Effects of Heat Treatment on the Corrosion and Mechanical Properties of Stainless Steel 316L as Used in Biomedical Applications

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Abstract. This work examines the influence of heat treatment processes, using oil and water at various temperatures as quenching media, on the mechanical, corrosion, and microstructural properties of 316L austenitic stainless steel as used as a biomaterial for temporary and permanent bone repairs or grafts and as a plate bone fixation during periods of treatment. The results show that the highest microhardness rate is obtained using normal water as a cooling media; this sample reached 157.7 Hv, a 9.97% higher value than that obtained using oil media and an 18.66% higher value than that obtained using one-hour heating. The microstructure images for the quenched samples in oil displayed more evenly and uniformly distributed carbon particles, suggesting the formation of a more pearlite structure as compared with the water-quenched samples, however. The highest polarization resistance value was obtained when using water cooling media with two hours heating time; this reached 2.849 V/μA. Dec., while the minimum value, reached 0.185 V/μA. Dec., was obtained using the hot water cooling medium. The minimum corrosion rate value was obtained using the oil cooling media; this was 0.34 x10-5 milli-in./year, while the maximum value reached 0.86x10-5 milli-in./year for the water cooling medium with a three-hour heating duration. The resulting equivalent von- Mises stress reached its maximum value at 285.24 MPa at 150 Kg patient weight and 5 mm plate thickness. The total deformation reached a minimum value of 0.0723 mm, while the stress safety factor reached a maximum value of 2.7 for a patient weight of 60 Kg when using 10 mm plate thickness. The equivalent elastic strain and the strain energy reached minimum values of 4.7 x 10-4 mm and 0.021 mJ for a patient weight of 60 Kg when using 5 mm plate thickness, respectively.

Keywords: Microhardness; Heat treatment; Tafel plots; Microstructure Image Analysis; Electrochemical 316L Stainless steel Corrosion; Stress Analysis and Fatigue life

1. Introduction

Stainless steels and Co-based alloys are highly biocompatible biomaterials that are widely used in clinical practice as orthopaedic implant materials [1]. Stainless-steel material offers excellent corrosion and creep resistance, with better ductility, formability, high thermal expansion, and heat capacity and lower thermal conductivity than other types of steels. This type of steel cannot be hardened by heat treatment, though it can be strengthened by work-hardening [2]. The stainless steels typically used in medicine are austenitic stainless steels of type 316L, where the notation “L” indicates that the steel has a low carbon content (<0.03%) and is therefore not susceptible to intergranular corrosion due to the precipitation of Cr-carbides at the crystalline grains boundaries. Such stainless steels contain 17 to 20% Cr, 13 to 15% nickel, 2 to 3% molybdenum, and small amounts of other elements [3].

The austenitic stainless-steel type 316L is highly attractive for biomedical applications due to its excellent corrosion resistance and relatively superior ductility [4]. This stainless-steel type is suitable for both temporary and permanent implants and similar orthopaedic products, though it is more susceptible to corrosion as compared to the titanium and titanium alloys also used in such purposes [5-6]. Stainless steel is thus often used for temporary implants, to help bone healing, and for fixed implants such as those required for artificial joints and implant devices, due to the benefits of its mechanical
properties relative to those of bone mineral, low cost and ease of fabrication as compared to cobalt-chromium alloys, pure titanium, and titanium alloys, however [3-8].

In the human body, stainless steels show inferior corrosion resistance as compared to cobalt-chromium alloys and titanium alloys; the corrosion resistance and mechanical properties of 316L SS are dependent on its microstructure, however, and these properties can be modified by phase transformation forming [4]. Chromium-nickel molybdenum austenitic stainless-steel types 304/304L (UNS S31600/S31603) were developed to improve corrosion resistance in moderately corrosive environments [9], as the addition of molybdenum improves the tensile, corrosion, and creep resistances, as well as minimising chloride pitting. The low carbon content of 316L, combined with the addition of nitrogen, enables 316L to resist atmospheric corrosion; it also has excellent resistance to intergranular corrosion and, in the annealed condition, it is non-magnetic, easily welded, and can be processed using conventional fabrication processes [9 to 11]. The main applications of 316L SS are in the medical, pharmaceutical, chemical and petrochemical industries, in food processing, and in water treatment [9].

