Development of corrosion-resistant equipment for tomato paste production using nanoparticle coating

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Abstract: Tomato paste is processed in industrial factories by means of systems and equipment that are mostly made of metal (mainly steel AISI 304). A lifelong problem in producing tomato paste is the entering of heavy metals into the tomato paste due to the reaction between the tomato juice and the metal surface. Heavy metals, even in small quantities in tomato paste, endanger human health. Nano coating is widely considered among the best methods of control and prevention of corrosion. The aim of this research is to study the effect of titanium oxide (TiO_2) nanoparticle coating in constructing corrosion-resistant equipment in tomato paste production. The steel samples AISI304 were covered with a thin layer of titanium oxide nanoparticle using electrophoretic. A corrosion simulator system was developed to measure the rate corrosion. The tests were conducted in a completely randomized factorial design with two factors and three replications. Tomato juice solution was tested at three temperature levels of 60°C, 70°C and 80°C and four coating voltages of 0, 10, 15 and 20 Volt. Results showed that titanium oxide nanoparticle coating significantly increased the corrosion resistance of AISI 304 steel in reacting with tomato juice. Increasing in temperature from 60°C to 80°Cenhanced the rate of corrosion in all samples to 86%. Samples with coating voltages of 10, 15 and 20 Volt decreased the corrosion speed to 85.2%, 79.0% and 67.6%, respectively. This sample increased the resistance of AISI 304 steel to corrosion at the rate of 85.8% in the worst situation of corrosion in the temperature 80°C.

Keywords: corrosion, tomato paste, titanium oxide, nanoparticle coating

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1 Introduction

Tomato is one of the most important vegetables and after potato is considered as the most important product in eggplant group. Tomato has a main role in society's health because of its nutritious properties and vitamins C and A (Karami, 2011). According to the Food and Agricultural Organization, in 2015 about 452000 hectares and 164 million tons of tomato are cultivated per year all over the world. Every year about 30-35 million tons of fresh tomato is processed in factories and their main product is tomato paste. Tomato cultivation in 2014-2015 was about 152000 hectares and 6 million tons led to 775000 tons tomato paste (Jihad, 2014).

Most of the systems and equipment used in food factories are made of metals such as stainless steel, aluminum, nickel, Monel or plastic (Malakoutian et al., 2011). Each one as well as the principles for hygienic design of industrial plants should at least have important features including good resistance to corrosion, proper polished rate and suitable mechanical behavior. Stainless steel has ideal characteristics for the production of equipment in food industry including factories of tomato paste. AISI304 is the most widely used type of stainless steel (Farahnaki and Gavahian, 2013). Some compounds in tomato paste such as salt (sodium chloride), citric acid and some chemical features such as the amount of pH (i.e. about 3.4-5) and tomato juice temperature (i.e. 60°C-90°C) are conducive to the corrosion process. Some heavy metals such as mercury, cadmium, lead, chromium and cobalt in small quantities may enter the tomato paste as a result of corrosion in factories.

The most important and common methods of corrosion control include anodic and cathode protection, retarder materials, coatings, corrosion-resistant materials

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and alloys, and perfect design equipment (Malakoutian et al., 2011). The use of coating among the methods of controlling and preventing corrosion is considered as an effective method (Zamanian, 2009). Currently, nano-coatings among all other types are highly regarded. Better appearance, high chemical resistance, lower permeability than corrosive environments, convenience for cleaning the surface, proper adhesion of the coating, and scratch resistance are the main features of nano-coatings (Shiravand, 2013).

