1-1-2011

Compatibility Of Metallic & Non-Metallic Turbine Engine Materials With Aviation Fuels

Olcay Met
Ryerson University

COMPATIBILITY OF METALLIC & NON-METALLIC TURBINE ENGINE MATERIALS WITH AVIATION FUELS

by

Olcay Met, Bachelor of Science,

Gaziantep, Turkey, 2007

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the Program of

Aerospace Engineering

Toronto, Ontario, Canada, 2011

Author's Declaration

I hereby declare that I am the sole author of this thesis or dissertation.

I authorize Ryerson University to lend this thesis or dissertation to other institutions or individuals for the purpose of scholarly research.

* Signature

I further authorize Ryerson University to reproduce this thesis or dissertation by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

* Signature

COMPATIBILITY OF METALLIC & NON-METALLIC TURBINE ENGINE MATERIALS WITH AVIATION FUELS

Master of Applied Science, 2011

Olcay Met, Aerospace Engineering

Ryerson University

Abstract

As known alternative fuels shall undergo two crucial regulations in order to be certified: emission gas rate and the compatibility with engine parts. The objective of this research is to assess the compatibility of engine materials with JetA. The methodology here is in accordance with ASTM D4054; the proposed materials are soaked in proposed fuel. Subsequent to the soak period specimens are subject to specific test standards such as ASTM and visual inspection. Through assessment of compatibility the actual objective is to establish a systematic methodology for future alternative fuel research studies. In another meaning it is aimed to develop in-house capability to create optimum medium for future alternative fuel studies at Ryerson University's Facility for Research on Aerospace Materials and Engineered Structure. Results demonstrate that being wetted at elevated temperatures played a significant role on the physical properties of most non-metallic materials and there is almost no surface deformation observed on metallic materials.

Acknowledgements

I would like to take this opportunity to express my deepest gratitude and special thanks to my supervisors, Dr. Fawaz and Dr. Behdinan, for all their guidance, tremendous support and encouragement throughout my research.

Furthermore, I would like to thank the Aerospace Engineering Department at Ryerson University for their financial support during my attendance, and letting me to be a part of their community.

I am indebted to Dr. Ghaemi for his support, comments, and patience during this work and would like to thank him for his help throughout my research.

Last but not least, I like to dedicate this work to my family. They have supported me and have been a constant source of encouragement. They have given me strength and have empowered me at a time that I had no strength to go on.

This work was funded by International Science and Technology Partnerships Program (ISTPP), and Pratt and Whitney Canada (P&WC), through collaboration with Ryerson University.

Table of Contents

List of Tables

List of Figures

Chapter 1 Statement of the Research and Objectives

1.1 Introduction

As the economical demands grow and environmental restrictions become more stringent, the automobile and aviation industries feel the pressure to develop new alternative fuels. Even though the aviation section is responsible for 2 % of the total amount of emission gases, the industry still is required to undergo the regulations by such environmental safety committees.

The investigation of new alternative fuels mainly covers emission gas rate and material compatibility. Since both categories are prominent, the latter one is the chief concern in this thesis. Aircraft turbine engines are formed of both metallic and non-metallic materials, and those components are continuously in contact with the fuel. Since this contact may cause serious contamination, and degradation of material properties, a detailed examination shall be conducted over the compatibility of materials with proposed fuels. Any adverse effect on materials by the fuel may cause safety issues. Another main goal being sought in this research is to enhance the in-house capability of Ryerson University for any possible future alternative fuel studies.

There are many material compatibility studies that shows similar process of assessment, however there are differences in soaking process in terms of soak period and temperature, depending on where the parts are used, and evaluation of change of physical properties. In this thesis, the methodology of examination is in accordance with ASTM D4054.

Four main steps of achieving the goals are:

- Develop the methodology for soak process and conducting after-soak tests which are outlined in ASTM D4054.
- Implement the stage of material immersion.
- Evaluate, based on ASTM test procedures and guidelines, whether the contact with fuel has any impact on materials` physical properties.
- Verify any change on materials` nature and whether those changes are within allowable limits.
- Most importantly, by conducting this research, develop inhouse capability of Ryerson's Facility for Research on Aerospace Materials and Engineered Structures (FRAMES) for prospective alternative fuel studies through purchasing any kinds of equipments required by ASTM standards.