Engineering parts are often susceptible to rapid degradation and fail catastrophically through corrosion-related incidents; this has a huge impact on the economy, with a cost of hundreds of billions of dollars [5, 12-13]. The effects of microstructure on the corrosion behaviours of stainless steel thus an important open field as researchers strive to understand the relationship between the effects of corrosion parameters and the outcomes for metallurgical structures. Corrosion as a process involves both electrochemical oxidation and reduction reactions, and most metal corrosion occurs between opposing electrochemical reactions based on the rate of equilibrium at the interface between the metal and an electrolyte solution. A thin film of moisture on a metal surface forms an electrolyte for atmospheric corrosion: the anodic oxidised reaction is based on a metal releasing electron, and the cathodic reaction solution is often O2 or H+ [14].

To enhance various mechanical and corrosion properties in metals, different techniques and methods have been developed, such as modification of their chemical composition and surface treatment techniques, including sandblasting, which reduces corrosion resistance while enhancing hardness; surface passivation; ion sputtering; carbonitriding; and nitriding [5, 8].

The main aims of this work was to develop a better understanding of, and to modify the influences of, the effects of rapid quenching in various cooling media, including oil and various water treatment processes, on the mechanical, corrosion, and microstructural properties of 316L type austenitic stainless steel as used as a biomaterial for various temporary and permanent procedures. Microhardness, microstructure image analysis, electrochemical corrosion, and stress analysis tests were thus performed to investigate the phase properties produced in stainless-steel specimens after the application of different heat treatment processes. All experiments were designed using the response surface methodology (RSM) and the analysis of variance (ANOVA) technique. The numerical simulation and investigation of the designed bone fixation plates were done by using the finite element program in SolidWorks 18.0, ANSYS 18.0, and Expert 11.0 software.

2. Materials and Methods

In this study, 316L stainless-steel material specimens of 8 mm diameter and 12 mm long were cut from a strip with dimensions of 200 x 20 x 10 mm. The main chemical composition of the 316L stainless steel used according to ASTM A240 316/316L standard specifications is given in table 1 (% weight, with all values at maximum unless otherwise indicated), while the physical and mechanical properties are shown in table 2.

Stainless-steel of types 316 and 316L cannot be hardened by applying heat treatment. In this study, the annealing heat treatment was instead used to negate the effects of previous strain-hardening of the metal by allowing it to recrystallise. The stainless-steel samples were then heated to 1,010 to 1,120 °C and soaked for 45 minutes, using a muffle furnace, before being cooled rapidly to room temperature. Several different quenching media were used for this: water, ice water, hot water, and oil. Water is the most widely used cooling medium, as it is simple, effective, and cools at a rate of 982°C per second. It tends, however, to
form bubbles on the surface of the metal, which can lead to soft spots; thus, another cooling media may be used to prevent this. Oil is used when the risk of distortion is high, and it is most suitable for alloy steel, as it has a slower cooling rate than water, though this is still faster than that of air. The quenching oil temperature for this work was kept within a range of 27 to 65 °C [16].

Table 1. Composition of 316L stainless steel

| Element       | Quantity |
|---------------|----------|
| Chromium      | 16.0 min. 18.0 max. |
| Nickel        | 10.0 min. 14.0 max. |
| Molybdenum    | 2.00 min. 3.00 max. |
| Carbon        | 0.030     |
| Manganese     | 2.00      |
| Phosphorous   | 0.045     |
| Sulphur       | 0.03      |
| Silicon       | 0.75      |
| Nitrogen      | 0.1       |
| Iron          | Balance   |

