*Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan* *Vol. 28 No. 3-2023*
*ISSN:1813-1786 (Print) 2313-7770 (Online)*

# Computational Study of Mechanical Behavior of Ti6Al4V-Coated and Aluminium-Coated 316L Stainless Steel Alloy Under Linear and Cyclic Loading

S. M. A. Bukhari[1], A. Naveed[2], N. Husnain[3], F. A. Siddiqui[4], M. F. Zaman[5], A. Ahmad[6], R. Ahmad[7], N. Wajahat[8]

[1,2,3,4,5,6,7] *Department of Mechanical Engineering, Faculty of Engineering and Technology, Bahauddin Zakariya University, Multan, Pakistan.*
[8] *Department of Computer Science, Government Associate College for Women Kabirwala, Khanewal, Pakistan*

[3] *naveedhusnain@bzu.edu.pk*

***Abstract-*** This study includes computational analysis of corrosion-resistant 316L Stainless Steel alloy after surface coating under linear and cyclic loading. Ti6Al4V is known for its strength and corrosion resistance whereas Aluminium alloy is known for its lightweight, enhanced surface finish and corrosion resistance. Based on this, two types of surface coatings are analyzed in this research work i.e. Ti6Al4V coating and Aluminium alloy coating. Effect of both the coatings on tensile and fatigue behaviors of coated 316L Steel specimens is explored. The testing specimen was designed in SolidWorks® 16.2 and analysis was done on ANSYS® Workbench 19.2. A thin layer (0.5 mm) of coating was made on 316L Stainless Steel specimen using ANSYS® Workbench 19.2. Coated specimens showed enhanced mechanical behavior as compared to specimens without coating. Moreover, the results indicated that Ti6Al4V coating provides superior properties as compared to Aluminium coating. Although Aluminium coating can reduce the cost and weight of the part but Aluminium coated 316L showed a reduced number of cycles while the cyclic load was applied whereas Aluminium coated specimen exhibited more strain as compared to Ti6Al4V coating. Ti6Al4V coating can be a good choice for Stainless Steel materials where certain desirable characteristics like high corrosion resistance, tensile strength, fatigue strength and low-crack initiation and propagation are required.

***Keywords-*** Surface coating, ANSYS, simulation, tensile properties, fatigue properties, coated steel, factor of safety.

## I. INTRODUCTION

Mechanical components are designed and fabricated using different materials based on their applications. In these demanding situations, the desired characteristics of the material can be obtained by two methods i.e. alloying and surface coatings. Due to a combination of two or more metals, alloys provide a number of unique and desirable properties for specific applications [1]. Another way to get the desirable properties is through surface coatings. Surface coating is an effective way of enhancing the performance and mechanical properties of components [2]. Surface coatings have unleashed various ways to manipulate the properties and reduce the cost of materials for specific applications. Surface coatings can provide several desirable properties such as enhanced wear resistance, corrosion resistance, hardness, tensile properties, etc. [3]. Coatings can also improve durability of substrate materials [4]. With the advancement in technology, different alloy coatings have been utilized on metals and alloys for certain characteristics. Use of advanced coatings and techniques, the substrate material can be protected as well as mechanical behavior can be enhanced [5]. The most common coating techniques include physical vapor deposition [6], chemical vapor deposition [7], Micro-Arc Oxidation [8], electrodeposition [9], and thermal spray coating technique [10].

316L Stainless Steel (316L SS) is widely used in various applications including aerospace, automotive, biomedical, nuclear, and household applications [11-13]. Its extensive applications are due to the properties it offers. 316L is known for its high strength, high-temperature oxidation resistance, and corrosion resistance [14-15]. Ti6Al4V is a high-strength Ti-alloy that offers high mechanical strength, lighter weight, enhanced machinability, and enhanced fatigue life [16-17] due to which it has vast applications in the aerospace and marine industry [18]. Aluminium alloy is another alloy that is commonly used in the automotive and aerospace industry due to its high strength-to-weight ratio, lighter weight, relatively low cost, and good corrosion resistance [19-20].

Several works on surface coatings on 316L substrate have been done. For example, Sharifnabi deposited an Mg-aided fluorapatite coating on 316L SS substrate material and measured the corrosion behavior of coated 316L SS. They reported that coatings were crack-free and corrosion was reduced [21]. Shabani-Nooshabadi prepared coatings of polyaniline-montmorillonite and deposited those coatings on 316L SS. Their ultimate goal was to prevent the substrate from corrosion. The prepared coating provided excellent resistance against corrosion [22]. CrN coatings are known for their hardness. In another research work, CrN coatings were applied on 316L SS to study wear and friction behavior in a liquid sodium environment. SEM, EDS, and XPS were used to analyze the worn surfaces of coatings after wear. The results demonstrated that the liquid sodium environment tends to improve the friction behavior of CrN coating on 316L SS as compared to the Ar environment [23]. Zhang also verified that CrN coating can enhance the corrosion resistance of 316L SS [24]. In another study, PremKumar coated 316L SS with $Nb_2O_5$ (NZ4). It was verified that $Nb_2O_5$ (NZ4) coatings can be used to enhance antibacterial activities, corrosion resistance, and biocompatibility [25]. Sridhar reported that hydroxyapatite coating on 316L can enhance corrosion behavior [26]. In another study, Zaffora verified that superhydrophobic coating on 316L SS can enhance can be self-cleaning and anti-corrosive [27]. Qian investigated the effect of Ni-based cladding coating on the microstructure and wear behavior of 316L SS. It was concluded that the cladded layer Ni can provide protection of 316L SS against wear [28].

Ti-based coatings have urged the interest of researchers in the recent past due to their high strength and high corrosion resistance. Moreover, these coatings enhance the wear resistance [29]. Naghibi studied the corrosion and tribocorrosion behavior of TiN coatings on 316L SS. Physical vapor deposition was used to deposit the TiN coating on the substrate material. The corrosion resistance was improved in Ringer's solution. Results from tribocorrosion analysis showed that coating made a repaired passive film after being subjected to wear [30]. In another study, Jin subjected 316L SS to TiN and TiCN coatings to protect it from corrosion. The results indicated that TiCN-coated material provides exceptional corrosion resistance as compared to other materials [31]. Saravanan also worked on TiN coating deposition to 316L SS. They reported that the surface hardness of coated material was enhanced significantly as compared to bare material. Moreover, the wear resistance of coated steel was also improved [32]. Yazıcı also backed these results that TiN coating can enhance the hardness and wear resistance [33]. In another research, Liu and his team studied the corrosion behavior of Ti/TiN coating on 316L SS. They prepared multilayered coatings using arc plating. These coatings provided resistance to corrosion [34]. Mani reported that TiN and TiAlN coating can protect the 316L SS substrate [35]. Balamurugan in another work, deposited $TiO_2$ coating on 316L SS. They used a body fluid environment as this research was intended for surgical purposes. The corrosion resistance of coated steel was improved [36]. Shukla and Prashanth attempted to coat high-strength and modern Ti6Al4V coating on 316L SS most recently. They prepared 316L plates through spark plasma sintering. They utilized laser powder-bed fusion to coat the Ti6Al4V substrate. The coating was successfully made with higher deformability. It was observed that the pre-scanning of 316L reduced the cracks [37].

Aluminium coating on steel has a tendency to provide exceptional oxidation and corrosion resistance in marine and sulfur-rich environments. This coating can provide resistance to thermal shock and bending [38]. Aluminium coatings provide excellent resistance to corrosion in distilled water. That's why Al-coated steel is commonly used in distilled water storage systems that prevent the steel [39]. Suehiro explored Al-coated steel for hot forming. After hot forming, it was verified that the weldability of coated steel was enhanced [40]. Al-coated steels are generally used for enhanced corrosion resistance in aerospace applications. The combination of Aluminium alloy with some other elements is also utilized by researchers with a positive outcome [41]. Ahmad investigated the impact of Aluminium coating on 316L SS. It was revealed that Al-coated 316L SS had more hardness as compared to the substrate whereas the surface characteristics were also improved [42].

