# Micromechanism and Failure Analysis of INCONEL601

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## Abstract

This paper presents an investigation of engineering failure modes for INCONEL601 tested after exposure to annealed heat-treatment (1.5 hour duration) and as received prior to annealing. Microstructural and failure surfaces were tested for chemical composition and examined by metallographic techniques and fatigue fractography. Scanning electron microscopy and enginery dispersive spectroscopy (SEM-EDS) revealed the presence of voids, dimples, and striations associated with fatigue crack propagation. The microstructural characterization of annealed INCONEL601 is notable for triangular voids that congregate along grain boundaries in contrast to the as received INCONEL601. In addition, the tensile and fatigue strengths of as-received samples were greater than annealed heat-treated INCONEL601.

## Keywords
INCONEL601, Fatigue fracture, Striation, Tensile fracture.

## 1. Introduction

Super alloys are widely used in the gas turbine industry where components are subjected to the combined effects of mechanical and thermal stresses, high temperatures, and corrosive environments. The output and efficiency of the turbine system increases as the hot gas temperature increases at the turbine inlet. As a result, advanced materials have been developed to better resist high stresses and corrosion effects at higher temperatures.

INCONEL alloy is one of a series of superalloys that use alloying elements such as aluminum, titanium, chromium, and nickel to develop enhanced properties. These alloying elements form passive films that increase resistance to corrosion in aggressive environments (Sahn et al. 1974). The combination of high strength and oxidation resistance at high temperatures of INCONEL in corrosive environments has led to a variety of applications. The physical and mechanical properties of INCONEL alloys, including failure and fracture analysis under static and dynamic loading have been extensively researched (Akio et al. 1988), (Gonzalez et al.1998), (Lin et al. 1977), and (Vankanhtesh et al.1998). (Norio et al. 1977) reported on microstructural observations that revealed high dislocation density interaction within the grain structure that resulted in strain hardening and improved strength as well as influencing fracture surface and crack initiation of INCONEL alloys. It was found that cracks were preferably initiated within or adjacent to grain boundaries and grew by crossing grains and propagating through the grain structure. In another study, the fatigue lifetime, crack initiation and propagation during dynamic loading of INCONEL was found to be primarily controlled by the growth of cracks smaller than 1 mm in length (Gary et al. 1977).

Microscopic investigations of INCONEL alloys indicated that the presence of gamma and gamma prime depends is product of the addition of INCONEL alloys (Pandy et al. 1996). The presence of gamma and gamma prime varied with heat treatment and, in consequence, the alloy properties. A study (Whittenberger et al. 1994) on INCONEL617 evaluated the mechanical properties under static tensile loading while fracture surface characteristics and crack growth of heat treated INCONEL617 were examined in (Shang et al. 1993). In other research, careful observation found that during high temperature fatigue, the effects of dynamic recovery tended to become increasingly evident. This was considered to be due to high dislocation density and thus high dislocation motion at higher fatigue cycles (Swaminathan et al. 1992).

