

Modification of stainless steel surfaces by electroless Ni-P and small amount of PTFE to minimize bacterial adhesion

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Abstract

Biofouling has been recognized as a widespread problem in design and operation of processing equipment. Since bacterial adhesion is a prerequisite condition for biofilm formation, prevention of bacterial adhesion and colonization on the processing equipment will have a major impact in preventing biofouling. According to the extended DLVO theory, the surface energies of both bacteria and stainless steel substrate have significant influences on bacterial adhesion. In this paper the surface energy of stainless steel 304 plates was modified by electroless plating Ni-P and small amounts of PTFE to minimize bacterial adhesion. The effects of pH, temperature, PTFE concentration in solutions on the deposition rate of electroless Ni-P-PTFE coatings were investigated. The thickness and the compositions of the coatings were measured using a digital micrometer and an energy dispersive X-ray microanalysis (EDX), respectively. Surface morphology of the coatings was analysed by a scanning electron microscope (SEM). The contact angle values and surface energies of the coatings and *E. coli* were measured with a Dataphysics OCA-20 contact angle analyser. Initial experiment results showed that stainless steel surfaces coated with Ni-P-PTFE reduced *E. coli* attachment by 87.7–92.8%, compared with stainless steel 304.

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Keywords: Nanocomposite coating; Biofouling; Surface energy; *E. coli*

1. Introduction

Biofouling has been recognized as a widespread problem in design and operation of processing equipment such as heat exchangers, cooling water systems and food processing equipment (Lalande, Rene, & Tissier, 1989; Notermans, Dormans, & Mead, 1991). Biofouling does not only present a considerable hygiene risk in the food industry, but also causes economic losses. Any method of preventing biofouling or lengthening processing time will give substantial cost benefits.

According to the extended DLVO theory, the surface energies of both bacteria and stainless steel substrate

have significant influences on the bacterial adhesion (Oliveira, 1997; Israelachvili, 1997; Zhao, Wang, & Müller-Steinhagen, 2004). Baier (1980) gave a relationship between surface energy and relative bacterial adhesion. His results showed that when the surface energy of substrates is in the range 20–30 mN/m bacterial adhesion is minimal. The surface energy of stainless steel 304 is about 40 mN/m, which is much higher than the optimum value. Recently, Zhao and Müller-Steinhagen (2001) derived the optimum surface energy of a solid surface, $\gamma_{\text{surface}}^{\text{LW}}$ on which bacterial adhesion force is minimal, using the extended DLVO theory:

$$\sqrt{\gamma_{\text{surface}}^{\text{LW}}} = (1/2) \left(\sqrt{\gamma_{\text{bacteria}}^{\text{LW}}} + \sqrt{\gamma_{\text{water}}^{\text{LW}}} \right) \quad (1)$$

where $\gamma_{\text{surface}}^{\text{LW}}$, $\gamma_{\text{bacteria}}^{\text{LW}}$ and $\gamma_{\text{water}}^{\text{LW}}$ are the Lifshitz-van der Waals (LW) surface energy of the solid surface, bacteria

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and water, respectively. They can be determined experimentally. As the equation isolates the effects of surface free energy upon bacterial adhesion from the numerous parameters in the DLVO theory, it appears relatively simple. In general, for a multi-component system, biofouling formed on processing equipment may consist of various types of bacteria and $\gamma_{\text{bacteria}}^{\text{LW}}$ in Eq. (1) is the average LW surface energy of the biofouling deposits or biofilms, which can be determined by measuring contact angles on the deposits. If the surface energy of stainless steel surface is reduced to the bacteria-resistant value by a surface modification technique, bacterial adhesion force to the surface could be decreased significantly, and the bacteria could be removed easily from the surfaces by working fluids.