Literature reveals that Ti-based coatings are widely employed for 316L SS and extensive research works have been used to predict the corrosion resistance and wear resistance of coated parts. Ti6Al4V coating has been most recently used on 316L substrate. But the effect of these coatings on the tensile and fatigue behavior of 316L SS remains unexplored. Fatigue occurs when a crack is formed, propagated, and results in material failure. Fatigue life can be viewed in terms of the number of cycles before failure [43]. Based on this gap, this research work incorporates a simulation-based comparative analysis of Ti6Al4V-coated and

Al-coated 316L SS. A dog-bone-shaped specimen is designed in SolidWorks® 16.2 and simulations are done in ANSYS® Workbench 19.2. Linear and cyclic loads of 10 N, 20 N, 30 N, 40 N, 50 N, 60 N, 70 N, 80 N, 90 N, and 100 N are applied to the specimens. Deformation, equivalent strain, von-Mises stress, fatigue life, and factor of safety are analyzed on the aforementioned loads for uncoated and both coated specimens. In the end, the results of both the coatings are compared and plotted.

## II. Materials and Methods

In this work, three different materials are used for the analysis i.e. high-strength Ti6Al4V alloy, Aluminium alloy, and 316L SS alloy. Out of these, 316L SS is selected as a substrate on which coatings are deposited. Ti6Al4V alloy and Aluminium alloy materials are used as surface coatings on 316L SS. A simple dog-bone-shaped specimen is selected for replications of the results. The specimen is about 63.7 mm in length and 9 mm in diameter at the outer ends, and 4 mm in diameter at the centre. Figure 1 shows the dimensions of the specimen. The properties of all the materials and simulation parameters are presented in Table I and Table II respectively. A very thin coating of about 0.5 mm is deposited on 316L SS and the tensile behavior due to linear force and fatigue behavior due to cyclic loading is investigated using computational analysis. Fatigue data of used materials is obtained through literature [44-45].

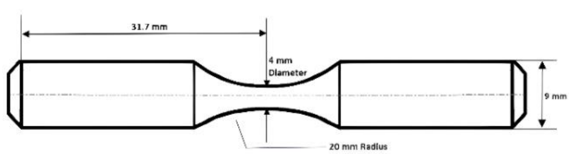



Figure 1: Dimensions of the specimen

Table I: Properties of 316l Ss Alloy, Ti6al4v Alloy and Aluminium Alloy

| **Property** | **316L SS Alloy** | **Ti6Al4V Alloy** | **Aluminium Alloy** |
|---|---|---|---|
| Density | 8 g/cm$^3$ | 4.43 g/cm$^3$ | 2.27 g/cm$^3$ |
| Yield Strength | 205 MPa | 880 MPa | 280 MPa |
| Ultimate Tensile Strength | 515 MPa | 950 MPa | 310 MPa |
| Young's Modulus | 193 GPa | 113.8 GPa | 71 GPa |
| Poisson's Ratio | 0.25 | 0.342 | 0.33 |

Table II: Simulation Parameters

| **Loading Type** | **Direction** | **Simulation Linkage** | **Force Values (N)** |
|---|---|---|---|
| Linear | X | Tensile Deformation | 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 |
| Cyclic | Y | Fatigue Analysis | 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 |

## III. Modeling and Simulation

The specimen for simulation was designed and modeled in SolidWorks® 16.2 and is displayed in Figure 2. The model was imported in the ANSYS® Workbench 19.2 in which the Static Structural module was selected. After that, the properties of materials as described in Table I were imported into ANSYS® in engineering data. All the material properties including strengths and SN-curve data were manually entered to create the required materials.

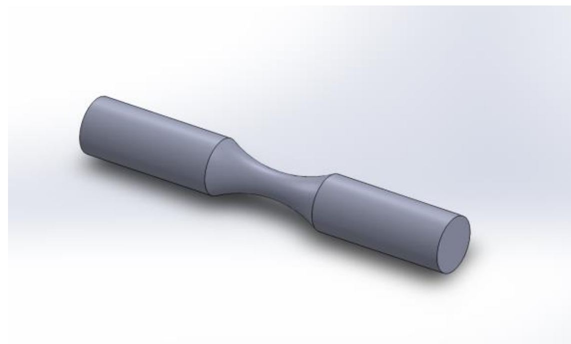


Figure 2: Geometry of specimen designed in SolidWorks®

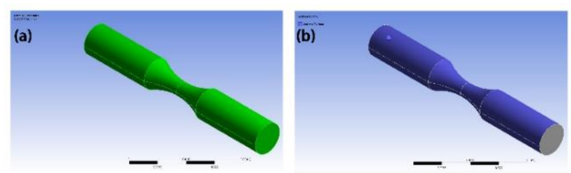



Figure 3: Model of (a) Solid substrate material, and (b) Surface coating

In the next step, a coating was created (through insert: surface coating command in geometry) with a thickness of 0.5 mm and materials for comparison purposes were assigned to both the solid body and coating. Stiffness behavior of "membrane and bending" was selected for surface coating. Three categories of specimens were analyzed one by one i.e. specimens without coating, specimens with Ti6Al4V coating and specimens with Al coating. The model was meshed to divide the specimen into finite elements [46]. Meshing was refined to get better results due to smaller element size. The final meshed geometry contained 22466 elements and 97870 nodes. The coarse meshing and smooth meshing of the specimen are shown in Figure 4.

After the meshing process was done, boundary conditions were applied. For the simulations of tensile behavior, the linear force with magnitudes of 10 N, 20 N, 30 N, 40 N, 50 N, 60 N, 70 N, 80 N, 90 N, and 100 N, was exerted in the X-direction on one end after fixing the other end face of the specimen. The solution of the total deformation, equivalent strain, and von-Mises (equivalent) stress was selected. After that, the model was solved and results were generated.

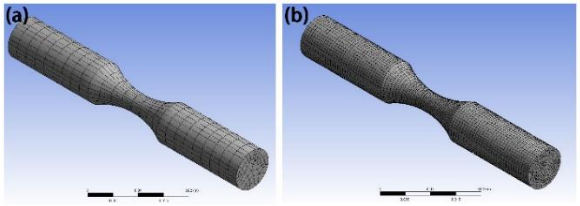
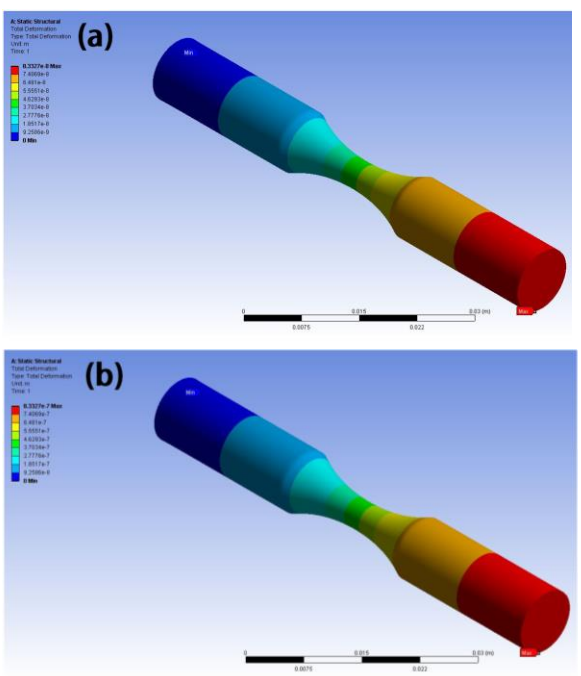



Figure 4: Meshed specimen with (a) Coarse meshing, and (b) Refined meshing

For fatigue simulation, boundary conditions were changed in the static structural project. A vertical force with the same magnitudes was applied in the downward direction at one end while keeping the other end fixed. This force was used to simulate a cyclic load at one end of the specimen to study the fatigue behavior of the coated 316L SS. The fatigue tool was employed in the solution and fatigue life, and the factor of safety simulations were selected. In the toolbar of the fatigue tool, the stress-life method was selected which is based on SN-curve which we already had in the material properties. The loading type of "fully reversed" was selected. After applying all the boundary conditions, the model was solved.
After the solution, the results of total deformation, equivalent strain, von-Mises stress, fatigue life, and the factor of safety are displayed in Figures 5, 6, 7, 8, and 9 respectively.