The common method throughout the research program conducted so far is that all test materials are being soaked in a candidate fuel for some period.

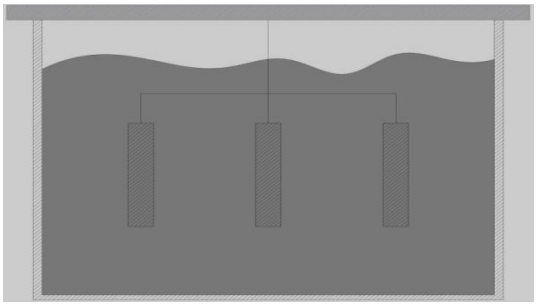


Figure 1.1 The Soaking Scheme

The soaking procedure shall not violate the following restrictions:

- Test materials are to be incubated completely
- The holders for test materials must not contaminate the test fuel(s).

1.2 Overview

Chapter 2 will present the literature review on compatibility studies of materials with alternative fuels. It will discuss the general mechanical properties of metallic and non-metallic materials, and will describe the change of their physical properties depending on time and temperature in contact with fuels.

Chapter 3 will outline the fundamentals of compatibility study, the materials to be tested, and the types of ASTM standards to be applied. The main focus of this chapter will be to explain the motivation and scope of this project, and will describe the experimental set-up and the test methodology.

Chapter 4 will focus on the description of materials in details and the preparation of materials procured in raw form. It will also focus on the equipments needed for the soaking period such as ovens and jars.

Chapter 5 will show results of the experimental work in this thesis and will propose recommendation regarding utilization of the materials in turbine engines.

Chapter 6 will draw conclusions based on the results of the experimental investigations that were discussed in Chapter 5. This chapter will also present the future work.

Chapter 2 Literature Review

2.1 Introduction

Environmental and economical demands require aircraft turbine engine manufacturers to evaluate a variety of alternative fuels. Environmental issues are put forward by international organizations, agreements (e.g., Kyoto Agreement), which involves all industrialized countries. Their primary objective is to restrict emission gases dissipation to a certain amount. Second demand, which is economical, is being brought up by military institutions and travel agencies through aircraft manufacturers. Therefore, turbine engine and car manufacturers, being the core of solution, have been conducting various researches on new fuel technologies.

Besides obtaining optimum emission rate by using alternative fuel, there is another prominent issue which is the compatibility of engine parts with newly-developed fuel. The reviewed documents are generally in favour of compatibility evaluation of various metallic and non-metallic materials. Since the compatibility issue is crucial to both aerospace and automobile industries that exhibit very similar methodology, reviewed literature covers both areas. In either means, parts, to be used in an engine, are incubated in designated fuels and subsequently subjected to some standardized tests including; visual inspection, tensile test, volume swell, hardness measurements, etc.

The need of reviewing previously done research studies is based on several reasons: the use of similar test fuels, materials, methodology. Even though the soaking period and temperatures are usually different, the review of literature will provide a good understanding of materials'

behaviour when exposed to various test fuels. Moreover, it provides a better insight into the compatibility-of-materials issues.

2.2 History of Alternative Fuel Research

In the period of World War II, the high demand of bio fuels was due to the increased use as an alternative for imported fuel. In this period, Germany was one of the countries that underwent a serious shortage of fuel. It was during this period that various other inventions took place like the use of gasoline along with alcohol that was derived from potatoes. Britain was the second country which came up with the concept of grain alcohol mixed with petrol. The war times were the periods when the various major technological changes took place but, during the period of peace, cheap oil from the gulf countries as well as the Middle East again eased off the pressure.

With the increased supply of fossil fuel, the geopolitical and economic interest in biofuel faded away. A serious fuel crisis again hit the various countries during the period of 1973 and 1979, because of the geopolitical conflict. Thus (OPEC), Organization of the Petroleum Exporting Countries made a heavy cut in exports especially to the non OPEC nations. The constant shortage of fuel attracted the attention of the various academics and governments to the issues of energy crisis and the use of bio fuels. The twentieth century came with the attention of the people towards the use of bio fuels. Some of the main reasons for the people shifting their interest to bio fuels were the rising prices of oil, emission of the greenhouse gases and interest like rural development.