Electroless nickel-phosphorus coatings have been widely applied in many industries, such as food processing and chemical engineering, etc. due to their good corrosion and wear resistance (Reidel, 1999). Polytetrafluoroethylene (PTFE) is chemically very inert and has a relatively high melting point (325 °C). PTFE also has non-stick property due to its low surface energy. Its coefficient of friction (0.05) is lower than that of almost any other polymer (Liu & Zhao, 2003). The incorporation of PTFE nanoparticles into the Ni-P matrix can take advantage of the different properties of Ni-P alloy and PTFE. The resulting properties of electroless Ni-P-PTFE coatings, such as non-stick, anti-adhesive, lower friction, good wear and good corrosion resistance, have been used extensively in many industries (Ger, Hou, Wang, & Hwang, 2002; Liu & Zhao, 2004; Santos et al., 2004). Because electroless Ni-P-PTFE coatings are metal-based, their thermal conductivity, anti-abrasive property and mechanical strength are superior to standard PTFE coatings. The porosity of Ni-P-PTFE coating is negligible, as PTFE particles block the pores. Therefore, the corrosion-resistant properties of Ni-P-PTFE coatings are superior to Ni-P coatings (Takashi, Shuji, & Yuichi, 1996). However, the hardness and robustness of the Ni-P-PTFE composite coatings decreases with increasing PTFE content in the coatings (Pena-Munoz, Bercot, Grosjean, Rezrazi, & Pagetti, 1998; Zhao, Liu, Müller-Steinhagen, & Liu, 2002). For example, the microhardness electroless Ni-P coating reduces to HK 220 from HK 820 if large amounts of PTFE particles (up to 30% by volume) are incorporated into the Ni-P matrix (Straffelini, Colombo, & Molinari, 1999).

In this paper, stainless steel 304 plates were coated with Ni-P and small amounts of PTFE particles. The adhesion of *E. coli JM109* to the Ni-P-PTFE coating with low PTFE content (1.95 vol% or 0.55 wt%) was evaluated, and was compared with the Ni-P-PTFE coating with high PTFE content (28.4 vol% or 9.95 wt%), Ni-P coating and untreated stainless steel 304 surfaces.

2. Material and methods

2.1. Electroless plating Ni-P-PTFE

In this investigation, the surface energy of stainless steel 304 sheets of 10 mm × 15 mm × 0.35 mm was modified with Ni-P-PTFE. The pretreatment and coating procedures are listed in Table 1. The composition and the plating conditions for the electroless Ni-P-PTFE solutions used in the present investigation are listed in Table 2. A 60% PTFE emulsion from Aldrich with particle size in the range 0.05–0.5 µm and a cationic surfactant C₂₀H₂₀F₂₃N₂O₄I (FC-4) were used. Both the PTFE emulsion and the surfactant were diluted with demineralised water and stirred for 1 h. Then the solution was filtered with a filter of pore size 0.2 µm before use. As the PTFE particles were dispersed uniformly in the plating bath by the surfactant, no mechanical agitation or ultrasonic homogenizer were used during electroless Ni-P-PTFE deposition. In order to increase the adhesion force, a 0.5 µm Ni-P sub-layer was deposited on stainless steel substrates before electroless plating Ni-P-PTFE. The coating thickness of Ni-P and Ni-P-PTFE was measured using a digital micrometer. The coating compositions were analysed with an energy dispersive X-ray microanalysis (EDX) (model JSM-6310) at beam energy of 20 keV. The surface morphology of the coatings was analysed with a scanning electron microscope (SEM).

Table 1
Pre-treatment and coating procedures for electroless Ni-P-PTFE

Procedures	Conditions
1. Alkaline cleaning	60–80 °C, 5–10 min
2. Rinsing	Room temperature
3. Cathodic electrocleaning	Room temperature, 2–3 min
4. Rinsing	Room temperature
5. Pickling	Room temperature, 0.5–1 min
6. Activation	Room temperature, 1–3 min
7. Electroless plating Ni-P	70–93 °C, pH 4.0–5.6
8. Rinsing	Room temperature
9. Electroless plating Ni-P-PTFE	70–93 °C, pH 4.0–5.6
10. Rinsing	Room temperature

Table 2
Bath composition and operating conditions for electroless Ni-P-PTFE

Composition	
NiSO ₄ · 6H ₂ O	25 g/l
H ₃ C ₆ H ₅ O ₇ · 6H ₂ O	18 g/l
NaH ₂ PO ₂	30 g/l
NaCH ₃ COO	18 g/l
(NH ₂) ₂ CS	1 ppm
PTFE(60 wt%)	0–10 ml/l
C ₂₀ H ₂₀ F ₂₃ N ₂ O ₄ I(FC-4)	0–0.4 g/l
PH	4.0–5.6
Temperature	70–93 °C

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