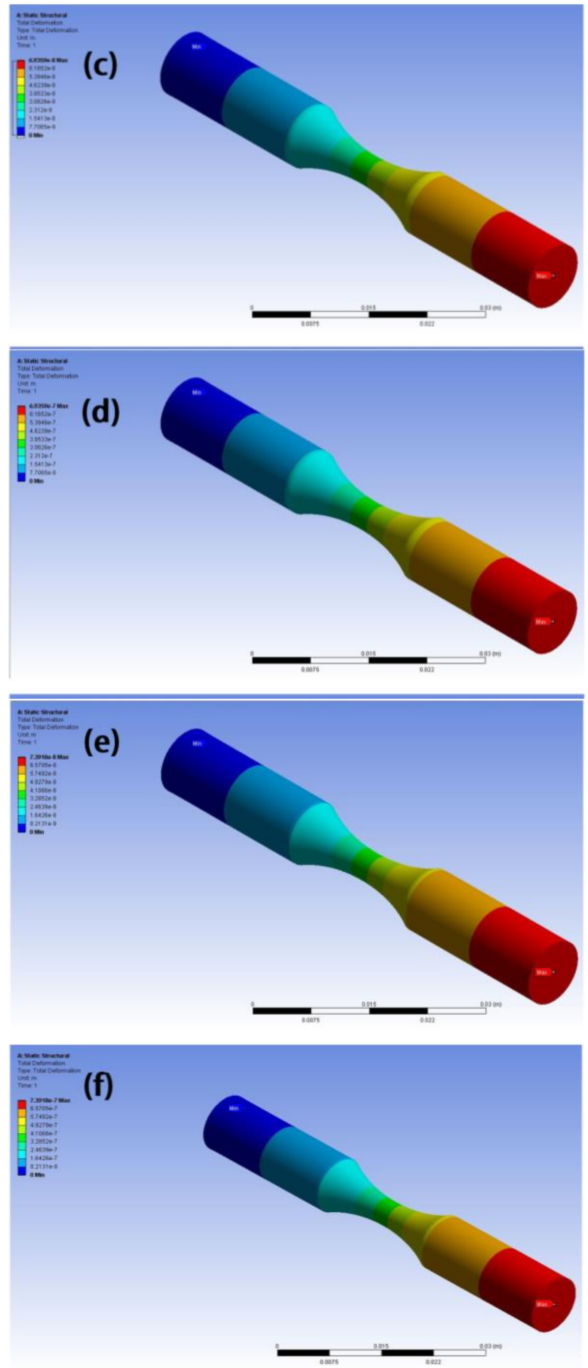




Figure 5: Total tensile deformation of (a) uncoated 316L SS specimen at 10 N, (b) uncoated 316L SS specimen at 100 N, (c) Ti6Al4V-coated 316L SS specimen at 10 N, (d) Ti6Al4V-coated 316L SS specimen at 100 N, (e) Al-coated 316L SS specimen at 10 N, and (f) Al-coated 316L SS specimen at 100 N

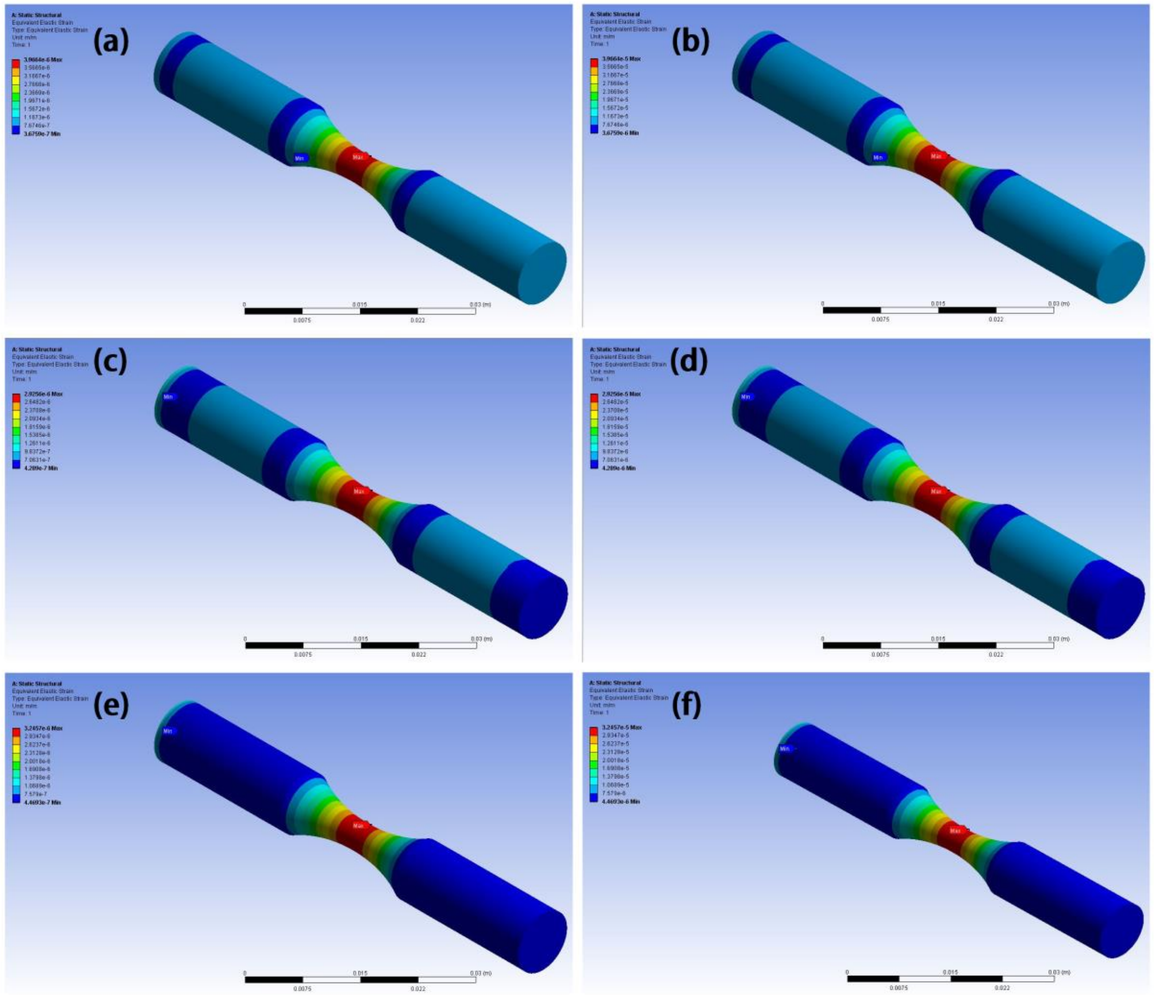



Figure 6: Equivalent strain of (a) uncoated 316L SS specimen at 10 N, (b) uncoated 316L SS specimen at 100 N, (c) Ti6Al4V-coated 316L SS specimen at 10 N, (d) Ti6Al4V-coated 316L SS specimen at 100 N, (e) Al-coated 316L SS specimen at 10 N, and (f) Al-coated 316L SS specimen at 100 N