Table 2. Physical and mechanical properties of 316L stainless steel [9, 15]

| Item                          | Quantity            | Item                          | Quantity          |
|-------------------------------|---------------------|-------------------------------|-------------------|
| Density                       | 7.90 g/cm³          | Thermal Conductivity (100°C)  | 14.6 W/m⁻¹K       |
| Modulus of Elasticity         | 200 GPa             | Electrical Resistivity        | 74 Microhm-cm at 20°C |
| Melting Range                 | 1390 – 1440°C       | Mean Coefficient of Thermal   | 16.6 x 10⁻⁶ cm/cm °C |
|                                |                     | Expansion (at 20-100 °C)      |                   |
| Specific Heat                 | 450 J/kg⁻¹K (0–100°C) | Elongation in 50 mm               | 40 % (min.)       |
| Yield Strength                | 290 MPa             | Reduction in area              | 96 %              |
| Ultimate Tensile Strength    | 485 MPa (min.)      | Rockwell Hardness B            | 95 (max.)         |
| Magnetic Permeability,        | H = 200; Oersteds,  | Brinell Hardness HB            | 217 (max.)        |
| Annealed – 1.02 max.          |                     |                               |                   |

Three sets of specimens were prepared for microhardness testing, microstructural analyses, and electrochemical corrosion tests. The microhardness investigations were implemented by testing three points for each experimental specimen with a load L= 30 N. These tests were done by using a digital microhardness tester, HV-10000B. Tensile test specimens were also produced from as-received stainless-steel samples of the same composition.

The Vickers pyramid method was used to determine the micro-hardness of the quenched samples after the various quenching regimes, with quenched specimens being first polished and mounted. The average values were recorded the test was repeated three times for each specimen. Vickers tests were implemented according to ASTM E 92 and the specimens were prepared according to ASTM E 340 standard specifications.

A 12 mm long slice was cut from one end (transverse to rolling) of each heat-treated specimen and subjected to standard mechanical polishing techniques using 200, 400, 800, 1000, and 1500 diamond abrasive paper grades. Etching of austenitic or 300 series stainless steel grades is difficult due to the anti-corrosive nature of chrome and the significant volume of nickel; 316L stainless steel has 18% chrome and 14% nickel, for example, making it harder to etch [1]. The etching solution, in which samples were immersed for several seconds, contained 45 g Etchant, 9 g Ferric chloride, 150 ml copper, and 75 ml ammonium chloride mixed with hydrochloric acid and distilled water [17]. The mounted, polished, and etched heat-treated specimens are shown in figure 1.
To investigate the phases produced in the stainless-steel specimens, a polarized microscope was used. Optical digital images were captured using digital cameras attached to the microscope; these were then analysed to determine the phase percent and grain sizes of the produced structures. These image analysis investigations were done using IMAGEJ2X Software.

3. Results and Discussion

3.1 Microhardness Tests

The effects of media cooling rates on the Vickers micro-hardness test results for 316L stainless steel specimens are given in table 3.

Table 3. The effect of cooling rates and cooling media on Vickers micro-hardness for 316L stainless steel specimens

| Exp. No. | Heating rate (Hr.) | Cooling media | Micro-hardness number |
|----------|-------------------|---------------|-----------------------|
|          |                   |               | Hv₁ | Hv₂ | Hv₃ | Hv (Average) |
| 1        | 1                 | Water         | 133.6 | 132.1 | 133.1 | 132.9 |
| 2        | 2                 | Water         | 147.5 | 154.5 | 151.2 | 151.1 |
| 3        | 3                 | Water         | 163.5 | 155.5 | 154.1 | 157.7 |
| 4        | 3                 | Ice water     | 151.4 | 157.6 | 158.8 | 155.9 |
| 5        | 3                 | Oil           | 143.1 | 141.3 | 145.7 | 143.4 |
| 6        | 3                 | Hot water     | 137.8 | 152.1 | 144.8 | 144.6 |