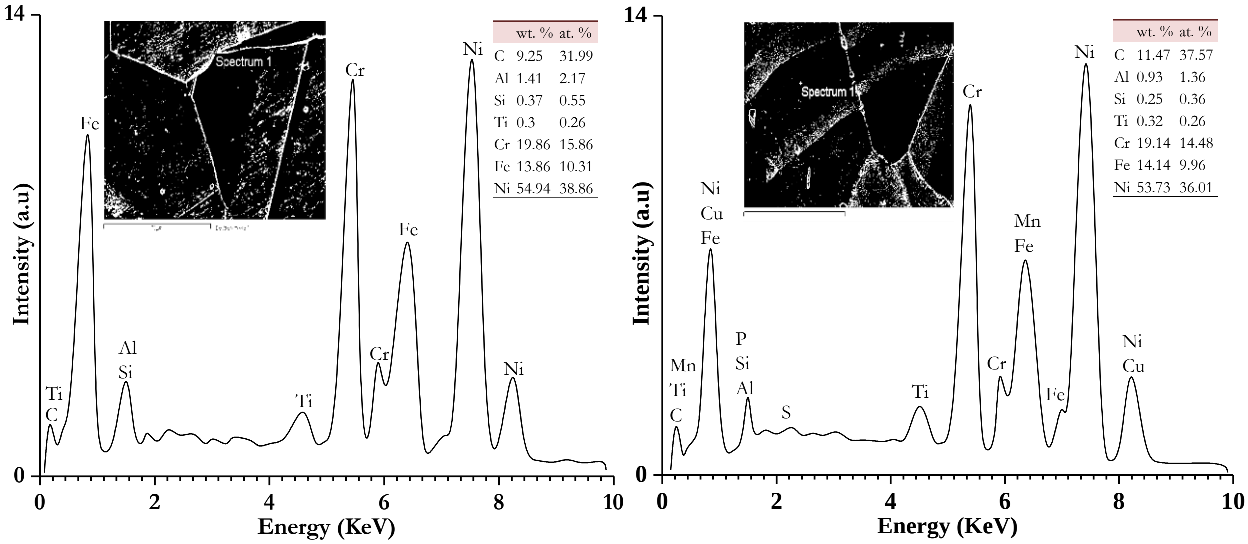
This current paper is a brief account of the author's work on tensile and fatigue tests on as received and annealed heat-treated INCONEL601 is using an universal testing machine and microstructural characterization using scanning electron microscopy and the energy dispersive spectroscopy (SEM-EDS).

## 2. Material and Experimental Procedure

INCONEL601 was supplied from INCO West Virginia with a chemical composition in weight percent as shown in Table 1. The alloy test samples were machined and prepared with a dimension of gauge length 25 mm and gauge diameter of 5 mm. Scanning electron microscope, X-ray analysis and morphological characterizations were carried out on as received (Fig. 1a) and annealed (Fig. 1b) INCONEL601alloy as shown in Fig. 1a and Fig. 1b respectively.

Table 1. Chemical composition of INCONEL601 in wt. %

| Cr | Fe | Al | Ti | C | Si | Mn | Ni |
|---|---|---|---|---|---|---|---|
| 22.14 | 16.09 | 1.59 | 0.36 | 0.3 | 0.27 | 0.21 | Bal. |




a) b)

Figure 1. SEM-EDS analysis of INCONEL601: a) as received alloy shows a uniform texture, no cavities and voids within grain boundaries. EDS spectrum shows Ni, Cr, and Fe peak elements, b) annealed alloy shows non- uniform precipitates and voids within grain boundaries. EDS spectrum show Ni, Cr, Fe and Cu peak elements

## 3. Experimental Results and Brief Discussion

Cross sections of as received and annealed heat-treated INCONEL601 as shown in Fig. 2a and Fig.2b. For as received samples voids were not observed along grain boundaries. Rather, continuous precipitation was found along the grain boundaries as shown in Fig. 2a. By contrast, the annealed sample (Fig. 2b) shows voids of triangular shape within grain boundaries as clearly seen in Fig. 2b. The enrichment of carbon and iron reduces the amount of aluminum, chromium, and nickel alloying elements especially along voids as indicated by X-ray analysis of as received and heat-treated alloy samples (Fig. 1a and Fig. 1b, respectively).

