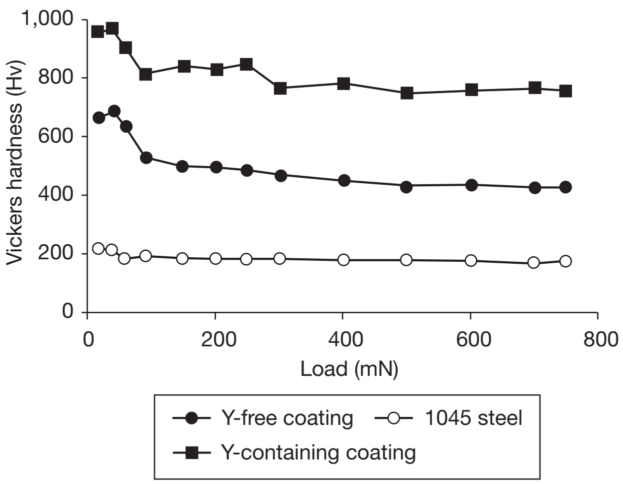

Figure 3. Hardness value of carbon steel AISI 1045, Y-free coating and Y-containing coating (all values were obtained by averaging at least three measurements).

coatings was about 3 and 5 times higher than that of carbon steel AISI 1045, respectively. These results demonstrated that Y significantly increased the hardness of the aluminide coating.

Wear behaviour

The mean volume loss of five measurements of specimens showed that there were significant differences among carbon steel AISI 1045 (695 $\mu m^3\ \mu m^{-1}$) and aluminide coating without and with yttrium after 1,000 laps (307 and 96 $\mu m^3\ \mu m^{-1}$, respectively) ($P < 0.05$). Both yttrium-free and yttrium-containing aluminide coating showed higher wear resistance than that of uncoated material. The wear resistances of aluminide coatings with yttrium and without yttrium were approximately 7 and 2.5 times as high as that of the substrate steel, respectively.

Effect of corn variety, moisture content, and machine velocity on volume loss of materials

The analysis of variance test showed that, in the slurry erosion test machine, erosion loss of carbon steel AISI 1045 (11.55 $mm^3\ m^{-2}$) (Fig. 4) was significantly different from other materials ($P < 0.05$), but there was no significant difference between erosion loss of Y-containing coating and Y-free coating (3.71 and 4.52 $mm^3\ m^{-2}$ respectively) ($P > 0.05$). According to Figure 4, for the first measurement of Y-free coating and Y-

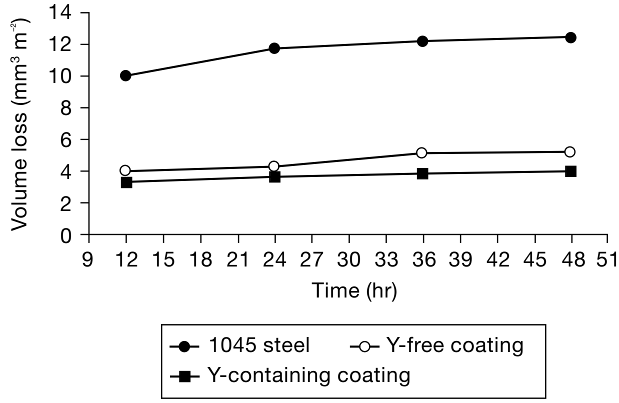

Figure 4. Volume loss of the aluminide coatings with and without yttrium, and carbon steel AISI 1045 (slurry erosion test machine).

containing coating the volume loss was not significantly different ($P = 0.01$). It was observed that when these two samples held high moisture content in the corn kernels, corrosive erosion occurred during the test. Also, the corrosive erosion resistance of Y-containing coating was higher than that of Y-free coating. Figure 4 shows that the slope of volume loss of Y-containing coating between the third and fourth measurements was lower than that of between previous steps, it can be showed that this coating had a good erosion resistance. Both aluminide coatings showed higher erosion resistance than that of uncoated material. The results showed that yttrium significantly improved the erosion resistance of the aluminide coatings. The erosion resistances of aluminide coatings with and without yttrium were approximately 4.5 and 3 times as high as that of the steel substrate. Results of MLR analysis showed that effect of time on the sample volume loss for carbon steel AISI 1045, Y-containing and Y-free coatings was significant ($P < 0.01$). According to Table 2, relationship among these parameters was derived as below:

$$VL = 2.52 + 0.0397t + 7.84Z_{Steel} + 0.817Z_{Y-free} \ ,$$

$$R^2 = 0.99$$

Table 2. Results of multiple linear regression for sample volume loss, time and type of material

Predictor	Coefficients	SE	*P*-value
Constant	2.52	0.345	0.001
t	0.397	0.009	0.002
Z_{Steel}	7.84	0.299	0.001
$Z_{Y\text{-}free}$	0.817	0.299	0.026

SE: standard error.