Figure 2 shows that the heat treatments generally caused a decrease in the Vickers micro-hardness value, based on the hardness of the as-received material being 185 Hv [2, 18]. This hardness decrease occurred because of austenite retention and, potentially, the formation of delta ferrite. After an increase in the heating period from 2 to 3 hours, the austenite retention rate increased, as did the formation of delta ferrite, offering a further slight change in hardness, as illustrated by the results for samples 2, 3, and 4 in the table.
Figure 2. The effects of cooling rates and cooling media on Vickers micro-hardness for 316L stainless steel specimens

The highest microhardness rate was obtained when samples were heated for three hours followed by rapid cooling with water; here, the micro-hardness reached 157.7 Hv, a hardness value higher than those achieved when using other cooling media such as ice water, hot water, or oil by 1.16, 9.06, and 9.97%, respectively. The maximum obtained micro-hardness rate when using the water-cooling media and three hours heating time was higher than when using the same cooling media with a heating time of two or one hours, by 4.37 and 18.66%, respectively.

3.2 Microstructure Image Analysis

After image analysis was complete, the area fraction represented by the black area and the average area units were converted to µm. When stainless steel is heated to a temperature higher than the upper critical temperature and cooled rapidly using water or oil, or indeed any conventional liquid, the resulting single-phase solution includes complex carbides such chromium carbide, iron carbide, and manganese carbide that can lead to a supersaturated solution forming, which may cause saturated excess carbon atoms to be dissolved in the solution during rapid cooling, causing the crystal structure to have a centred body prism-shaped.

The structural image analysis of the current samples shows that these had two main phases. The martensitic grains phase was presented as a dark phase with precipitation of fine chromium carbides at the grain boundaries during the cooling phase occurring on the grain boundary of the minor ferrite light phase, as shown in figure 3. The volume of the martensitic grains increases in the microstructure with the increase in heating temperatures [13].

Figure 3 (a) shows an optical micrograph of the typical characteristics of a 316L austenite steel specimen, highlighting the increase in the number of twins observed and evidence of the presence of chromium carbide precipitates along the grain boundaries, which might otherwise be expected to be insignificant due to the reduced carbon content (0.017 mass%) [19]. The microstructure images for the samples quenched in oil (figure 3 (e)) portray better properties than those of water-quenched samples, as the carbon particles in the oil quenched samples are more evenly and uniformly distributed, forming more pearlite structure [15]. As mentioned, stainless steel types 316 and 316L cannot be hardened by heat treatments as, during heating, the martensitic grains increase in number and precipitated on the grain boundary of the ferrite; as ferrite is a soft material, it does not harden by quenching.
3.3 Electrochemical 316L Corrosion Tests:
Electrochemical corrosion tests were implemented using a corrosion cell containing a plasma setup with a simulation body environment tester, as shown in figure 4. These tests were done at 37 °C in a fluid solution prepared by dissolving one tablet of I 15525 RINGER, supplied by Merck KGaA, Germany. The tests were implemented according to ASTM G71-81 for Galvanic corrosion in electrolytes and ASTM F2129-07 for Cyclic potentiodynamic polarization measurements. The MLab Multi-Channel Potentiostats/Galvano stats were used to investigate the corrosion behaviours of samples that present different phase fraction areas.

A popular corrosion measurement technique is the Tafel plot. This technique is used to measure the corrosion current ($I_{\text{CORR}}$) against the applied potential directly based on the polarization resistance ($R_p$) value and the Tafel constants, $\beta_a$ and $\beta_c$, which allow the corrosion rate to be calculated. This technique can also be used to measure polarization resistance ($R_p$), which is the resistance of the specimen to oxidation during the application of an external potential, from which the corrosion rate can be determined. The polarization resistance ($R_p$) value is equal to the slope of the linear region, $\Delta E/\Delta I$. The following formula can thus be used to determine the $R_p$ value, the Tafel constants, and the corrosion current:

$$R_p = \frac{\beta_a \beta_c}{2.3 (I_{\text{CORR}})(\beta_a + \beta_c)} \quad (1)$$

where $\Delta E$ is expressed in volts (V); $\Delta I$ is expressed in microamps ($\mu$A); $\beta_a$ and $\beta_c$ are the anodic and cathodic Tafel constants (V/Decade) of current; $2.3 = \log_{10} 10$, and $I_{\text{CORR}}$ is the corrosion current ($\mu$A).

