Analysis of corrosion rate at bone implant replacement materials with immersion time variations in simulated body fluid

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Abstract. Biomaterials are materials used to replace parts of living systems. 316 L stainless steel has long been used as a substitute material for bone dislocation victims. This research aims to substitute 316 L stainless steel bone implant material with Cr-Ni coated ST 41 carbon steel which has been immersed with varying time-intensity with Simulated Body Fluid. Material testing uses the method of potentiodynamic polarization, electrochemical impedance spectroscopy, and Scanning Electron Microscope. The results of this study are in the form of a comparison of corrosion rate and surface characteristics between 316 L stainless steel and Cr-Ni coated ST 41 Carbon Steel. The immersion time of the material for 12 hours and 366 shows a low corrosion rate with a corrosion rate of 0.0051714 mm year⁻¹ with and 0.001557 mm year⁻¹ for ST41 carbon steel material with Cr-Ni coating, whereas in Stainless Steel 316 L has a corrosion rate value of 0.0029546 mm year⁻¹ and 0.0013166 mm year⁻¹. Surface characteristics show insignificant differences between ST41 steel with Cr-Ni coating and 316 L stainless steel. The results of the study show that Cr-Ni coated ST41 carbon steel material can substitute 316 L stainless steel as a biomaterial in bone implants because it has a low corrosion rate and different insignificant surface characteristics.

Keywords: biomaterials, ST41 carbon steel, 316 L stainless steel, Cr-Ni, simulated body fluid

1. Introduction
Biomaterials are materials that have direct contact with biological systems in living things, where the material is required to meet certain requirements [1]. In its application is used to replace or restore the function of components that have failed / damage in this case is bone [2]. Biomaterials used in orthopedic applications must have several aspects meet in the selection of implant material [3]. Biocompatibility defined as the ability or capacity of a material to be used in close contact with living tissue without causing adverse effects [4]. High Corrosion Resistance, implant material can survive in the body during the healing phase [5]. Mechanical Compatibility this refers to the appropriate mechanical properties according to the function to be performed and the site to be implanted [6]. Osseointegration is defined as a direct barrier of the implant with the formation of bone tissue around the implant without fibrous tissue growth at the bone-implant interface [7]. High Wear Resistance, the wear resistance of the material plays an important role in
the functioning of the biomaterial, avoiding loosening of the implant and the reaction in the tissue where it is stored, thus improving the quality of life of patients [7].

Stainless steel is one type of metal widely applied in the medical field. Type 316L stainless steel has long been used as a bone implant material. Material properties and high corrosion resistance are the reasons for the use of 316L stainless steel as a bone implant material. The complicated machining process and expensive materials, causing the price of bone implants that are not affordable for the community. Substitution material is required as a solution to the problem.

In this research, carbon steel is used as the basic material for bone implants that replace 316L stainless steel. ST 41 material is a carbon steel alloy used in this study. Some of the advantages of ST 41 carbon steel are that it is cheap, easy to fabricate, available on the market, and most importantly, the characteristics are almost the same as human bones in general. However, there are undesired ion releases [8] as well as the adhesion process of weak protein molecules on the surface [9] if used on bone implant material. Prevention by modifying the implant in the material layer with the nature of inhibiting ion release is an economical solution.

As a bone implant material, some studies report that the Cr-Ni report is focused on oxidation and corrosion resistance [10, 11]. The Cr-Ni layer is capable of making chromium nitride coatings synthesized in materials by implantation and precipitation of plasma ions [10]. Cr-Ni coatings with superior corrosion resistance and inhibit unwanted ion release are considered as potential long-term protective materials in medical applications [12]. Research on implants uses Simulated Body Fluid (SBF) as its corrosive media. Simulated Body Fluid (SBF), also known as Synthetic Body Fluid, is a solution to resemble the actual human body (blood) condition. This Simulated Body Fluid made by regulating the concentration of ions such as those contained in the human body so that the pH (Degree of Acidity) resembles the condition of the human body. In the process of making SBF, reagents as precursors are needed to control the concentration of ions in the SBF solution such as NaCl, KCl, HCl, and tris-hydroxy methyl aminomethane (CH$_2$OH)$_3$CNH$_2$ [3]. This research aims to substitute implant material with ST41 carbon steel with Cr-Ni coating as a comparison of 316L stainless steel.