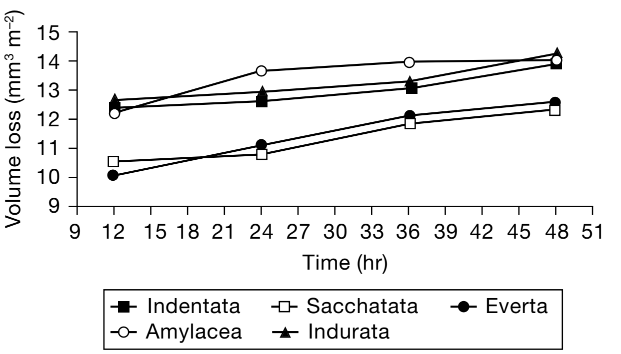

Figure 5. Mean volume loss of Y-containing coating specimens against different corn varieties.

where VL is the mean of sample volume loss in mm^3 mm^{-2}, t is time in hr, Z_{steel} is an indicator variable that takes the value 1 for the data corresponding to carbon steel AISI 1045, and zero otherwise. Similarly, $Z_{Y\text{-}free}$ is an indicator variable that takes the value 1 for data corresponding to Y-free coatings and zero otherwise. The reference level of this equation is Y-containing coating.

Data given represent the mean of sample volume loss of Y-containing coating against different corn varieties, moisture content and machine velocity.

Figure 5 shows that erosion loss against varieties Amyalcea, Indurata, Indentata was higher than that against varieties Everta and Sacchatata ($P < 0.05$). This can be the result of a lower sphericity percent of Amyalcea, Indurata, Indentata kernels than that of Everta, Sacchatata kernels. According to the results, there was no significant difference between average volume loss of Y-containing coating specimens against Indurata, Amyalcea, and Indentata (13.2, 13.42, and 13 mm^3 m^{-2} respectively) after 48 hours ($P > 0.05$). Similar result was found for Everta and Sacchatata (11.47 and 11.37 mm^3 m^{-2} respectively).

Table 3 shows the results of MLR analysis for sample volume loss, time, and type of corn variety. Results showed that effect of corn variety type (other than Indentata and Amylacea) on the volume loss of Y-containing coating specimens was significant ($P < 0.01$). Relationship among these parameters was derived as below:

$$VL = 11.6 + 0.0518t - 0.2Z_{Indentata} - 1.82Z_{Sacchatata} - 1.72Z_{Everta} + 0.225Z_{Amylacea}\ ,\ R^2 = 0.95$$

where VL is the mean of sample volume loss in mm^3 mm^{-2}, t is time in hr, and $Z_{Indentata}$, $Z_{Sacchatata}$, Z_{Everta}, and $Z_{Amylacea}$ are indicator variables. The reference level of this equation is Indurata.

Table 3. Results of multiple linear regression for sample volume loss, time and type of corn variety

Predictor	Coefficients	SE	*P*-value
Constant	11.6	0.211	0.001
t	0.0518	0.005	0.001
$Z_{Indentata}$	–2	0.211	0.36
$Z_{Sacchatata}$	–1.82	0.211	0.001
Z_{Everta}	–1.72	0.211	0.001
$Z_{Amylacea}$	0.225	0.211	0.305

SE: standard error.

Table 4. Results of multiple linear regression for sample volume loss, time and kernel sphericity

Predictor	Coefficients	SE	*P*-value
Constant	18.78	1.669	2.617E-09
t	0.0518	0.0108	0.000169
Kernel sphericity (S)	–0.124	0.0257	0.000163

MLR was done for sample volume loss as dependent variable and time and kernel sphericity as independent variables. Results showed that effect of these two variables on the sample volume loss was significant ($P < 0.01$). According to Table 4, relationship among these variables is linear as:

$$VL = 18.78 + 0.0518t - 0.124S\ ,\ R^2 = 0.73$$

where S is spericity in %.

The results demonstrated that, by increasing the moisture content, the erosion loss increased ($P < 0.05$) (Fig. 6) but for 15% and 17% of moisture content there was not significant differences between erosion loss in these moisture contents (11.28 mm^3 m^{-2} for 13%, 12.44 mm^3 m^{-2} for 15%, and 12.87 mm^3 m^{-2} for 17%) ($P > 0.05$). It can be shown that, during the test, when the corn kernels had high moisture content, the speci-

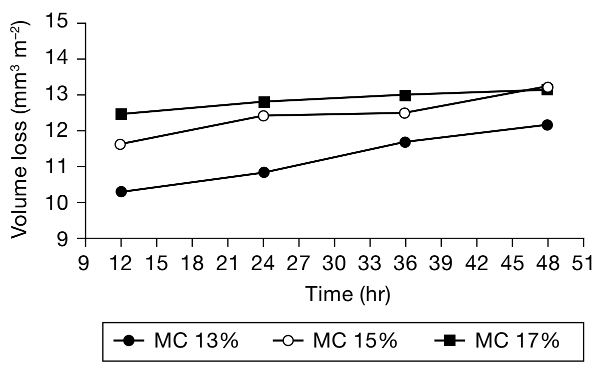

Figure 6. Mean volume loss of Y-containing coating specimens for different moisture content.