The polarization resistance ($R_p$) value thus helps to evaluate the relative ability of a material to resist corrosion in addition to the data from corrosion current and corrosion rate, being inversely proportional to corrosion current. For the samples of materials of equal surface area, the lowest corrosion current and thus the highest $R_p$ predicates the highest corrosion resistance. The corrosion rate (in milli inches per year) can thus be calculated using the following equation:

$$\text{Corrosion Rate (MPY)} = 0.13 \times \frac{I_{\text{CORR}}}{A * d} \quad (2)$$

where MPY = milli-inches per year; $0.13 = \text{a metric time conversion factor}$; $A$ is the area (cm$^2$); and $d$ = density (g/cm$^3$).
Figure 3. Microstructure images for 316L stainless steel specimens (20x magnifications)
Figure 4. Electrochemical corrosion testing using the corrosion cell and plasma setup.

Figure 5 shows the Tafel plots for the examined 316L stainless steel samples after the application of different heating rates and cooling media, while table 4 gives the Tafel analysis for the corrosion potential (E_{CORR}), the corrosion current (I_{CORR}), and the Tafel constants, βa and βc for the samples. Figure 6 shows the effect of different heating rates and cooling media on the corrosion potential (E_{CORR}), the corrosion current (I_{CORR}), the polarization resistance, and the corrosion rate for the examined 316L stainless steel samples.

Figure 6 (a) shows that a higher corrosion potential value was obtained when using normal or hot water as cooling media and for three hours heating time and water as compared to one-hour of heating, with the latter values reaching -994.5, -991.7, and 975.3 mV, respectively. These values were reduced by a further 47.82 to 56.15% from the figures for using water when ice water and oil were used with two and three hours of heating time, respectively. The relationship between the parameters and corrosion current (I_{CORR}) is shown in figure 6 (b), where the I_{CORR} reaches its maximum value when water is used as a cooling media and where three or one hour heating times were observed when using normal and hot water as cooling media, at 475.0 and 411.1 nA, respectively. The minimum value was obtained when oil was used as a cooling medium, at a value of 107.5 nA. Figure 6 (c) shows the higher polarization resistance value obtained when using a water-cooling media with two hours heating time, 2.849 V/μA. Dec., while the minimum value was 0.185 V/μA. Dec., obtained using the hot water-cooling media. Figure 6(d) shows that the minimum corrosion rate value was obtained using the oil cooling media at 0.34 x10^{-5} milli-in./year, while the maximum value was 0.86x10^{-5} milli-in./year, obtained using the water-cooling media with a three-hour heating duration.

Figure 7 (a) shows the effect of the corrosion potential (E_{CORR}) and the corrosion current (I_{CORR}) on the polarization resistance for the 316L stainless steel samples. The figure shows that the value of the polarization resistance increased based on increases in the values of E_{CORR} and I_{CORR}. Figure (7b) shows the effect of the same parameters on the corrosion rate, and indicates that the value of the corrosion rate decreases significantly with decreases in the I_{CORR} value and slightly increases with the E_{CORR} value.
Heating rate (1 Hr.), Cooling media (Water)

Heating rate (2 Hr.), Cooling media (Water)

Heating rate (3 Hr.), Cooling media (Water)

Heating rate (3 Hr.), Cooling media (Ice Water)

Heating rate (3 Hr.), Cooling media (Oil)

Heating rate (3 Hr.), Cooling media (Hot Water)

Figure (5): Tafel plots for 316L stainless steel samples with different heating rates and cooling media

Table 4. Tafel analysis for the corrosion potential (E_{CORR}), the corrosion current (I_{CORR}), and the Tafel constants $\beta_a$ and $\beta_c$ for 316L stainless steel samples with different heating rates and cooling media.