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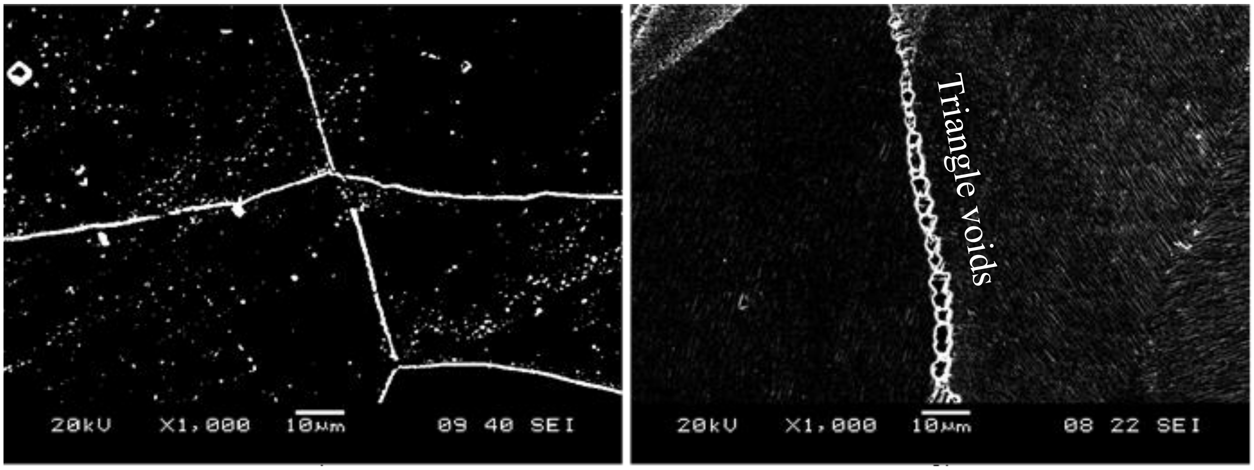


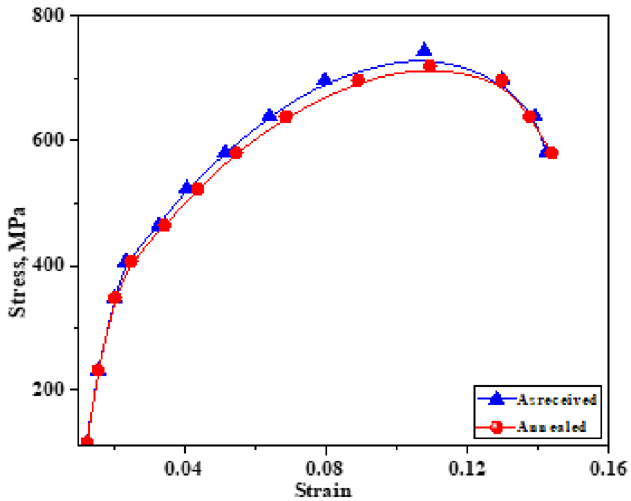

a) b)

Figure 2. SEM microstructure of INCONEL601: a) as received no triangular voids in grain boundaries, and b) annealed alloy shows triangular-shaped voids in grain boundaries

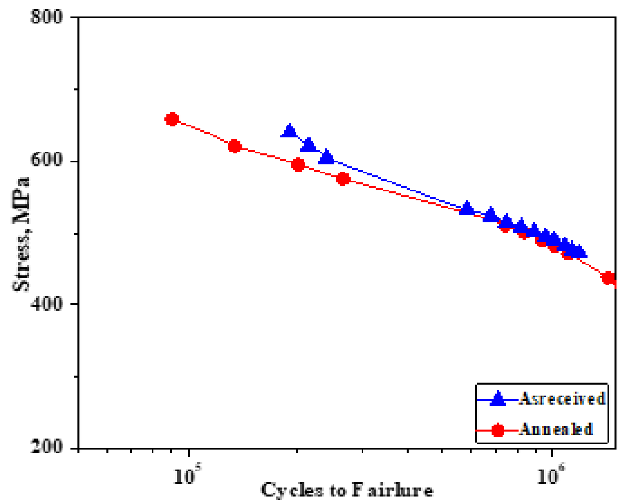
The tensile and fatigue response of INCONEL601 for as received and annealed samples shows a strength increase of as received alloy greater than that of annealed alloy (Figs. 3a and 3b) respectively. It was also noted that the strain (total axial strain at failure) of as received and annealed alloys were slightly different.