2. Research methods
This research began cutting ST41 type carbon steel sheets and 316L stainless steel types with chemical composition can be seen in Table 1 to a size of 20mm x 10mm with a thickness of 5mm using a cutting grinding machine with special cooling liquid spraying for the metal cutting process. Furthermore, the surface of the specimen is polished using MP-2B type polish machine and sandpaper size of 100, 200, 500, 1000, and 2000 and using metal polish fluid so that a low surface roughness specimen is obtained to reduce the anode and cathode reaction that occurs due to direct contact with the environment [16]. The next process was carried out by Cr-Ni coating process by electroplating method on carbon steel specimens of Type ST41 as inhibitors of metal ion release. The electroplating process is shown in the Figure 1.

Before further testing, the ST41 carbon steel and 316L stainless steel specimens were coated with a resin leaving one side of the test specimen, which was wired for polarization testing. The next process is the immersion in a certain period of immersion of both ST41 carbon steel specimens coated with Cr-Ni and 316L stainless steel into simulated body fluid (SBF) or synthetic body fluid with the chemical composition shown in Table 2. The time needed for the immersion process, which is 12 hours, 168 hours, 240 hours, and 336 hours. Potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy tests are performed after the immersion process is complete. The purpose of the PDP testing process is to determine the characteristics of metal corrosion based on the relationship of anodic and cathodic currents while the EIS is to determine the material’s resistance to corrosion and mass transport that occurs in the coating of
the material. The testing process uses an auto lab type galvanostat electrochemical instrument with Ag / AgCl electrodes as reference electrodes and Pt as electrode counters. Data from the galvanostat test results are in the form of corrosion currents \( I_{\text{corr}} \) and Corrosion Rate whose value is proportional to the corrosion rate of the specimen, the greater the \( I_{\text{corr}} \) value, the greater the tendency for the material to corrode [2].

### Table 1. Material composition

| Material | Fe | C  | Si | Mn | P   | S   | Cr | Mo | Ni |
|----------|----|----|----|----|-----|-----|----|----|----|
| ST 41   | 98.9% | 0.19% | 0.18% | 0.6% | 0.021% | 0.015% | -  | -  | -  |
| 316 L   | 62.2% | 0.03% | 0.75% | 2.0% | -   | -   | 18% | 3.0% | 14.0% |

![Figure 1. Electroplating process](image)

### Table 2. Solution Body Fluid Compositon

| Composition   | Weight       |
|---------------|--------------|
| NaCl          | 6.547 gram   |
| NaHCO₃        | 2.268 gram   |
| KCL           | 0.373 gram   |
| Na₂HPO₄·2H₂O  | 0.178 gram   |
| MgCl₂·2H₂O    | 0.305 gram   |
| CaCl₂·2H₂O    | 0.368 gram   |
| NaSO₄         | 0.071 gram   |
| (CH₂OH)₂CNH₂  | 6.051 gram   |

Material characteristics testing is used as identification of the surface of the material that has been implanted and with a simulated body fluid solution. Using a Carl Zeiss electron type (EVO MA 10) with a magnification of up to 50,000x with a resolution of 10 micrometer. This test aims to determine the corrosion products and layers that form on the surface of the material.
3. Results and discussion

3.1 Potentiodynamic Polarization

In potentiodynamic polarization testing using galvanostat were ST 41 carbon steel specimens with Cr-Ni coating and 316L stainless steel have been immersed into Simulated Body Fluid with immersion time of 12 hours, 168 hours, 240 hours and 336 hours can be seen from Figure 2. From the graph, The increase occurred a significant increase in the ST 41 carbon steel specimen with Cr-Ni coating in the immersion period of 12 hours and then the graph returned down to the immersion time of 336 hours. At 336 hours of immersion, the two specimens showed almost the same corrosion rate of 0.0015577 mm year\(^{-1}\) on ST41 carbon steel and 0.0013166 mm year\(^{-1}\) on 316L stainless steel.