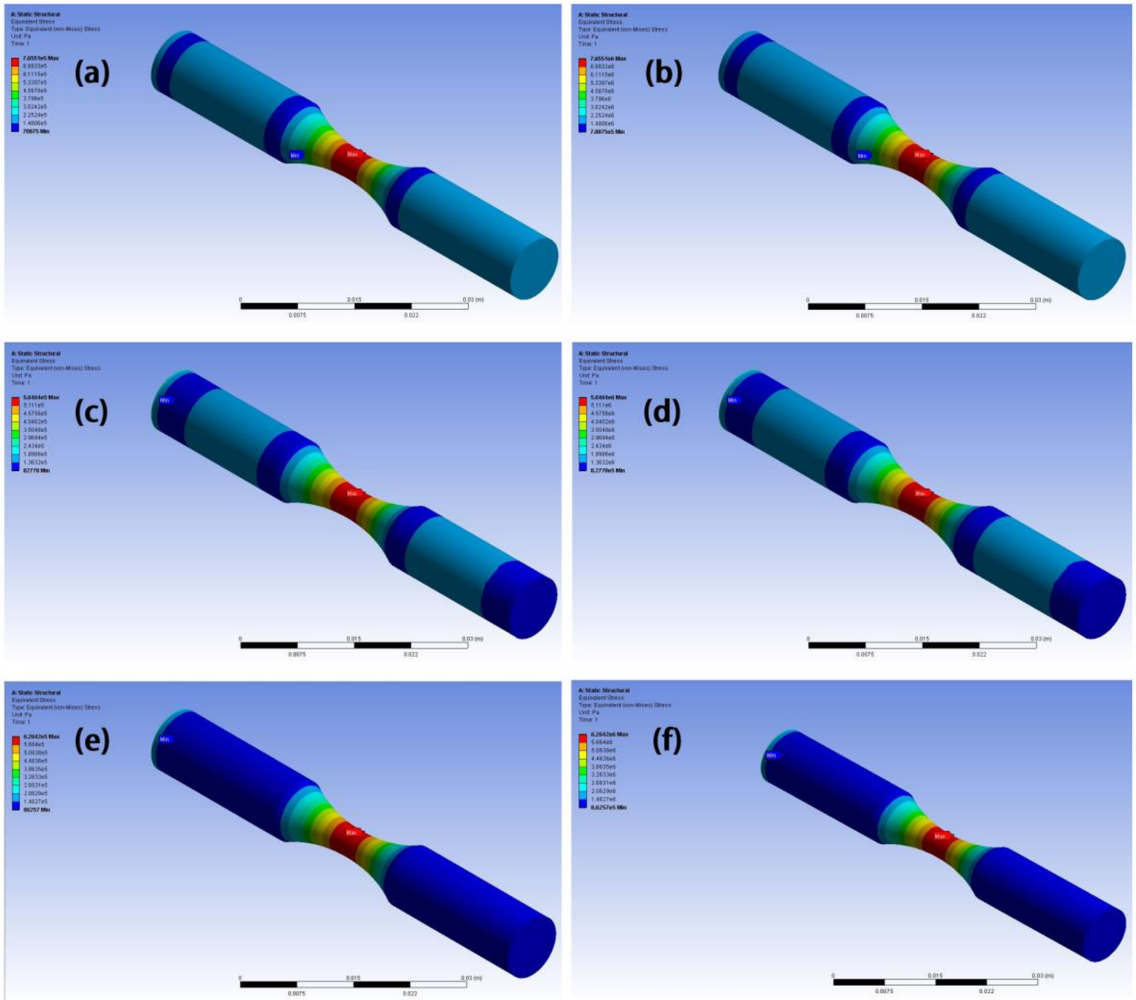



Figure 7: von-Mises stress of (a) uncoated 316L SS specimen at 10 N, (b) uncoated 316L SS specimen at 100 N, (c) Ti6Al4V-coated 316L SS specimen at 10 N, (d) Ti6Al4V-coated 316L SS specimen at 100 N, (e) Al-coated 316L SS specimen at 10 N, and (f) Al-coated 316L SS specimen at 100 N

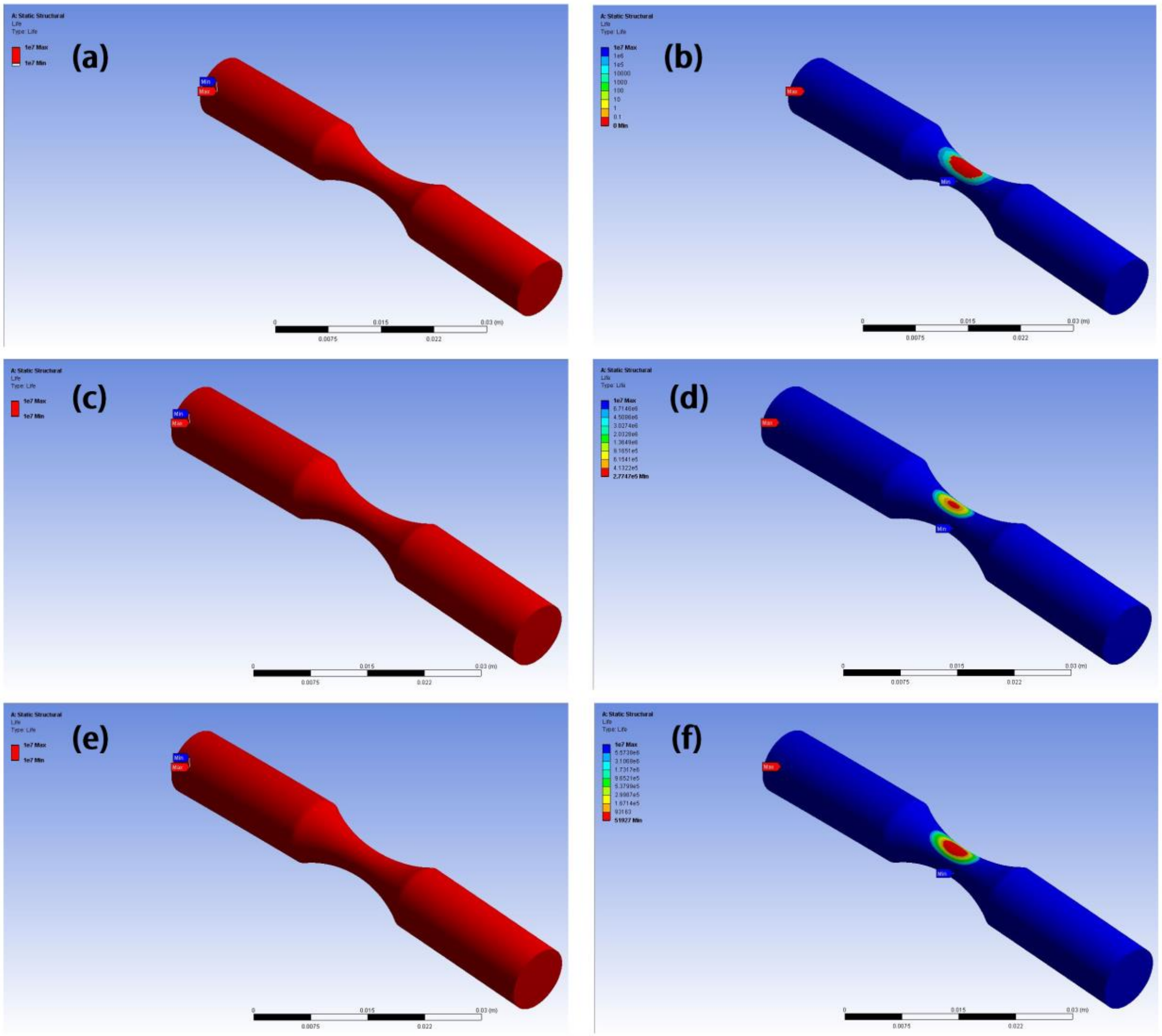



Figure 8: Fatigue life of (a) uncoated 316L SS specimen at 10 N, (b) uncoated 316L SS specimen at 100 N, (c) Ti6Al4V-coated 316L SS specimen at 10 N, (d) Ti6Al4V-coated 316L SS specimen at 100 N, (e) Al-coated 316L SS specimen at 10 N, and (f) Al-coated 316L SS specimen at 100 N