The corrosion of different steels in various food environments and also the use of titanium oxide nano-structured coatings by electrophoretic in protecting against corrosion of metals have been studied by various researchers. Ofoegbu et al. (2011) studied the corrosion behavior of carbon steel (coverless), galvanized steel and 304L steel in food processing environments by loss weight methods over a period of 98 days with intervals of 14 days. The results showed that the corrosion resistance of 304L steel was more than other steels and the use of this type of steel was recommended in the food industry (Ofoegbu et al., 2011). Khojir and Soheilifar (2011) examined the corrosion resistance of 304L steel with a coating of titanium oxide nanoparticles by electron beam evaporation method in seawater. They also investigated the corrosion properties of coating by electrochemical method and in a 3.5% NaCl solution. The results showed that titanium oxide nanoparticles coating on 304L steel increased the corrosion resistance to sea water as well. The rate of corrosion in annealing samples at 473 K and in the presence of oxygen was lower than other temperatures (Khojir and Soheilifar, 2011). Mahmoudi et al. (2011) applied nano-structured coating of titanium oxide on 3016l steel by electrophoretic deposition method and reviewed the effect of voltage and coating time on the quality of coating. Results revealed that increasing the voltage and coating time increased the coating thickness and surface cracks. The most consistent coating was at 10 and 20 voltages in 120 seconds (Mahmoudi et al., 2011).

This study, due to the use of nano coatings for specific applications in various industries, the use of corrosion-resistant nano-coating (Nano titanium oxide) for the equipment of tomato paste production was investigated.

2 Materials and methods

2.1 Preparation of nano titanium oxide solution

Acetyl acetone and Merck Germany ethanol with the purity of 99% as a solvent, Germany Titanium oxide Nanoparticles powder with particle size of about 25 nm and Iodine (I2) with the purity of 99.9% as a distributor and multiplier of positive charge on the surface of Titanium nanoparticles were used for preparing the nano titanium oxide solution. The production process of titanium oxide nanoparticle solution is shown in Figure 1.

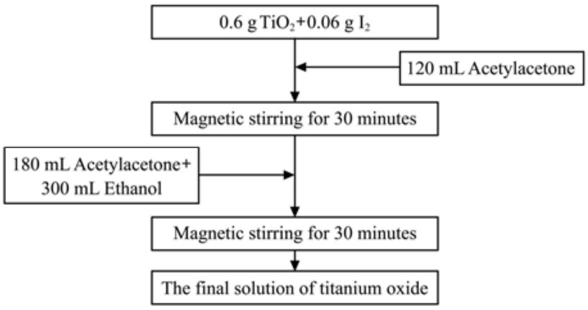


Figure 1 The production process of titanium oxide solution.

2.2 Preparation of coated samples

AISI 304 steel with the dimensions of 30×15×1.5 was used to coat titanium oxide nanoparticles. Table 1 shows the chemical composition and weight of components in used samples.

Table 1 The chemical composition of AISI steel

Component	Mn	P	S	Si	Cr	Ni	N	Fe	C
Maximum weight (g)	2.00	0.045	0.03	0.75	19.5	10.5	0.1	66.995	0.08

Figure 2 illustrates the steps taken to coat titanium oxide nanoparticles. Coating process with electrophoretic method was done after making nano titanium oxide solution and preparing samples using a direct current source (Figure 3(a)) in 0, 10, 15 and 20 Volt in fixed time of 120 seconds. AISI 304 steel was used as anode and cathode during the coating process having the distance of 12 mm between the electrodes. Due to its positive charge on the surface of titanium oxide nanoparticles, the coating was done on the cathode (Figure 3(b)). Samples were dried for 24 hours at room temperature after coating process to create a smooth coating with no cracks and pores. Then, heating at a relatively high temperature to 500°C was necessary to create a coating with good adhesion to the substrate, density and high strength (Afshar and Amirnezhad, 2009).

After drying at room temperature, the samples were heated for two hours at 450°C by a Carbolite Furnaces S30 2AU under a flow of argon gas (Figure 4). Figure 5 shows a sample of uncoated AISI 304 (a) and a sample coated with titanium oxide Nanoparticles (b) after the process of drying and heating.