2.3 Commonly Used Aviation Fuels

2.3.1 Jet A

Jet A is the standard jet fuel type in the U.S. since the 1950s and is only available there. Jet A is similar to Jet-A1, except for its higher freezing point of −40 °C (vs. −47 °C for Jet A-1). Like Jet A-1, Jet A has a fairly high flash point of 38 °C (100 °F), with an auto ignition temperature of 210 °C (410 °F). The annual U.S. usage of jet fuel was 21 billion gallons (80 billion litres) in 2006.

2.3.2 JP8

JP-8 or JP8 (for Jet Propellant 8") is a jet fuel, specified in 1990 by the U.S. government. It is kerosene-based. It is a replacement for the JP-4 fuel; the U.S. Air Force replaced JP-4 with JP-8 completely by the fall of 1996, to use a less flammable, less hazardous fuel for better safety and combat survivability. Commercial aviation uses a similar mixture under the name Jet-A. JP-8 in addition contains icing inhibitor, corrosion inhibitors, lubricants, and antistatic agents.

JP-8+100 is a version of JP-8 with an additive that increases its thermal stability by 56°C (100°F). The additive is a combination of a surfactant, metal deactivator, and an antioxidant. It was introduced in 1994. The additive reduces coking and fouling in engine fuel systems.

2.5 History of Fuel-Material Compatibility

2.5.1 Early Development of Compatibility Research

The very first published alternative fuel studies appeared in the 70's. Since the significance of material compatibility was noticed, many researches have been conducted to evaluate the physical properties of materials, that are used in aircraft turbine engines, under exposure to fuels. It appears that one of the very early research studies was conducted in military aviation industry. A nitrile rubber was incubated in Jet A and several blends (Naphthalene, Tetralin, Decalin, etc.). The methodology of soaking process employed few different ways; soaking independently in each fuel, and soaking with periodically cycling between fuels. (Coleman and Gallop, 1982)

The main attack by the fuel was its aromatics. Naphthalene was particularly effective in promoting swell and softening, but had about the same effect on elastic properties as mononuclear aromatics at the same level. However, this research covered only one type of elastomeric and involved cycling of samples between fuels, and the sample was subject to limited test standards. (Coleman and Gallop, 1982)

In another work, the difficulty of a quantitative measure of the effect of processing variables on the shear strength of solid state diffusion bonds due to the scatter in test data was examined. For test strips Al alloys were utilized. Even though the bond strength depends on the usual processing variables ie. Temperature, pressure, bonding time and interface deformation, the oxide film present on Al alloys is a major obstacle to the formation of high quality bonds. Hence a different bonding technique called diffusion bonding was introduced. This method was achieved using the bonding jig shown in figure 2.2. (Harvey et all, 1985)

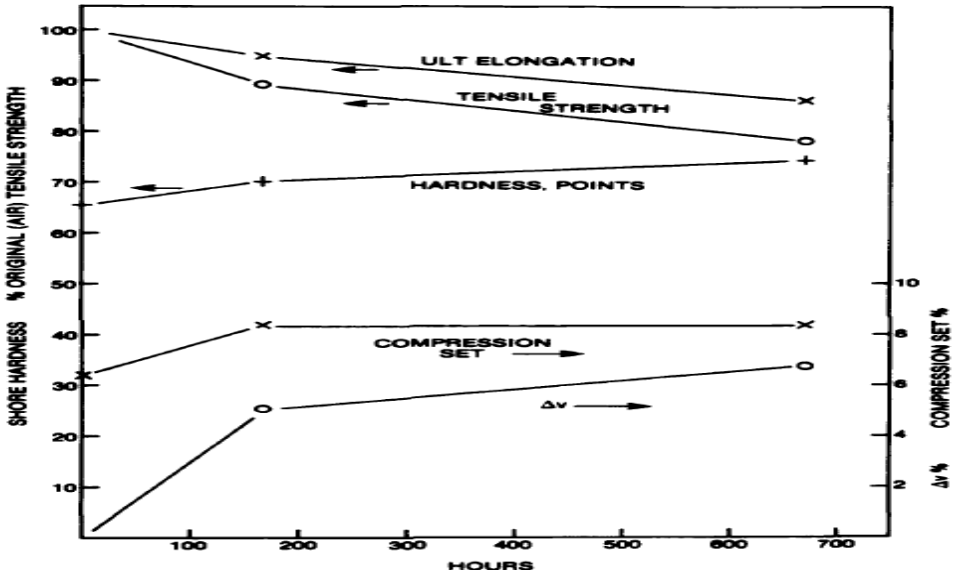


Figure 2.1 Effect on rubber (SA 463) properties of room temperature storage in Jet A-1 (Courtesy of J.R. Coleman and L.D. Gallop)