| Exp. No. | Heating rate (Hr.) | Cooling media | Corrosion potential (E_{CORR}) (mV) | Corrosion current (I_{CORR}) (nA) | Tafel constants, $\beta_a$ (mV/Dec.) | Tafel constants, $\beta_c$ (mV/Dec.) | polarization resistance (RP) (V/μA. Dec.) | Corrosion Rate (MPY) (Milli-in./year) |
|---------|-------------------|---------------|-------------------------------------|----------------------------------|-------------------------------------|-------------------------------------|---------------------------------|---------------------------------|
| 1       | 1                 | Tap Water     | -975.3                              | 411.1                            | -139.2                              | 165.5                              | 0.926                           | 0.86 x 10^{-5}                 |
| 2       | 2                 | Tap Water     | -672.8                              | 141.9                            | -88.9                               | 98.3                               | 2.849                           | 0.30 x 10^{-5}                 |
| 3       | 3                 | Tap Water     | -994.5                              | 475.0                            | -101.3                              | 152.9                              | 0.275                           | 1.00 x 10^{-5}                 |
| 4       | 3                 | Ice water     | -650.6                              | 153.2                            | -301.9                              | 81.6                               | 0.317                           | 0.32 x 10^{-5}                 |
| 5       | 3                 | Oil           | -636.9                              | 107.5                            | -98.9                               | 41.1                               | 0.284                           | 0.23 x 10^{-5}                 |
| 6       | 3                 | Hot water     | -991.7                              | 162.5                            | -95.5                               | 40.1                               | 0.185                           | 0.34 x 10^{-5}                 |
Figure 6. The effects of heating rate and cooling media on (a) the corrosion potential ($E_{CORR}$); (b) the corrosion current ($I_{CORR}$); (c) the polarization resistance; and (d) the corrosion rate for 316L stainless steel samples.

3.4 Stress Analysis and Fatigue life
The human femur is responsible for carrying most body weight, and its length is about 26% of a person’s height. It is naturally the strongest and heaviest bone in the human body [20]. To implement the stress analysis process, the design of a femur bone fracture fixation plate in 316L stainless steel (200 x 16mm) with 5 and 10 mm thickness was completed in Solid Works 17.0 design software, as shown in figure 8.

The simulation models showing the stresses and strain distribution were created using finite element ANSYS R18.0 software. Figures 9 (a) to (c) show the fixation plate design, the finite element analysis (FEA) mesh, and the mesh refinement required for more accurate study of the stress analysis results, respectively.

Design Expert 11.0, full factorial design (FFD), and response surface methodology (RSM) techniques were used to analyse and develop the results. Analysis of variance (ANOVA) was used to assess the...
influence of input parameters, including patient weight and fixation plate thickness (5 and 10 mm), on the output performance parameters, including the equivalent von Mises stress, the total deformation, the equivalent elastic strain, and the stress safety factor. Four patient weights were selected, 60, 90, 120, and 150 Kg, in order to examine the plate durability and the stresses and strain distribution resulting from such weights.

All ANOVA analyses were done using the quadratic model and an inverse transformation. The P-values for all analysed systems were less than 0.05, indicating that the model terms were significant. The equivalent von Mises stress ANOVA analysis for the 316L stainless steel femur fracture fixation plate is shown in table 5. The model’s F-value of 263.54 implies that the model is significant overall. Tables 6 and 7 show the stress analyses results for 316L femur bone fracture fixation plates of 5 and 10 mm thickness, respectively. Figures 10 to 13 show the stress analysis results for both fracture fixation plate thicknesses with 60, 90, 120, and 150 Kg patient weights, respectively.

![Figure 7](image1.png)

**Figure 7.** The effect of the corrosion potential ($E_{\text{CORR}}$) and the corrosion current ($I_{\text{CORR}}$) on (a) the polarization resistance and (b) the corrosion rate for the examined 316L stainless steel samples

![Figure 8](image2.png)

**Figure 8.** The design of the 316L stainless steel femur fracture fixation plate
Figure 9. (a) The fixation plate design; (b) finite element analysis (FEA) meshing process; and (c) the meshing refinement process.