Stress-strain (SS) curves of as received and annealed INCONEL601 (Fig. 3a) indicate that the tensile strength of as received alloy is higher than that of annealed alloy. In Figure 3b the maximum stress vs. cycles to failure (S-N) curves show a higher fatigue strength of as-received than for annealed alloy with a value of 495 and 475MPa respectively. The yield and fracture strengths of as received and annealed heat treatment alloys show similar values of 370MPa, whereas the ultimate tensile strength of as received is slightly greater than that of annealed alloy 785 and 775MPa respectively as shown in (Fig. 3a).

The annealed INCONEL601 has similar grain boundary microstructures that exhibit triangular cavities within the grain boundaries, though the tensile and fatigue properties of annealed alloy were not considerably different than those of the as received alloy (Fig. 4). This characteristic may be due to the grain boundaries being filled by large carbides. Consequently, these mechanical properties are little altered as between the as-received and annealed heat-treatment alloys. Grain boundary micro cracks account for the observed increase in effective stress and earlier fatigue failure. In addition, crack propagation is more enhanced especially along coarser grain structures. However, grain boundaries on the external surface of the sample impede further crack growth propagation. Therefore, cessation of propagation occurs when cracks approach a grain boundary. It is expected that crack propagation from the surface into the body of the sample might stop at an early stage in a small-grained alloy. However, the heat treatment of the INCONEL601 samples produced only scattered small grains. Consequently, the cyclic loading response of the annealed alloy produced no significant effects on grain size morphology.



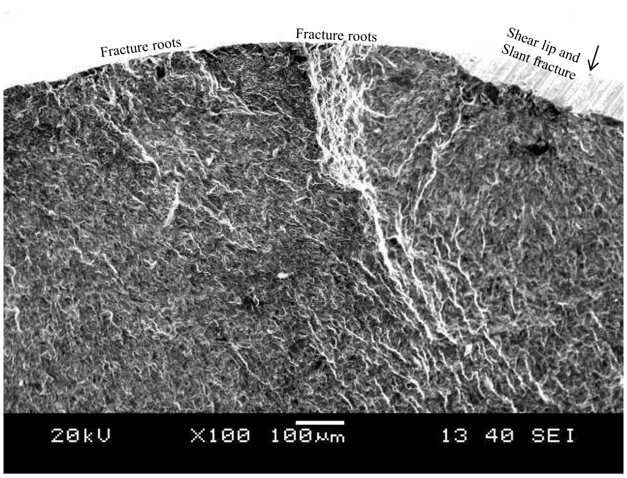

a)



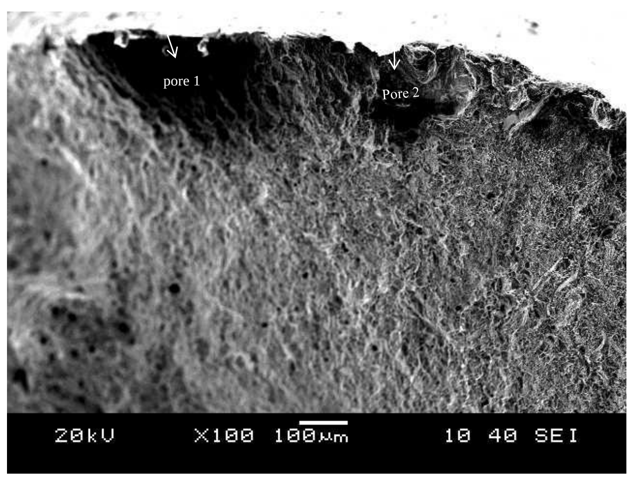

b)

Figure 3. a) Stress strain curves, and b) stress–number of cycle to failure curves of INCONEL601 alloy

Fracture surface initiated at localize surface discontinuities maybe resulted due to manufacture process (e.g. porosities, inclusion) or surface design (e.g. grinding, scratches, pits). Figure 4 show surface crack initiation sites in form of shear lip or slant fracture and pores as shown in Fig. 4a and Fig. 4b respectively.