Improved bonding and testing techniques have reduced the scatter in shear strength data for small diffusion-bonded lap shear test pieces. This enabled the precise measurement of shear stress-strain curves for lap joints and led to reproducible shear strength values. (Harvey et all, 1985)

Another research was conducted on swelling behaviour of fluorocarbon elastomers in methanol and water. The fluorocarbon elastomer used in this investigation was a copolymer of vinylidene fluoride and hexafluorpropylene. Samples were exposed to the fluid for 72 hours at room temperature. (Myers and Abu-Isa, 1985)

At the end of soak period, the volume change of the fluorocarbon elastomer after exposure to water is -l%, indicating slight shrinkage. For methanol a very large positive volume change of 89% is determined, showing that methanol is different in its interaction with the fluorocarbon elastomer than water. (Myers and Abu-Isa, 1985)

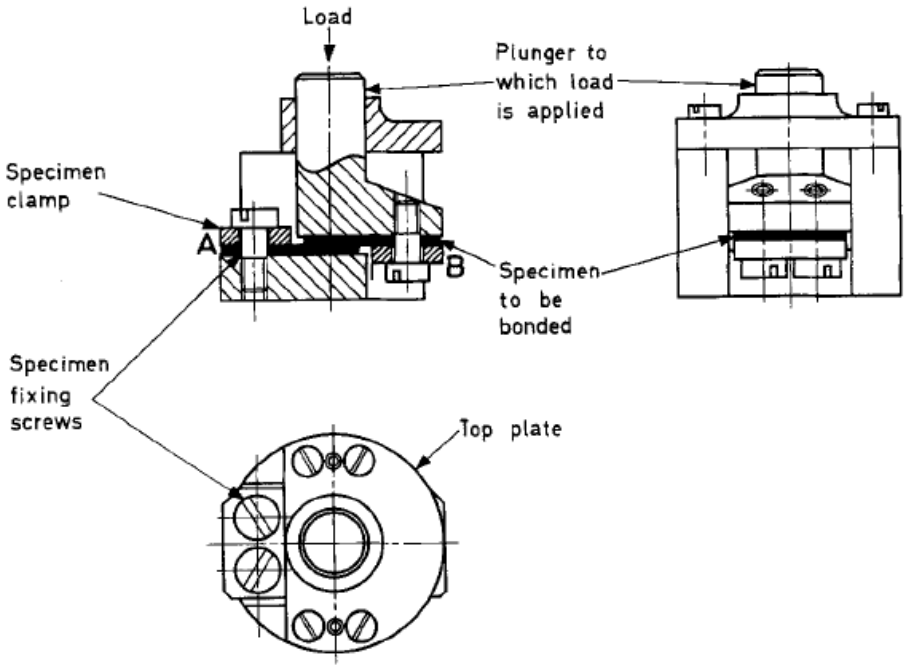


Figure 2.2 Diffusion Bonding Jig (Courtesy of J. HARVEY, P.G. PARTRIDGE, and C. L. SNOOKE, 1985)

Another early prominent research was completed in Southwest Research Institute. Several kinds of non-metallic materials were soaked in baseline fuel JP-8 and four blends: MIL-F-46162B, MIL-F-46162C, MIL-F-53080, Middle distillate fuel stimulant. The test materials were towable fuel drum (Elastomer A), collapsible fuel tank material and associated seam section (Elastomer B and C, respectively), and Berm liner and its seam section (Elastomer D and E, respectively). JP-8 was allowed to contain maximum 25 % of aromatics. (Fodor, 1989)