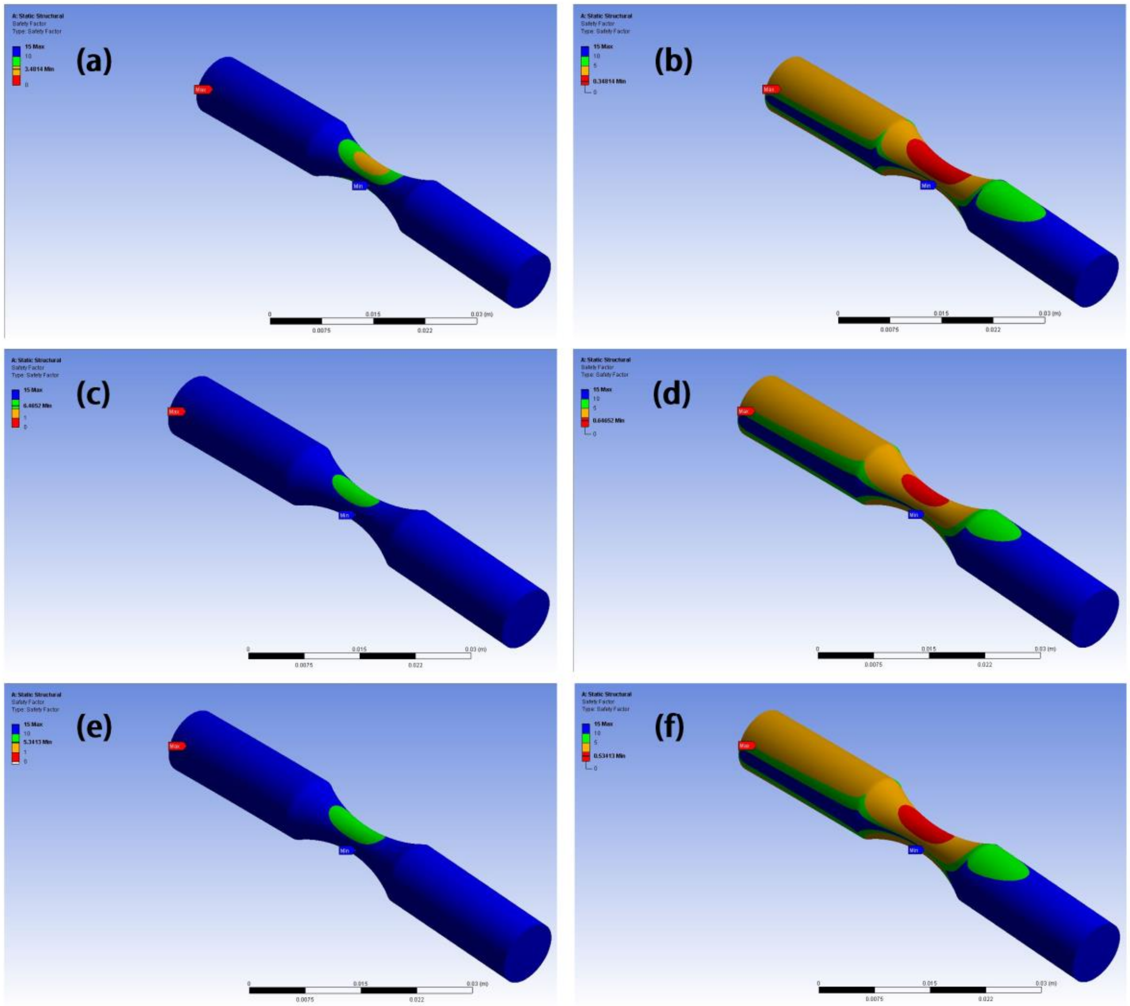



*Figure 9: Factor of safety of (a) uncoated 316L SS specimen at 10 N, (b) uncoated 316L SS specimen at 100 N, (c) Ti6Al4V-coated 316L SS specimen at 10 N, (d) Ti6Al4V-coated 316L SS specimen at 100 N, (e) Al-coated 316L SS specimen at 10 N, and (f) Al-coated 316L SS specimen at 100 N*

## IV. Results and Discussions

*4.1 Total Tensile Deformation Results:*

Total tensile deformations of specimens without coating and both the coated specimens i.e. Ti6Al4V-coated and Al-coated 316L SS specimens were obtained by simulating tensile forces in the X-direction as mentioned earlier. As displayed in table III and Figure 5, the deformation values depict that Ti6Al4V offers better resistance to deformation as compared to Al-coated specimens and specimens without coating. As shown in Figure 5(e) and 5(f), the Al-coated specimen undergoes more deformation as compared to other Ti-based coating but it is still, less than the deformation that is observed in specimen without coating. This can be due to the fact that Ti6Al4V offers better yield and ultimate strength as compared to Aluminium and 316L SS. Moreover, Young's Modulus is greater for Ti-based alloy in comparison with Aluminium alloy. A graph representing total deformation against the applied forces i.e. 10 N, 20 N, 30 N, 40 N, 50 N, 60 N, 70 N, 80 N, 90 N, and 100 N for both coated and uncoated specimens is shown in Figure 10. The graph depicts that deformation increases linearly with the increase in force however, the line in the case of uncoated specimen is more elevated as compared to the Ti6Al4V-coated and Al-coated specimen. To withstand a larger magnitude of force, coating thickness can be increased. Moreover, the shape of the specimen is another factor. Having a notched area or less diameter, the specimen is more prone to deformation.

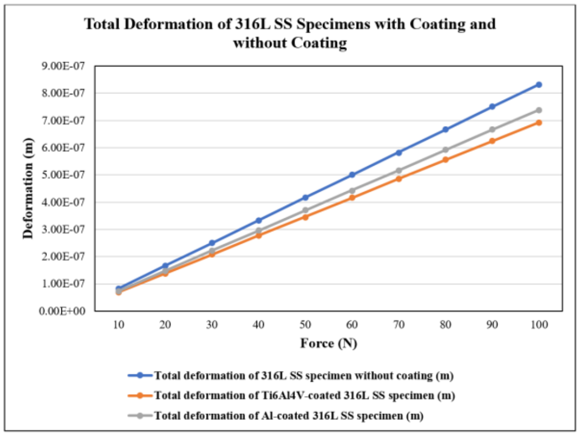



Figure 10: Deformations of coated and uncoated specimens at different force magnitudes

*4.2 Equivalent Strain Results:*

Strain results also show similar trend as that of deformation. Figure 6 shows the strain results of coated and uncoated specimens. Ti6Al4V-coated specimens tends to have less strain as compared to uncoated and Al-coated specimens. Due to more deformation, uncoated specimens have more strain whereas strain of the Al-coated specimens lie in between both. This behavior is also due to the superior tensile behavior of Ti6Al4V alloy as compared to 316L SS and Aluminium alloy. The simulations show that there is more strain on the center notched part because that area has smaller diameter as compared to sides of the specimen. In the context of applied forces, the trend is linear, and a straight line is obtained. Same as like deformation, uncoated specimens' line is more elevated as compared to the Al-coated specimens whereas Ti6Al4V-coated specimens yield lesser strain as compared to both uncoated and Al-coated specimens as shown in Figure 11.

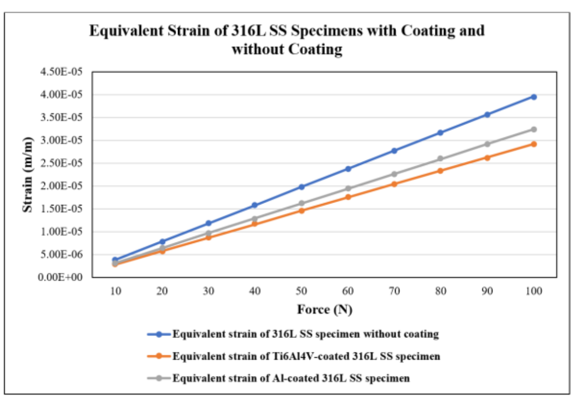



Figure 11: Equivalent strains of coated and uncoated specimens at different force magnitudes

*4.3 von-Mises Stress Results:*

Stress results also displayed a similar behavior to that of deformation and strain results. Specimens without coating have more stress as compared to coated specimens. At a force of 10 N, uncoated specimen has a stress of 0.766 MPa whereas at 100 N, stress value increases to 7.66 MPa. Among coated specimens, Ti6Al4V-coated specimens tend to show lesser stress values as compared to Al-coated specimens. At 100 N force, Ti6Al4V coating shows a stress value of 5.56 MPa which is less than uncoated and Al-coated specimens. Stress behavior of both coated and uncoated specimens is also a straight line like deformation and strain graph. Figure 12 shows the von-Mises stresses plotted against different force magnitudes for all the three specimens i.e. uncoated, Ti6Al4V-coated and Al-coated.