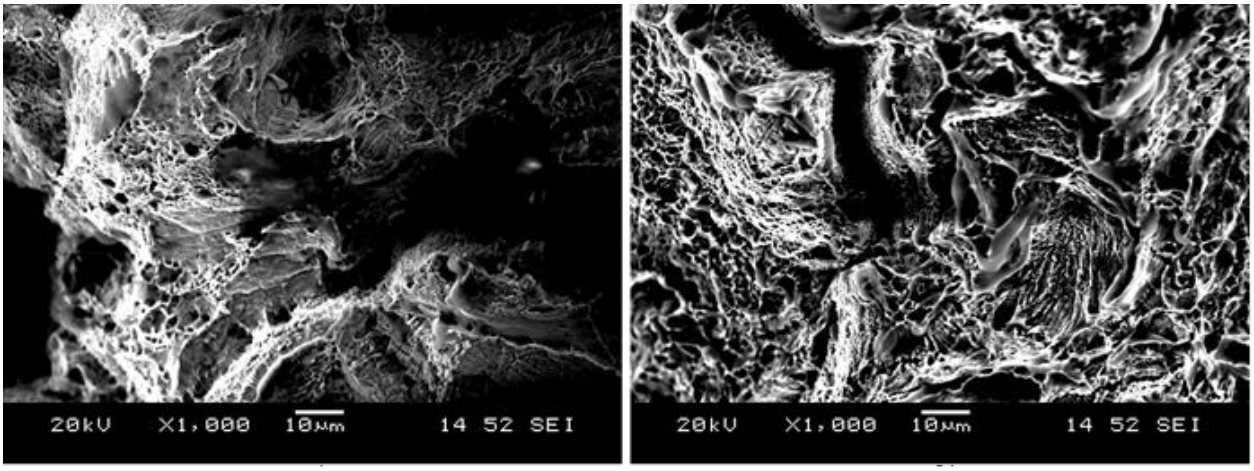

a)




b)

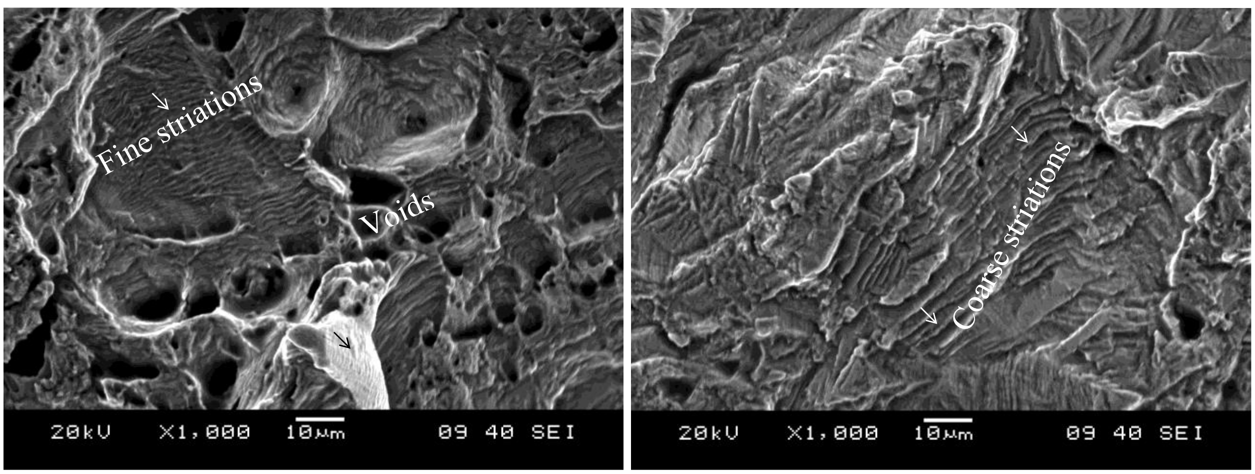
Figure 4. End view of surface crack initiation and propagation of INCONEL601. a) slant tensile fracture surface, and b) surface pore as fatigue fracture origin. Crack propagation direction from top to bottom

Figure 5 show tensile fracture surface facets for received and annealed alloy. There was no evidence of striations which are associated with fracturing of alloys due to fatigue loading.