The soak process was carried out at 80 C for 14 days for five samples of each material, and three samples were placed into each bottle, the remaining two into the other bottle which were sealed with Teflon-lined screw caps. Subsequent to the immersion period, hardness value was measured for each elastomer two times; after 2 days and 6 weeks. And as data from the paper suggested,

elastomer A is more sensitive to exposure to fuels. The others did not show significant sensitivity to any of the fuels. (Fodor, 1989)

Another work was done on the resistance of elastomers with parylene coating against aggressive fuels. Fuel system seals, O-rings, hoses, and diaphragms coated with parylene were subject to hardness, tensile strength, elongation, and volume swell tests. The coated specimens were compared with uncoated ones. Parylene-coated fluorocarbon (FKM), nitrile (NBR), hydrogenated nitrile (HNBR), and silicone elastomers were candidates in this paper and as fuel methanol was used. Samples were soaked for 168hours at 158 F. (Jeff Pyle, *Machine Design;* May 14, 1993; 65, 9; ABI/INFORM Global pg. 77)

As a result, The parylene-coated specimens exhibited significant reduction in volume swell, moderate reduction in elongation, functional level of increase in tensile properties, and good retention in hardness. (Jeff Pyle, *Machine Design;* May 14, 1993; 65, 9; ABI/INFORM Global pg. 77)

2.5.2 Latest Development of Compatibility Research

The second period of development started in mid 1990`s and continues to the present. This period can be viewed as the rapid and intense growth of alternative fuel research. This second era was initiated by one of the most detailed projects. Wide range of materials (adhesives, sealants, foams, etc..) and test standards(hardness, elongation, peel strength, etc..) was covered in this research. More than 100 materials have been soaked in a Teflon sealed glass containers at different temperatures for 28-day period. Airframe materials, engine materials, and some older airframe materials were soaked at 200,325, and 160 F, respectively. The test fuels used as baseline fuel and additives are JP-8, JP8+100 and MDA/BHT, respectively. (Heneghan et all, 1996)

As a result of this research, none of the materials showed any detrimental effects due to the additive package. A fascinating result, not associated with the JP-8+100 program, is that some materials currently in use are not compatible with JP-8, or are being used at temperatures that are beyond their operating range. (Heneghan et all, 1996)

Another interesting research, again in the very early stage of later development, was conducted on the compatibility of non-metallic materials with JP-8 and JP-8+100. This study of compatibility is very similar to the previous worked mentioned above in terms of material types, fuel types, and test standards. Test materials tested were included adhesives, bladders, O-rings, and few. The materials were all immersed in three fuels (JP-8, JP-8+100, and JP-8+100(4X)) at 160, 200, and 325 F for 28 days with fuel changes every 7 days. Test samples were blotted dry and tested within 30 min after removal. (Fletcher, 1997)

The initial results of this research showed many failures that needed to be analyzed for root cause. Primarily, the failures occurred because the temperature limitation of the material had been breached. Later tests were performed at lower temperatures to prove this conclusion. (Fletcher, 1997)

Similar research was carried out on both elastomer and metallic materials. This research covered the testing of various fuels; JP-8, ASTM low-sulphur reference diesel fuel (LSDF), Reference No.2 Diesel fuel, and Biodiesel. As well as the variety of test fuels, compatibility covered wide range of materials: Elastomer (Teflon, Nylon 6/6, Nitrile rubber, Viton A401C, Fluorosilicone, Polyurethane, Polypropylene), Metallic(C110 copper, SAE 1010 steel, C260 brass, 6061 aluminum, A319 cast aluminum, C510 bronze). Both elastomer and metallic materials were incubated in each fuel at 51.7 C for 22, 70, and 694 hours. Subsequently ASTM D 471 and D 412 were applied. (Bessee and Frey, 1997)

According to the above research, some of the materials were affected severely and the rest maintained their physical properties with minimum variation to non-soaked state. Nitrile rubber, nylon 6/6, and high-density polypropylene were affected, but Teflon and Viton appeared to have good resistance and minimal changes in physical properties. Copper-containing metals showed severe corrosion. (Bessee and Frey, 1997)

An interesting research on compatibility was conducted by US army aviation (. The candidate fuel being used was JP-8+100. Various metallic and non-metallic materials were subjected to testings(e.g., tensile, hardness). Having the paper classified, there is no information about how the soaking process was carried out. The results obtained of that research was quiet satisfying. There were no material compatibility issue with JP-8+100 figured out. (Owens et all, 2000)