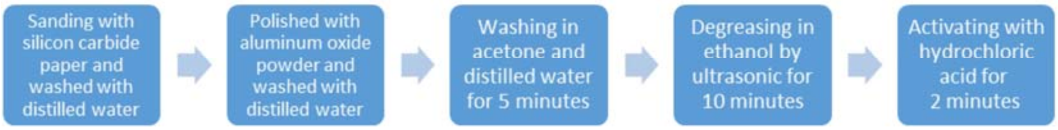
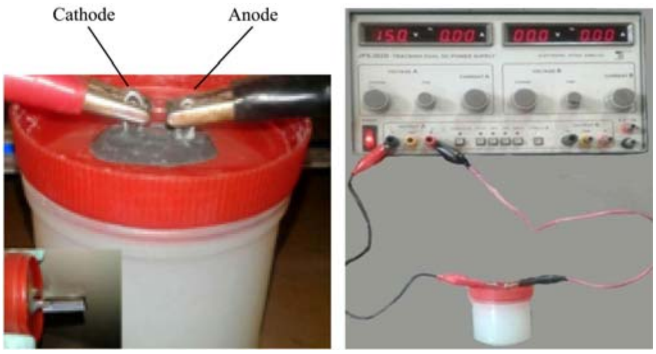


Figure 2 Preparing samples before coating



(a) Anode and cathode contacts (b) Current source

Figure 3 Using the direct current power supply for deposition process

Figure 4 Furnace under an argon gas

(a) Uncoated (b) Coated

Figure 5 AISI304 sample with titanium oxide Nanoparticles in 15 Volt

2.3 Preparation of tomato juice

First, tomatoes were washed and peeled to produce smooth tomato juice without pulp (National Iranian Standard, 2014b). Then, they were heated for 30 minutes at 80°C. Stones and impurities were removed by filtration and pure tomato juice was obtained. To prevent spoilage and mold according to the National Standard No. 19917, the allowable level of 3% salt was added to the solution (National Iranian Standard, 2014a). The final tomato juice solution was kept for testing in the later stages at the temperature of 4°C.

2.4 Evaluation of the rate of corrosion

Corrosion simulator system was designed and made to assess the rate of corrosion of AISI 304 steel in reaction to tomato juice (Figure 6). An anchoring mechanism was designed and made according to ASTM G4-01 standard to keep samples during the test inside pipes and prevent unwanted movement (Figure 7). This mechanism was installed in the flow path, after the pump and before the flow control valves. The flow rate of 8 liters per minute was supplied for each branch.

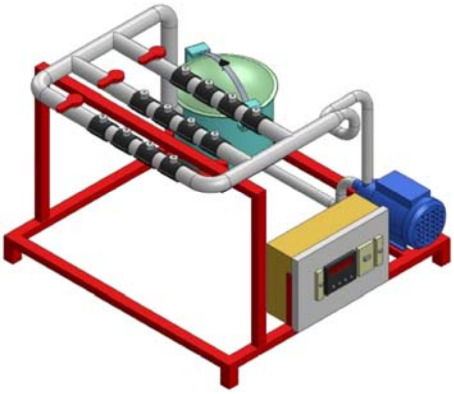


Figure 6 Corrosion simulator system

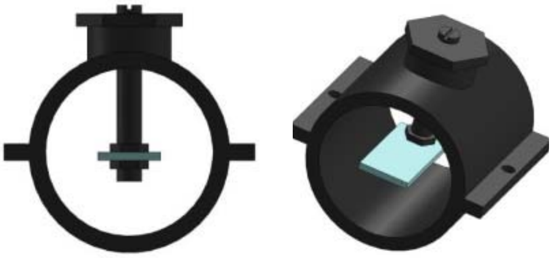


Figure 7 Anchoring mechanism and the location of the samples

Surface preparation of samples was done as below to perform the corrosion test of uncoated AISI 304 (American Society for Testing and Materials, 2005). Sanding with silicon carbide paper and aluminum number 100, 240, 360, 400, 600, 800, 1000 and washing with distilled water.