Table 5. Equivalent von Mises stress ANOVA analysis for the 316L stainless steel femur fracture fixation plate.

| Source                     | Sum of Squares | df | Mean Square | F-value | p-value |
|----------------------------|----------------|----|-------------|---------|---------|
| Model                      | 0.0000         | 4  | 0.0000      | 263.54  | 0.0004  | significant |
| A-Patient weight           | 0.0000         | 1  | 0.0000      | 903.95  | <       |
| B-Bone Fracture Fixation   | 3.147E-06      | 1  | 3.147E-06   | 77.51   | 0.0031  |
| plate thickness AB         | 3.696E-07      | 1  | 3.696E-07   | 9.10    | 0.0569  |
| A²                         | 2.582E-06      | 1  | 2.582E-06   | 63.60   | 0.0041  |
| B²                         | 0.0000         | 0  |             |         |         |
| Residual                   | 1.218E-07      | 3  | 4.060E-08   |         |         |
| Cor Total                  | 0.0000         | 7  |             |         |         |

Table 6. The stress analysis results for 5 mm thickness - 316L femur bone fracture fixation plate.

| Patient weight (Kg) | Equivalent (von Mises) stress (MPa) | Total deformation (mm) | Equivalent Elastic strain (mm/mm) | Strain energy (mJ) | Stress safety factor |
|---------------------|--------------------------------------|------------------------|----------------------------------|--------------------|---------------------|
Table 7. The stress analysis results for 10 mm thickness - 316L Femur Bone Fracture Fixation Plate

| Patient weight (Kg) | Equivalent (von Mises) stress (MPa) | Total deformation (mm) | Equivalent Elastic strain (mm/mm) | Strain energy (mJ) | Stress safety factor |
|---------------------|-------------------------------------|------------------------|----------------------------------|-------------------|---------------------|
| 60                  | 93.29                               | 0.0723                 | 0.00047                          | 0.0302            | 2.68                |
| 90                  | 139.93                              | 0.1085                 | 0.00070                          | 0.0680            | 1.79                |
| 120                 | 186.57                              | 0.1446                 | 0.00093                          | 0.1210            | 1.34                |
| 150                 | 233.22                              | 0.1808                 | 0.00167                          | 0.1890            | 1.07                |

Figures 10 to 13 (b) and (h) show that the resulting equivalent von-Mises stress distribution for fracture fixation plate thicknesses and patient weights increased with increases inpatient weight and decreases in the fixation plate thickness, with the
maximum value at 285.24 MPa in a 150 Kg patient with 5 mm plate thickness.

**Figure 11.** Stress analysis results for 5 and 10 mm fracture fixation plate thicknesses with 90 Kg patient weight

**Figure 12.** Stress analysis results for 5 and 10 mm fracture fixation plate thicknesses and 120 Kg patient weight
Figure 13. Stress analysis results for 5 and 10 mm fracture fixation plate thicknesses and 150 Kg patient weight

Figures 10 to 13 (c) and (i) show the total deformation values occasioned by the application of external forces equivalent to the daily mechanical work activities, which are reduced with decreases in the patient weight and increases in the fixation plate thickness, reaching a minimum value of 0.0723 mm for a patient weight of 60 Kg with a 10 mm plate thickness.

Figures 10 to 13 (d) and (j) show that principal elastic strain of the bone fixation plate is reduced with decreases in the patient weight and the fixation plate thickness, reaching a minimum value at $4.7 \times 10^{-4}$ mm for a patient weight of 60 Kg when using 5 mm plate thickness.

Figures 10 to 13 (e) and (k) show the internal strain energy for the bone fixation plate based on external mechanical work in daily human activities, depending on patient weight. The minimum principal elastic strain value was 0.021 mJ for a patient weight of 60 Kg when using 5 mm plate thickness; this also increased with increases in patient weight and fixation plate thickness.