a) b)

Figure 5. Tensile fracture surfaces of INCONEL601. a) As received, and b) annealed alloy. No evidence of striations




a) b)

Figure 6. Fatigue fracture of INCONEL601 fine and coarse striations bands. a) as received, and b) annealed alloy

The existence of the dimples in many areas of grain boundary facets indicates the development of increased ductility. The preferred crack initiation process is by initiation at grain boundaries and propagation along grain boundaries until final fracture. The dimple shapes and their varied sizes are evident as shown in Fig. 5b. Moreover, the larger dimples are probably formed at carbides particles and presumably initiated by a large inclusion (Fig.4). As seen in Fig. 6, fracture occurs by a process of micro-void coalescence. Some features on the fracture surface resemble cleavage facets. A series of beach marks and striations can be observed as shown in Fig. 6. Secondary cracks are visible along set of striation bands (Fig. 6b). The development of many voids leads to rupture of dimples (Fig. 7).

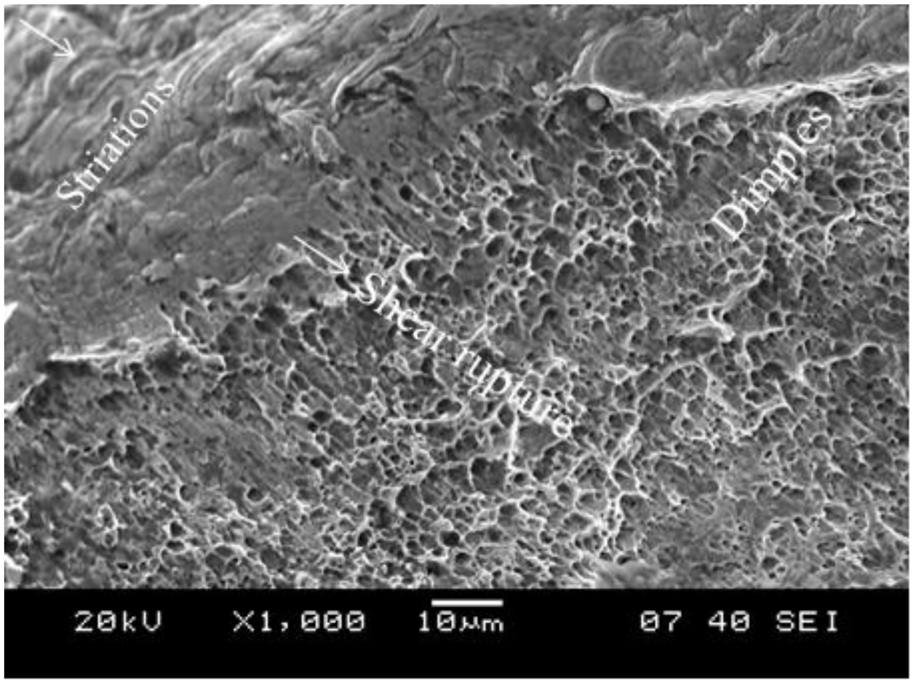



Figure 7. Transition between ductile intergranular fatigue striation and dimples rupture. From upper left to bottom right

Mechanical testing of the alloy is performed in both SSC curves (Fig. 3a) and S-N curves (Fig. 3b). The effects of annealing heat treatment have been examined against the characteristics of as received INCONEL601 alloy. Annealed heat treatment produced little effect on the tensile strength and fatigue strength relative to as received INCONEL601 alloy. Slight changes were found between as received and annealed heat treated INCONEL601 alloy fracture surfaces produced from tensile and fatigue testing. However, striation features observed due to cyclic loading (Fig. 6) is the main distinction from tensile fracture surfaces (Fig. 5). The fracture appearance is typical of ductile failure with no evidence of cleavage fracture. It was therefore concluded that tensile and fatigue strength was higher for as received than for annealed INCONEL601 alloy. Moreover, the cracks originating along grain boundaries are the primary cause for increasing rate of cyclic fracture, with the existence of dimples on the fracture surfaces indicating the occurrence of fast dimple rupture (Fig. 7). It may be observed from the tensile test results that fracture surface of the INCONEL601 alloy sample become ductile for the annealed INCONEL601 alloy as shown in Fig. 5a and Fig. 5b, respectively. The ductility may be associated with reduction of the effective stress. The tensile fracture surfaces show grain boundary facets and dimples, which are both evidence of softening and ductility. Rupture dimples and voids produced while the fatigue fracture occurred as shown in Fig. 7. A variety of sizes of dimples was found on the facets and at arrays of regular striations at the transgranular facets. Moreover, secondary cracking occurred at the roots of striations.