Degreasing and washing in absolute ethanol and acetone for 10 minutes and dried in a warm air stream. After drying, the samples were carefully weighed on a digital balance with the accuracy of 0.0001 g. Then they were exposed to react with tomato juice in split flow by anchoring mechanism. After 72 hours all samples were brought out of the splits and cleaned and then weighted again. For each level of experiments, the tests were carried out for five periods in 72 hours (fresh tomato juice was replaced after 72 hours).

Lost weight method was used to measure the rate of corrosion in samples. First, the rate of losing was calculated by Equation (1) (Davis, 2000):

$$K = \frac{\Delta W}{At} \tag{1}$$

where, K: Reduction in weight per unit based on mg cm^{-2} h^{-1}; ΔW: The amount of losing weight in mg; A: surface area of samples in cm^2; t: Test time in h.

The rate of corrosion was obtained from the following relation (Davis, 2000):

$$CR = 87.6\frac{K}{\rho} \tag{2}$$

where, CR: Corrosion speed in mm year^{-1}; ρ: Coupon density in g cm^{-3}.

AISI 304 density is 7.9 g cm^{-3} based on ASTM GI standard.

2.5 Statistical analysis

The tests were conducted in a full factorial design with two factors in three replications. Samples coating voltages were defined in four levels (v_0=0, v_1=10 V, v_2=15 V, v_3=20 V) and fixed time of 120 seconds. Another factor was tomato juice temperature which was defined in three levels (T_1=60°C, T_2=70°C, T_3=80 °C). The total number of tests were 36. The data were analyzed using SAS software. ANOVA was used to determine the significant differences between different levels of factors and Duncan's multiple range test was used for comparing the means.

3 Results and discussion

The results of analysis of variance for different temperatures and coating voltages were shown in Table 2. As Table 2 shows the temperature and coating voltage as well as their interaction had significant effect on the rate of corrosion speed. Being significant with the probability of 99% showed a considerable difference among the various levels of factors. Due to the significant two-way interaction between temperature and coating voltage, it can be concluded that these two factors didn't perform separately.

Table 2 Variance analysis of the effect of temperature and coating voltage on corrosion (mm year^{-1})

SOV	df	SS	MS	F
Temperature(T)(°C)	2	0.577×10^{-3}	0.2887×10^{-3}	794.79**
Coating voltage (V)	3	6.235×10^{-3}	2.0785×10^{-3}	5720.88**
Temperature× coating voltage (T×V)	6	0.6435×10^{-3}	0.1072×10^{-3}	295.18**
Error	24	0.0087×10^{-3}	0.0003×10^{-3}	-
Total	35	7.4655×10^{-3}	-	-

Note: ** Significance level: 0.01. df = degree of freedom, SS = sum of squares, MS = mean of squares, F = F ratio.

The results of Duncan's multiple range test for comparing the means of different levels of temperature were shown in Table 3. According to Table 3, the corrosion speed was classified into three categories (a, b, c). Increasing temperature from 60°C to 80°C improved the corrosion speed from 0.0114 to 0.212 mm per year. The rate of corrosion speed in 80°Cwas 1.32 times bigger than 70°C and 1.86 times bigger than 60°C. Increasing temperature increased chemical reactions speed and solubility of salt which increased the speed of corrosion in samples surface as well. As the temperature increased, the solubility of oxygen decreased and caused the corrosion protection layer caused by oxygen reaction with steel surface material not to be created and so the corrosion rate increased.

Table 3 Duncan's multiple range test results to compare the effect of temperature mean on corrosion (mm year^{-1})

Temperature (°C)	Corrosion speed mean (mm year^{-1})
T1	0.0114^a
T2	0.0161^b
T3	0.0212^c

The changes of corrosion speed with respect to different temperatures and voltages are shown in Figure 8. Based on Figure 8, increasing temperature from 60°C to 80°C increased the corrosion speed in all samples. The effect of increased temperature on the corrosion rate in uncoated samples was significant. When the temperature increased, coating prevented rapid changes of corrosion. So, the corrosion rate of coated samples was more consistent than coatless ones.