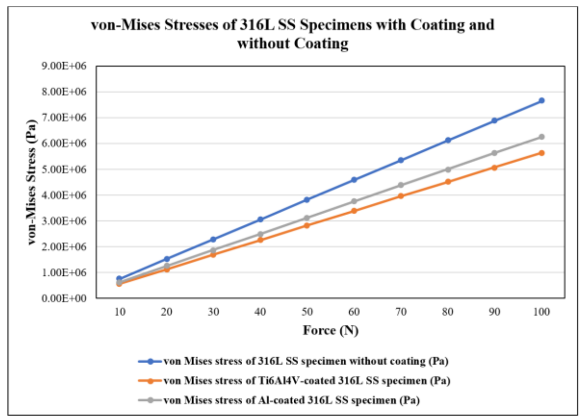



Figure 12: von-Mises stresses of coated and uncoated specimens at different force magnitudes

*4.4 Fatigue Life Results:*

In the ANSYS® Workbench 19.2, the stress-life fatigue measurement method is employed which works on data taken from SN-curve. Cyclic load in the vertical direction is applied which is fully reversed-type. Fatigue life is displayed in terms of the "number of cycles" before failure. Figure 8 shows fatigue life results of specimens at maximum and minimum loads i.e. 10 N and 100 N respectively. It is verified that Ti6Al4V-coating provides more resistance to fatigue failure as compared to Aluminium coating and uncoated 316L SS material. Although both the coatings try to protect the specimen but fatigue life of Ti-based alloy is exceptional. Ti6Al4V-coated specimen withstands loads up to 60 N while exhibiting $10^7$ cycles i.e. infinite life whereas Al-based coating retained this life of $10^7$ cycles till 60 N. On the other hand, uncoated specimen retained this life till 50 N and life became 0 at 80 N. As far as maximum load of this study is concerned, Ti6Al4V-coated specimen shows 277470 cycles, Al-coated specimen shows 51927 cycles and uncoated specimen shows 0 cycles which means that this material can fail without completing a single cycle at 100 N. It clearly shows that fatigue life improves with surface coating and Ti-based alloy coating outperforms Al-coating in terms of fatigue life. Figure 13 shows the graph of fatigue life against applied cyclic loads.

Table III: Tensile Simulation Results and Comparison of Coated and Uncoated Specimens

| Force (N) | Specimens without coating | | | Ti6Al4V-coated specimens | | | Al-coated specimens | | |
|---|---|---|---|---|---|---|---|---|---|
| | Max. Deformation (m) | Max. Strain (m/m) | Max. Stress (Pa) | Max. Deformation (m) | Max. Strain (m/m) | Max. Stress (Pa) | Max. Deformation (m) | Max. Strain (m/m) | Max. Stress (Pa) |
| 10 | 8.33E-08 | 3.97E-06 | 7.66E+05 | 6.94E-08 | 2.93E-06 | 5.65E+05 | 7.39E-08 | 3.25E-06 | 6.26E+05 |
| 20 | 1.67E-07 | 7.93E-06 | 1.53E+06 | 1.39E-07 | 5.85E-06 | 1.13E+06 | 1.48E-07 | 6.49E-06 | 1.25E+06 |
| 30 | 2.50E-07 | 1.19E-05 | 2.30E+06 | 2.08E-07 | 8.78E-06 | 1.69E+06 | 2.22E-07 | 9.74E-06 | 1.88E+06 |
| 40 | 3.33E-07 | 1.59E-05 | 3.06E+06 | 2.77E-07 | 1.17E-05 | 2.26E+06 | 2.96E-07 | 1.30E-05 | 2.51E+06 |
| 50 | 4.17E-07 | 1.98E-05 | 3.83E+06 | 3.47E-07 | 1.46E-05 | 2.82E+06 | 3.70E-07 | 1.62E-05 | 3.13E+06 |
| 60 | 5.00E-07 | 2.38E-05 | 4.59E+06 | 4.16E-07 | 1.76E-05 | 3.39E+06 | 4.44E-07 | 1.95E-05 | 3.76E+06 |
| 70 | 5.83E-07 | 2.78E-05 | 5.36E+06 | 4.86E-07 | 2.05E-05 | 3.95E+06 | 5.17E-07 | 2.27E-05 | 4.38E+06 |
| 80 | 6.67E-07 | 3.17E-05 | 6.12E+06 | 5.55E-07 | 2.34E-05 | 4.52E+06 | 5.91E-07 | 2.60E-05 | 5.01E+06 |
| 90 | 7.50E-07 | 3.57E-05 | 6.89E+06 | 6.24E-07 | 2.63E-05 | 5.08E+06 | 6.65E-07 | 2.92E-05 | 5.64E+06 |
| 100 | 8.33E-07 | 3.97E-05 | 7.66E+06 | 6.94E-07 | 2.93E-05 | 5.65E+06 | 7.39E-07 | 3.25E-05 | 6.26E+06 |

Table IV: Fatigue Simulation Results and Comparison of Coated and Uncoated Specimens

| Force (N) | Specimens without coating | | Ti6Al4V-coated specimens | | Al-coated specimens | |
|---|---|---|---|---|---|---|
| | Min. Fatigue Life (Cycles) | Min. Factor of Safety | Min. Fatigue Life (Cycles) | Min. Factor of Safety | Min. Fatigue Life (Cycles) | Min. Factor of Safety |
| 10 | 1.00E+07 | 3.48 | 1.00E+07 | 6.47 | 1.00E+07 | 5.34 |
| 20 | 1.00E+07 | 1.74 | 1.00E+07 | 3.23 | 1.00E+07 | 2.67 |
| 30 | 1.00E+07 | 1.16 | 1.00E+07 | 2.16 | 1.00E+07 | 1.78 |
| 40 | 5.41E+06 | 0.87 | 1.00E+07 | 1.62 | 1.00E+07 | 1.34 |
| 50 | 5.91E+05 | 0.70 | 1.00E+07 | 1.29 | 1.00E+07 | 1.07 |
| 60 | 7.91E+04 | 0.58 | 1.00E+07 | 1.08 | 6.20E+06 | 0.89 |
| 70 | 2.66E+04 | 0.50 | 7.45E+06 | 0.92 | 9.48E+05 | 0.76 |
| 80 | 0.00E+00 | 0.44 | 2.69E+06 | 0.81 | 4.17E+05 | 0.67 |
| 90 | 0.00E+00 | 0.39 | 7.17E+05 | 0.72 | 8.62E+04 | 0.59 |
| 100 | 0.00E+00 | 0.35 | 2.77E+05 | 0.65 | 5.19E+04 | 0.53 |

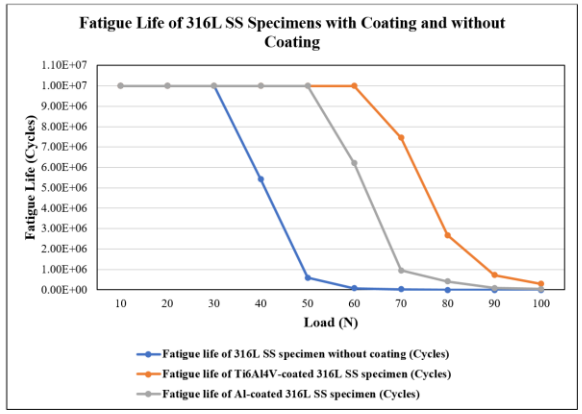



Figure 13: Fatigue lives of coated and uncoated specimens at different cyclic loads

*4.5 Factor of Safety Results:*

The factor of safety is a concept extensively used in the engineering and design field which describes the safety margin in components. It can potentially reduce the risk of failures [47]. For safer systems, the factor of safety must be greater than one. Simulation results indicate that Ti6Al4V-coated specimens have more factor of safety (minimum) as compared to Al-coated and uncoated specimens. These results have complete accordance with fatigue life results. The Ti6Al4V-coated specimen yielded factor of safety greater than one at 10 N, 20 N, 30 N, 40 N, 50 N, and 60 N. In comparison, an Al-coated specimen has a factor of safety greater than one till 50 N load and uncoated specimen has safety factor greater than one till 30 N only. Figure 9 reveals the factor of safety's value for Ti6Al4V coating is greater than both the other coated and uncoated specimens. It can be observed that the centre of coating at the notched area has the minimum factor of safety and is more likely to fail under cyclic loading. At all the load magnitudes, Ti6Al4V coating provides a better safety factor. The factor of safety comparison for both coatings is shown in Figure 14.