## 4. Conclusions

Tensile and fatigue strength were measured in different heat treatment as received and annealed of INCONEL601 alloy result showed a slight reduction in tensile and fatigue strength. Changes in heat treatment altered the alloy microstructure especially the grain boundaries morphologies through the development of voids triangular geometry that led to reduced strength both tensile and fatigue life.
Stress-strain curves exhibited an initial regime of linear elastic behavior for both as received and annealed INCONEL601 alloys with yield strength approximately 370MPa followed by plastic deformation. The plastic region exhibited differences in behavior. The as received INCONEL601 alloy revealed higher strength than annealed INCONEL601 alloy with a value of 785 and 775MPa respectively.
S-N curves exhibited fatigue strength behavior of as received greater than annealed INCONEL601 alloy of approximately 495 and 475MPa, respectively.

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## Biographies

**Aezeden Mohamed** has a B.Sc., M.Sc., and PhD degrees in Mechanical and Manufacturing at the University of Manitoba, Canada. His areas of research are experimental in nature includes but not limited; mechanical properties, materials characterizations, corrosion and corrosion control, and biomedical engineering. He has carried out research and taught at the University of Manitoba and Memorial University in Canada. In addition to his technical research interests, he earned diploma in Higher Education Teaching from University of Manitoba, Canada. He has published over 10 papers in Canadian Engineering Education Association. Currently, he is a Senior Lecturer at the University of Technology, Papua New Guinea.

**John Yuahan Pumwa,** is a Professor of Mechanical Engineering and the Acting Dean of Engineering at the PNG University of Technology. Professor Pumwa's research interests are in the areas of Tribology (friction, wear and lubrication), engineering materials, friction and wear, energy, biodiesel and renewable energy, modeling and simulation and engineering education. Prior to joining the faculty at Mechanical Engineering, PNG University of Technology, he was a member of the production engineering team at New Britain Palm Oil Limited. He joined the company immediately after graduating from the PNG University of Technology.

Professor Pumwa graduated *from the PNG University of Technology* with her BEng., degree in Mechanical Engineering. He also graduated from the University of Wollongong, N.S.W., Australia with a MEng (Hons) in Mechanical Engineering. He also graduated from Texas A&M University with a Ph.D. degree in Interdisciplinary engineering. He is a Fellow of the American Society of Mechanical Engineers (FASME) and a Fellow of the Institution Engineers, PNG (FIEPNG) and a member and Chartered Engineer of the Institution of Mechanical Engineers (MIMechE), UK. Professor Pumwa completed his postdoctoral research at Korea Advanced Institute of Science and

Technology (KAIST) with Professor Nam Soo Woo. Professor Pumwa was also attached at Baylor University, Engineering Department as a research Professor conducting research in biodiesel production and testing using coconut oil with supervision of Professor Walter Bradley in Waco, Texas.

Professor Pumwa has taught a number of courses in mechanical engineering; statics, dynamics, mechanics, engineering materials, ethics, failure analysis, vibration and design of experiments. He has served as a Acting Vice Chancellor for almost a year while waiting for the Vice Chancellor to arrive on campus. He has served on a number of university committees (admissions, staffing and appeals) and also board member of PNG Ports for a number of years. He is currently teaching failure analysis to final year students and engineering ethics to third year mechanical engineering students.

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