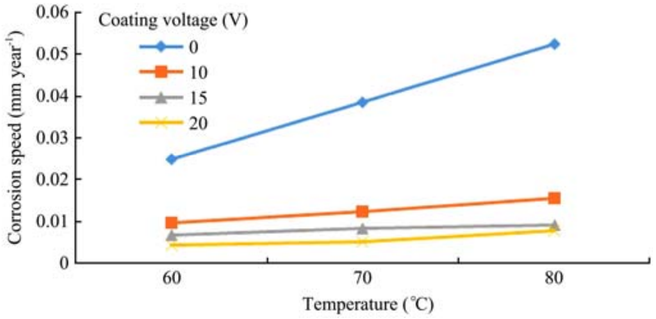


Figure 8 The chart of corrosion speed changes with temperature in different coating voltages

Duncan test was carried out to compare the means of different levels of titanium oxide nanoparticle coating voltages (Table 4). As shown in Table 4, the corrosion speed was classified into four classes (a, b, c, d). These results revealed that the corrosion speed in coated samples was less than coatless ones in reacting to tomato juice.

Table 4 The results of Duncan test to compare the mean effect of titanium oxide Nanoparticles coating voltage on corrosion speed (mm year^{-1})

Coating voltage (V)	Corrosion speed mean (mm year^{-1})
V_3	0.0057^a
V_2	0.0081^b
V_1	0.0125^c
V_0	0.0386^d

Corrosion speed changes with coating voltages in different temperatures are shown in Figure 9. Based on the figure, the corrosion speed for coatless samples in 0 Volt was more than other voltages. Applying a coating of titanium oxide nanoparticle at voltages higher than zero drastically reduced the corrosion rate at all temperatures. Increasing coating voltages from 10 to 20 Volt lowered the corrosion speed in all samples.

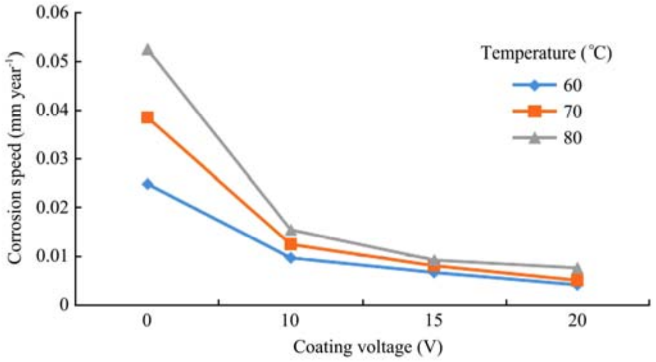


Figure 9 The chart of corrosion speed changes with coating voltages in different temperatures

Applying a coating of titanium oxide nanoparticle by electrophoretic method had a proper consistency on the AISI 304 steel surface because of its simple and precise control of the coating process. A dense, friction-resistant and hydrophobic layer with a minimum surface cracks was made after heating the samples' coating which was corrosion-resistant. Shaneghi et al. (2009) and Khalidinia et al. (2015) reported similar.

Figures 10, 11 and 12 show the changes of corrosion speed over time in 60°C, 70°C and 80°Cfor samples with different coating voltages. As Figure 10 shows, the corrosion speed in coatless samples was very high at first but it reduced over time. Corrosion speed in all samples coated in different voltages was less than coatless samples and changed a little over time.