*4.6 Comparison of Uncoated, Ti6Al4V-coated and Al-coated substrate:*

This research work integrated the behavior of coated stainless steel with two different types of coatings. The Ti6Al4V-coated specimen showed better performance as compared to the Al-coated specimen under the given conditions. Substrate material showed more stresses, strains, and fatigue failure, but with the support of coatings, those threats were minimized.

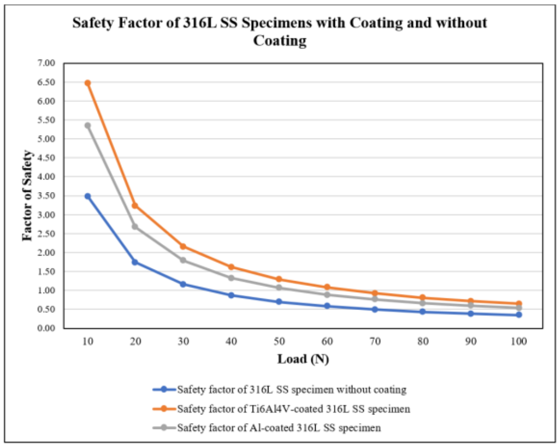



Figure 14: Factor of safety of coated and uncoated specimens at different cyclic loads

Surface coating of Ti6Al4V on stainless steel proved to be very effective in terms of tensile and fatigue behavior when other desirable characteristics like exceptional corrosion resistance and wear resistance are also required. On the other hand, Al-coated steel can also provide benefits of enhanced properties in conjunction with lightweight and corrosion resistance but this enhancement is less than that of Ti6Al4V coating. The simulation results and comparison between both coatings and uncoated material are presented in Table III and Table IV.

## V. CONCLUSION

The computational analysis of the tensile and fatigue behavior of uncoated 316L SS, Ti6Al4V-coated 316L SS and Al-coated 316L SS is presented in this study. Two types of loads i.e. linear and cyclic loads are applied to coated and uncoated steel specimens. Coating materials and magnitude of loads are varied to study the effect of these parameters on the performance of the material. The effect of both coatings is studied under similar conditions. The conclusions drawn from this work are listed below:

- Surface coatings can be effective to enhance the mechanical performance of parts. But the right coating material must be selected which can provide a combination of desired properties. For example, Aluminium coating can reduce the cost, weight, and corrosion but, in terms of mechanical properties, Ti6Al4V coating is better.
- The maximum value of deformation, equivalent strain and von-Mises stress with Ti6Al4V coating are 6.94E-07 m, 2.93E-05 m/m and 5.65E+06 Pa respectively. Whereas, the maximum value of deformation, equivalent strain and von-Mises stress with Aluminium coating are 7.39E-07 m, 3.25E-05 m/m, and 6.26E+06 Pa respectively. Which means Ti6Al4V coating provides better mechanical performance of components along with enhanced wear and corrosion resistance as compared to the general Aluminium coating when subjected to linear and cyclic loads due to enhanced mechanical characteristics.
- The deformation, strain and stress in Al-coated steel specimens are noted to be higher for all force values than that of Ti6Al4V-coated SS alloy whereas uncoated specimens are weaker in terms of deformation and strain than both the coated specimens.
- Ti6Al4V coating provides excellent fatigue life as compared to bare 316L SS as well as Al-coated 316L SS. Due to this, Ti6Al4V-coated steel can withstand larger cyclic loads without failure as crack propagation is slow on Ti6Al4V alloy.
- Uncoated 316L SS alloy can have lower fatigue life as compared to Ti6Al4V-coated steel.
- Ti6Al4V-coated 316L SS has more factor of safety as compared to Al-coated steel and bare steel due to which it is less susceptible to failure.

## REFERENCES

[1] Darvell, B.W., *Chapter 12 - Metals II : Constitution*, in *Materials Science for Dentistry (Tenth Edition)*, B.W. Darvell, Editor. 2018, Woodhead Publishing. p. 363-381.

[2] Choudhury, N.R., A.G. Kannan, and N. Dutta, *Chapter 21 - Novel nanocomposites and hybrids for high-temperature lubricating coating applications*, in *Tribology of Polymeric Nanocomposites (Second Edition)*, K. Friedrich and A.K. Schlarb, Editors. 2013, Butterworth-Heinemann: Oxford. p. 717-778.

[3] Bhushan, B. and B.K. Gupta, *Handbook of tribology: materials, coatings, and surface treatments.* 1991.

[4] Swamy, R.N. and S. Tanikawa, *An external surface coating to protect concrete and steel from aggressive environments.* Materials and Structures, 1993. 26(8): p. 465-478.

[5] Fotovvati, B., N. Namdari, and A. Dehghanghadikolaei *On Coating Techniques for Surface Protection: A Review*. Journal of Manufacturing and Materials Processing, 2019. 3, DOI: 10.3390/jmmp3010028.

[6] de Damborenea, J., C. Navas, J.A. García, M.A. Arenas, and A. Conde, *Corrosion–erosion of TiN-PVD coatings in collagen and cellulose meat casing*. Surface and Coatings Technology, 2007. 201(12): p. 5751-5757.

[7] Prengel, H.G., W.R. Pfouts, and A.T. Santhanam, *State of the art in hard coatings for*

*carbide cutting tools.* Surface and Coatings Technology, 1998. 102(3): p. 183-190.

[8] Nie, X., A. Leyland, and A. Matthews, *Deposition of layered bioceramic hydroxyapatite/TiO2 coatings on titanium alloys using a hybrid technique of micro-arc oxidation and electrophoresis.* Surface and Coatings Technology, 2000. 125(1): p. 407-414.

[9] Bahgat Radwan, A., K. Ali, R.A. Shakoor, H. Mohammed, T. Alsalama, R. Kahraman, M.M. Yusuf, A.M. Abdullah, M. Fatima Montemor, and M. Helal, *Properties enhancement of Ni-P electrodeposited coatings by the incorporation of nanoscale Y2O3 particles.* Applied Surface Science, 2018. 457: p. 956-967.

[10] Kramer, M.S., L.E. Byrnes, and G.L. Holmes, *Method and apparatus for application of thermal spray coatings to engine blocks*. 1993, Google Patents.

[11] Wang, X., L. Zhao, J.Y.H. Fuh, and H.P. Lee, *Experimental characterization and micromechanical-statistical modeling of 316L stainless steel processed by selective laser melting.* Computational Materials Science, 2020. 177: p. 109595.

[12] Segura, I.A., J. Mireles, D. Bermudez, C.A. Terrazas, L.E. Murr, K. Li, V.S.Y. Injeti, R.D.K. Misra, and R.B. Wicker, *Characterization and mechanical properties of cladded stainless steel 316L with nuclear applications fabricated using electron beam melting.* Journal of Nuclear Materials, 2018. 507: p. 164-176.

[13] Vukkum, V.B. and R.K. Gupta, *Review on corrosion performance of laser powder-bed fusion printed 316L stainless steel: Effect of processing parameters, manufacturing defects, post-processing, feedstock, and microstructure.* Materials & Design, 2022. 221: p. 110874.

[14] Benafia, S., D. Retraint, S. Yapi Brou, B. Panicaud, and J.L. Grosseau Poussard, *Influence of Surface Mechanical Attrition Treatment on the oxidation behaviour of 316L stainless steel.* Corrosion Science, 2018. 136: p. 188-200.

[15] Lodhi, M.J.K., K.M. Deen, M.C. Greenlee-Wacker, and W. Haider, *Additively manufactured 316L stainless steel with improved corrosion resistance and biological response for biomedical applications.* Additive Manufacturing, 2019. 27: p. 8-19.