![Polarization curve](image)

Figure 2. Polarization curve. a) ST 41 carbon steel with Cr-Ni layer, b) Stainless steel 316L
3.2 Electro impedance microscopy
In the Electro Impedance Microscopy test, it can be seen in the comparison of Figure 3a that, in the test results of the ST 41 material with the smallest impedance Cr-Ni layer is known in the blue colored arch with 240 hours immersion while the greatest impedance is seen in the black colored arch with 12 hours immersion. A high impedance value indicates a decreased corrosion rate caused by the formation of a passive layer on the surface. Quite many factors influence the outcome of the existing impedance resistance. Whereas in Figure 3b 316L Stainless Steel can be seen that the smallest impedance is seen in blue colored curves with a soaking time of 240 hours while the highest impedance is seen in the purple-colored lines with a soaking time of 336 hours. In the purple line still does not have the best level of impedance resistance or stability of the impedance so that the impedance resistance cannot be determined exactly but if immersion is done longer than 336 hours it may be possible to see the impedance resistance of the sample.

3.3 Scanning electron microscope
The results of the scanning electron microscope with a 12-hour immersion in a Simulated Body Fluid (SBF) solution found that SS 316 L had not seen the damage to the specimen surface in the form of corrosion, on ST 41 carbon steel specimens coated with Cr-Ni there was corrosion on the surface of the sample (Figure 4). In the Specimens with an immersion time of 336 hours in Simulated Body Fluid (SBF) solution, it can be concluded that SS 316 L began to look corrosion-shaped holes in the specimens, on ST 41 carbon steel coated with Cr-Ni, there was a spot of corrosion
4. Conclusion
Based on the results of the research, ST 41 carbon steel material with Cr-Ni coating has almost the same characteristics in surface characteristics and corrosion rate. It can be seen in the dynamic potassium polarization testing the corrosion rate, which has been immersed for 366 hours on ST 41 carbon steel with Cr-Ni coating of 0.0015577 mm year\(^{-1}\) while 316L stainless steel has a corrosion rate of 0.0013166 mm year\(^{-1}\). Whereas in the Electro Impedance Microscope test the lowest corrosion rate is 12 hours immersion with corrosion rate in ST 41 carbon steel with Cr-Ni coating of 0.0051714 mm year\(^{-1}\) and 316L stainless steel of 0.0029546 mm year\(^{-1}\). In Scanning Electron Microscope testing, it can be concluded that the longer the immersion time in the specimen, the more massive the corrosion formed.

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6. References

[1] Shukla K, Rane R, alphonsa J, Maity P 2017 *Surface & Coating Technology* **324** 167 – 174

[2] Pramudia M, Prasetyo T, Umami M K, Alfita R, Nahari R V, Widodo T D and Raharjo R 2019 The effect of steel ball diameter variation in dry shot peening process on surface roughness and corrosion rate of AISI 316L implant *Material International Conference on Mechanical Engineering Research and Application, IOP Publishing* 012092

[3] Sharma P, Pulak M P 2019 *Material Science & Engineering C* **99** 838 – 852

[4] Mohamed A H G, Mitsuo N 2013 *Journal of the Mechanical Behavior of Biomedical Materials* **20** 407 – 415

[5] Asri R, Harun W S, Lah N A, Ghani S A, Samykano M 2017 *Material Science & Engineering C* **77** 1261 – 1274

[6] Niomi M 2008 *Journal of the Mechanical Behavior of Biomedical Materials* **11** 30 – 42

[7] Gobbi SJ, Gobbi VJ 2018 *Journal of Scientific & Technical Research* **12** 1 – 2

[8] Totolin V, Pejakovic V, Csanvi T, Hekele O, Hubber M, Ripoll M R 2016 *Material & Design* **104** 10 – 18

[9] Juncen Z, Yuyun Y, Micael A F, Rainer D, Aldo R B and Sannakaisa V 2016 *Applied Materials & Interfaces* **8** 26482 – 26492

[10] Yuwei Y, Yongxin W, Chunting W, Junlong L, Yirong Y 2015 *Tribology International* **91** 131 – 139

[11] Shan L, Wang Y, Li J, Jiang X, Chen J 2015 *Tribology International* **82** 78 -88

[12] Yi P, Peng L, Huang J, 2016 *Material Science and Engineering C* **59** 669–676.