Table 5. Results of multiple linear regression for sample volume loss, time and kernel moisture content

Predictor	Coefficients	SE	*P*-value
Constant	11.7	0.215	0.001
t	0.0376	0.005	0.001
$Z_{MC\ 13\%}$	–1.59	0.186	0.001
$Z_{MC\ 15\%}$	–0.427	0.186	0.049

Table 6. Results of multiple linear regression for sample volume loss, time and machine rotation velocity

Predictor	Coefficients	SE	*P*-value
Constant	12.8	0.205	0.001
t	0.0644	0.005	0.001
$Z_{150\ RPM}$	–4.9	0.178	0.001
$Z_{300\ RPM}$	–1.68	0.178	0.001

mens could be attacked by corrosive erosion, because the moisture content of the corn kernels could cause corrosion. Mathematical model for sample volume loss with variation of time moisture contents of kernel, according to the MLR analysis, was obtained as below (see Table 5):

$$VL = 11.7 + 0.0376t - 1.59Z_{MC13\%} - 0.427Z_{MC15\%}\ ,\quad R^2 = 0.94$$

where $Z_{MC13\%}$ and $Z_{MC15\%}$ are indicator variables. The reference level of this equation is MC = 17%.

Figure 7 shows that by increasing the rotation velocity, the erosion loss increased (9.83, 13.06, and 14.74 mm^3 m^{-2} for 150, 300, and 450 rpm, respectively after 48 h) ($P < 0.01$). It can be shown that when the rotation velocity of the slurry erosion test machine increased, so did the impact force of corn kernels on specimens and so, the erosion loss increased. Effect of time and machine rotation velocity on the sample volume loss, according to the results of MRL analysis, was significant ($P < 0.01$) (see Table 6) and relationship among these parameters was obtained as below:

$$VL = 12.8 + 0.0644t - 4.9Z_{150RPM} - 1.68Z_{300RPM}\ ,\quad R^2 = 0.99$$

where $Z_{150\ RPM}$ and $Z_{300\ RPM}$ are indicator variables. The reference level of this equation is 450 rpm.

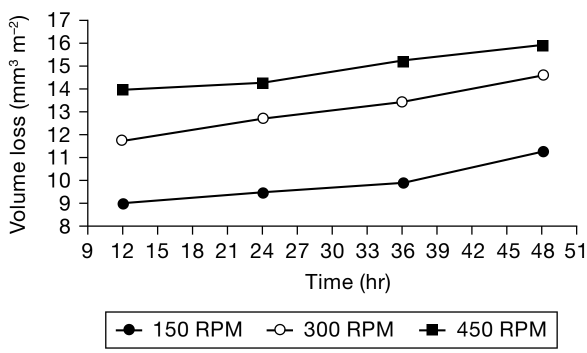

Figure 7. Mean volume loss of specimens for different rotation velocities.

Conclusions

This research was conducted to investigate the beneficial effect of aluminide coatings on the resistance of carbon steel AISI 1045 against erosion. Results of the present research demonstrated that:

1. Yttrium remarkably improved the wear and erosion resistance of the aluminide coating.
2. Both aluminide coatings had higher hardness than that of substrate material.
3. The erosion loss of materials was significantly ($P < 0.05$) influenced by moisture content (at 15 % and 17% of moisture content) but there wasn't significantly different between erosion loss in these moisture contents ($P > 0.05$).
4. Interaction effect of the time and kernel moisture content on the sample volume loss was significant ($P < 0.01$).
5. The erosion loss of materials was significantly ($P < 0.01$) influenced by rotation velocity.
6. Interaction effect of the time and machine rotation velocity on the sample volume loss was significant ($P < 0.01$).
7. Erosion loss corresponding to varieties Amyalcea, Indurata, and Indentata was higher than that of varieties Everta and Sacchatata. This can be the result of a lower sphericity percent of Amyalcea, Indurata, Indentata kernels than that of Everta, Sacchatata kernels.
8. Interaction effect of the time and kernel sphericity on the sample volume loss was significant ($P < 0.01$).
9. Erosion loss of different materials was significantly ($P < 0.01$) different.

Acknowledgements

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