[16] Sankara Narayanan, T.S.N., J. Kim, and H.W. Park, *High performance corrosion and wear resistant Ti-6Al-4V alloy by the hybrid treatment method.* Applied Surface Science, 2020. 504: p. 144388.

[17] Zhang, J., X. Li, D. Xu, and R. Yang, *Recent progress in the simulation of microstructure evolution in titanium alloys.* Progress in Natural Science: Materials International, 2019. 29(3): p. 295-304.

[18] Mironov, S., Y.S. Sato, and H. Kokawa, *Friction-stir welding and processing of Ti-6Al-4V titanium alloy: A review.* Journal of Materials Science & Technology, 2018. 34(1): p. 58-72.

[19] Dursun, T. and C. Soutis, *Recent developments in advanced aircraft aluminium alloys.* Materials & Design (1980-2015), 2014. 56: p. 862-871.

[20] Gándara, M.F., *Aluminium: the metal of choice.* Mater. Tehnol, 2013. 47(3): p. 261-265.

[21] Sharifnabi, A., M.H. Fathi, B. Eftekhari Yekta, and M. Hossainalipour, *The structural and bio-corrosion barrier performance of Mg-substituted fluorapatite coating on 316L stainless steel human body implant.* Applied Surface Science, 2014. 288: p. 331-340.

[22] Shabani-Nooshabadi, M., S.M. Ghoreishi, Y. Jafari, and N. Kashanizadeh, *Electrodeposition of polyaniline-montmorrilonite nanocomposite coatings on 316L stainless steel for corrosion prevention.* Journal of Polymer Research, 2014. 21(4): p. 416.

[23] Chen, Y., S. Wang, Y. Hao, J. Pu, X. Jiang, L.-F. Huang, and L. Wang, *Friction and Wear Behavior of CrN Coating on 316L Stainless Steel in Liquid Sodium at Elevated Temperature.* Tribology International, 2020. 143: p. 106079.

[24] Zhang, H., G. Lin, M. Hou, L. Hu, Z. Han, Y. Fu, Z. Shao, and B. Yi, *CrN/Cr multilayer coating on 316L stainless steel as bipolar plates for proton exchange membrane fuel cells.* Journal of Power Sources, 2012. 198: p. 176-181.

[25] K, P.P., D. N, K. Manikantan Syamala, and R. N, *Antibacterial effects, biocompatibility and electrochemical behavior of zinc incorporated niobium oxide coating on 316L SS for biomedical applications.* Applied Surface Science, 2018. 427: p. 1166-1181.

[26] Sridhar, T.M., U. Kamachi Mudali, and M. Subbaiyan, *Sintering atmosphere and temperature effects on hydroxyapatite coated type 316L stainless steel.* Corrosion Science, 2003. 45(10): p. 2337-2359.

[27] Zaffora, A., F. Di Franco, B. Megna, and M. Santamaria, *One-Step Electrodeposition of*

*Superhydrophobic Coating on 316L Stainless Steel.* Metals, 2021. 11(11): p. 1867.

[28] Qian, S., Y. Dai, Y. Guo, and Y. Zhang, *Microstructure and Wear Resistance of Multi-Layer Ni-Based Alloy Cladding Coating on 316L SS under Different Laser Power.* Materials, 2021. 14(4): p. 781.

[29] Santecchia, E., A.M.S. Hamouda, F. Musharavati, E. Zalnezhad, M. Cabibbo, and S. Spigarelli, *Wear resistance investigation of titanium nitride-based coatings.* Ceramics International, 2015. 41(9, Part A): p. 10349-10379.

[30] Naghibi, S.A., K. Raeissi, and M.H. Fathi, *Corrosion and tribocorrosion behavior of Ti/TiN PVD coating on 316L stainless steel substrate in Ringer's solution.* Materials Chemistry and Physics, 2014. 148(3): p. 614-623.

[31] Jin, J., J. Zhang, M. Hu, and X. Li, *Investigation of high potential corrosion protection with titanium carbonitride coating on 316L stainless steel bipolar plates.* Corrosion Science, 2021. 191: p. 109757.

[32] Saravanan, I., A. Elaya Perumal, S.C. Vettivel, N. Selvakumar, and A. Baradeswaran, *Optimizing wear behavior of TiN coated SS 316L against Ti alloy using Response Surface Methodology.* Materials & Design, 2015. 67: p. 469-482.

[33] Yazıcı, M., H. Kovacı, A.F. Yetim, and A. Çelik, *Structural, mechanical and tribological properties of Ti and TiN coatings on 316L stainless steel.* Ceramics International, 2018. 44(12): p. 14195-14201.

[34] Liu, C., G. Lin, D. Yang, and M. Qi, *In vitro corrosion behavior of multilayered Ti/TiN coating on biomedical AISI 316L stainless steel.* Surface and Coatings Technology, 2006. 200(12): p. 4011-4016.

[35] Pugal Mani, S., M. Kalaiarasan, K. Ravichandran, N. Rajendran, and Y. Meng, *Corrosion resistant and conductive TiN/TiAlN multilayer coating on 316L SS: a promising metallic bipolar plate for proton exchange membrane fuel cell.* Journal of Materials Science, 2021. 56(17): p. 10575-10596.

[36] Balamurugan, A., S. Kannan, and S. Rajeswari, *Evaluation of $TiO_2$ coatings obtained using the sol–gel technique on surgical grade type 316L stainless steel in simulated body fluid.* Materials Letters, 2005. 59(24): p. 3138-3143.

[37] Shukla, R. and K.G. Prashanth, *Ti6Al4V Coating on 316L Substrate by Laser-based Fusion Process.* Transactions of the Indian Institute of Metals, 2023. 76(2): p. 435-445.

[38] Bahadur, A., *Aluminum Coatings for Steel.* Materials and Manufacturing Processes, 1996. 11(2): p. 225-232.

[39] Smith, W.J. and F.E. Goodwin, *Hot Dip Coatings*, in *Reference Module in Materials Science and Materials Engineering*. 2017, Elsevier.

[40] Suehiro, M., J. Maki, K. Kusumi, M. Ohgami, and T. Miyakoshi, *Properties of aluminum coated steels for hot-forming.* Shinnittetsu Giho, 2003: p. 15-20.

[41] Silva Campos, M.d.R., C. Blawert, N. Scharnagl, M. Störmer, and M.L. Zheludkevich, *Cathodic protection of mild steel using aluminium-based alloys.* Materials, 2022. 15(4): p. 1301.

[42] Mukhtar, S., M. Kamran, and M.U. Manzoor, *studying the effect of aluminium coating on stainless steel 316l and alpha iron.* Journal of faculty of engineering & technology, 2016. 23(2): p. 09-17.

[43] Masood Arif Bukhari, S., N. Husnain, F. Arsalan Siddiqui, M. Tuoqeer Anwar, A. Abbas Khosa, M. Imran, T. Hassan Qureshi, and R. Ahmad, *Effect of laser surface remelting on Microstructure, mechanical properties and tribological properties of metals and alloys: A review.* Optics & Laser Technology, 2023. 165: p. 109588.

[44] Janeček, M., F. Nový, P. Harcuba, J. Stráský, L. Trško, M. Mhaede, and L. Wagner, *The very high cycle fatigue behaviour of Ti-6Al-4V alloy.* Acta Physica Polonica A, 2015. 128(4): p. 497-502.

[45] Khairul, M., S. Sapuan, F.M. AL-Oqla, E. Zainudin, and M. Rababah, *Continuum damage analysis, experimental and simulation for investigating the fatigue life performance of 316L steel at high temperatures.* International Journal of Materials and Structural Integrity, 2017. 11(4): p. 175-192.

[46] Husnain, N., F.A. Siddiqui, R. Ahmad, S.M.A. Bukhari, I. Nasir, M.F. Shafi, and M.A. Hanif, *Experimental and Computational study of the most Influential Parameters of a Lab-Scale Forced Draft Cooling Tower by considering different number of Packing Ribs.* Technical Journal, 2022. 27(04): p. 20-27.

[47] Matthews, C., *15 - The 'Schloss Adler' railway – design safety*, in *Case Studies in Engineering Design*, C. Matthews, Editor. 1998, Butterworth-Heinemann: London. p. 157-175.