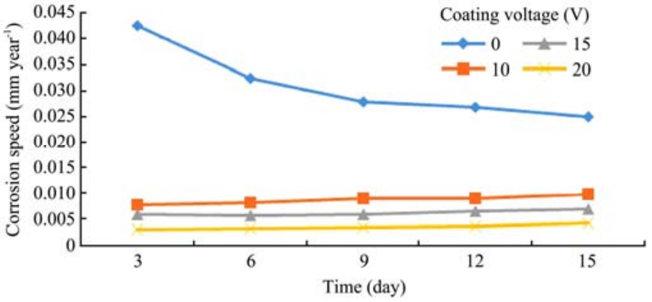


Figure 10 The chart of corrosion speed changes over time in 60°C temperature

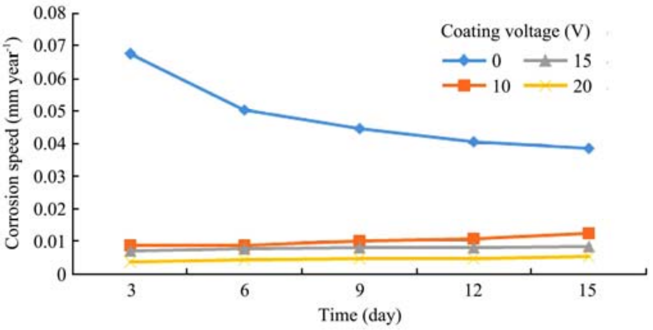


Figure 11 The chart of corrosion speed changes over time in 70°C temperature

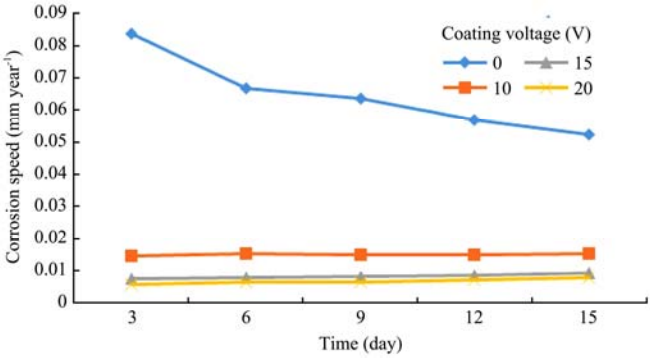


Figure 12 The chart of corrosion speed changes over time in 80°C temperature

Figure 11 shows that the corrosion speed in coatless samples reduced over time. Corrosion speed in coated samples in different voltages was much less than that of in coatless samples and changes were little over time. Corrosion speed in coated samples in 10, 15 and 20 Volt in comparison with that of in coatless ones was close to each other and their corrosion speed changed constantly over time.

As Figure 12 shows, the corrosion speed in coatless samples was very high at first, but it reduced over time. Corrosion speed in coated samples in different voltages was very low and changes were constant over time. The rate of corrosion speed in coatless samples was high at first, but it reduced irregularly and non-linearly. The results were in line with Ofoegbu et al. (2011), Oladel and Okoro (2011). The corrosion speed in coated samples with titanium oxide nanoparticles constantly increased over time. This increase in corrosion speed was caused at an acceptable level with a gentle slope. So, it can be concluded that the stability of corrosion speed in coated samples was more than coatless ones over time.

4 Conclusion

In this study, titanium oxide nanoparticles coating of AISI 304 steel using electrophoretic method in four different voltages in a fixed time was performed. A simulator system was designed and developed to measure the corrosion speed in producing process of tomato paste. The amount and speed of corrosion were compared between coated and uncoated samples in three different temperatures. Titanium oxide nanoparticle coating in electrophoretic method on AISI 304 steel increased the resistance to corrosion in reaction to tomato juice. Increasing tomato juice temperature from 60°C to 80°Craised the corrosion speed in all samples at the rate of 86%. Corrosion speed of AISI 304 steel in coated samples in 10, 15 and 20 Volt decreased at to 85.2%, 79.0% and 67.6%, respectively. Coated sample in 20 Volt has the best function among all samples in terms of being corrosion-resistance. This sample increased the resistance of AISI 304 steel to corrosion at the rate of 85.8% in the worst situation of corrosion in the temperature 80°C.

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