Figures 10 to 13 (f) and (l) show the stress safety factors for the bone fixation plates, which are increased with decreases in the patient weight and increases in the fixation plate thickness, reaching a maximum value of 2.7, with a patient weight of 60 Kg when using 10 mm plate thickness.

These results indicate that it is not possible to use a 316L stainless steel fixation plate with a thickness of less than 10 mm, as this poses a danger to the patient when the patient's weight exceeds 60 kg due to the likelihood of a collapse under the patient's weight based on the resulting stress safety factor being lower than 1, causing failure of such surgery to treat a femur bone fracture based on the stress safety factor of the normal human femur being 1.72 [12].

Figure 14 shows the 3D graphs of the stress analysis results for all patient weights and bone fracture fixation plate thicknesses. Figure 15 (a) shows that the 3D graphs of the equivalent von-Mises stress values increase with increases in the patient weight and decreases in the fixation plate thickness, reaching a maximum value at 285.24 MPa for a 150 Kg patient with 5 mm plate thickness. Figures 14 (b) and (e) show the effect of patient weight and plate thickness on the total deformation and stress safety factors, which are reduced with decreases in the patient weight and increase in the fixation plate thickness, reaching a minimum value at 0.0723 mm and a maximum value at 2.7, respectively, for a patient weight of 60 Kg when using 10 mm plate thickness.
Figure 14. 3D graphs of stress analysis results for all patient weights and bone fracture fixation plate thicknesses

Figures 14 (c) and (d) show the effect of the same input parameters on the equivalent elastic strain and the strain energy in the designed plate, which reduce with decreases in patient weight and fixation plate thickness, reaching minimum values at 4.7 x 10^-4 mm and 0.021 mJ, respectively, for a patient
weight of 60 Kg when using a 5 mm plate thickness. Figure 15 (e) shows the stress safety factors for the designed bone fixation plates, which are increased with decreases in the patient weight and increases in the fixation plate thickness, reaching a maximum value as 2.7 for a patient weight of 60 Kg using 10 mm plate thickness.

4. Conclusions

The following conclusions can be deduced from the current research results:

1. The highest cooling rate was obtained when using normal water as a cooling media after heating for three hours; this reached 157.7 Hv, which is a higher value than that created by using oil media by 9.97%, and 18.66% higher than when using one hour of heating.

2. The microstructure images for the quenched samples in oil displayed better properties as compared with the water-quenched samples due to the carbon particles in oil quenched samples being evenly and uniformly distributed, contributing to the formation of more pearlite structure.

3. The highest corrosion potential value was obtained when using normal water as a cooling medium and three hours heating time, at -994.5 mV. This value was reduced between 47.82 to 56.15% when using ice water and oil cooling media with two- and three-hours heating time, respectively.

4. The value of the polarization resistance increased with increases in the values of \( E_{\text{CORR}} \) and \( I_{\text{CORR}} \). The highest polarization resistance value was obtained when using water-cooling media with two hours heating time, 2.849 V/μA. Dec., while the minimum value was 0.185 V/μA. Dec., obtained when using the hot water-cooling medium.

5. The minimum corrosion rate value was obtained when using the oil cooling medium at 0.34 x10-5 milli-in./year, while the maximum value was 0.86x10-5 milli-in./year, obtained when using the water-cooling medium with a three-hour heating duration.

6. The total deformation and the stress safety factors, which are reduced with decreasing patient weight and increased with fixation plate thickness, respectively, reached their respective minimum value of 0.0723 mm and maximum value of 2.7 for a patient weight of 60 Kg using 10 mm plate thickness.

7. The equivalent elastic strain and the strain energy in designed plate were reduced with decreases in patient weight and fixation plate thickness, reaching minimums value of 4.7 x 10-4 mm and 0.021 mJ respectively for a patient weight of 60 Kg when using 5 mm plate thickness.

5. References

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