After we stepped into the third millennium, fuel-material compatibility gained momentum. Besides automobile and aviation sectors, there has been quite important fuel researches conducted for satellite systems. One of them was carried out by NASA and US Air Force joint program. The intension of this study was to evaluate the compatibility of materials of construction of small satellites with HAN (hydroxyl ammonium nitrate)-based propellant. As test fuels 13M HAN and XM46 were used. The materials covered were of only metallic materials: A16061, carbon steel, nickel 200, titanium, Ti-6Al-4V, and 304, 310, 316, 410 stainless steel. Materials were soaked in candidate fuels at various temperatures, ranging from 25 to 65 C and durations from 6 to 369 days. (Reed and Harasim, 2001)

Some of the materials were affected detrimentally by candidate fuels: A16061 broke apart and had significant mass loss, carbon steel had significant mass loss, nickel 200 and 410 stainless steel were pitted and has significant mass loss , Ti-6Al-4V was pitted, the remaining had no obvious sign of attack. (Reed and Harasim, 2001)

As the compatibility becomes one of the major problems, studies towards sorting out that problem have been growing bigger. One significant research called synthetic Fischer-Tropsch JP-5/JP-8 aviation turbine fuel elastomer compatibility was carried out. There were few test fuels involved in that research: S-5 (blend of JP-5 and JP-8 without aromatics), JP-5 with 18% aromatics, S-5 + 10% A150 (by Exxon Mobil), S-5 + 25% A150, ECD-1(emission control diesel-1). There was only one material type to be tested; nitrile elastomer N0674-70 in forms of coupons and O-rings. Five samples of each form were incubated at 40 C for 43 days in each test fluid. After immersion ASTM D471 and D2240 were applied. (Muzzel et all, 2005)

For the coupons there were significant results observed on the materials. As the aromatic content increased, the volume swell increased as well. Unlike volume swell, as the aromatic level increased, hardness decreased. The most significant change was in S-5 + 25% A150. For O-rings, for both volume swell and hardness, increase was observed in all fluids but S-5. (Muzzel et all, 2005)

In another fuel study the impact of biodiesel on fuel system components was examined. The research involved several types of fuels; BP-15- Base fuel, B5 RME(5 % in BP-15 Rapeseed biodiesel), B5 SME(5 % in BP-15 Soy based biodiesel), B5 Oxidized SME, B20 RME(20 % in BP-15), B20 SME(20 % in BP-15), B20 Oxidized SME. The materials tested were all elastomers O-rings; Nitrile rubber (NB104-75, NO674-70), nitrile polymer (KB162-80), and Fluorocarbon polymer (VB153-75, V1164-75). Materials were soaked in candidate fuels at 60 C for 1000 hours. Subsequent to the soaking period, they were subjected to ASTM D1414, D471, and D395. (Terry, 2005)

As a result of this compatibility research; fluorocarbons were compatible with all the candidate fuels, nitrile rubber showed acceptable performance in all fluids with the exception of B20 SME

and B20 Oxidized SME where volume swell measurement were high. Equally NO674-70 showed good performance in all fluids with the exception of B20 SME. NB104-75 performed well in terms of hardness and volume change but overall exhibited substantial physical property changes across the range of test fluids, therefore not recommended. (Terry, 2005)

Another research was conducted on characteristic tensile properites of elastomers at lower deformation. The tensile load–deformation relationship of elastomers is considerably nonlinear. The local slope of the load– deformation curve drops off significantly and the gradient of the curve changes as the elastomer is stretched. A typical result of tensile test of elastomers is then a stress–strain curve of S-shape, for which Hooke's law is not valid. For characterization of elastomer properties, stress at 100% strain, stress at 300% strain, tensile strength and ultimate elongation are commonly used. Rubber dumbbell specimens of clay filled vulcanized styrene-butadiene rubber compound were used in this work. (Malac, 2005)

As a lower deformation region, we have arbitrary chosen the range up to 25% sample strain. The measured force-extension dependence in the range to 20% strain for the tested specimen is shown in Fig. 2.3. The dependence is evidently nonlinear and measured extension data are not equally spaced apart. (Malac, 2005)

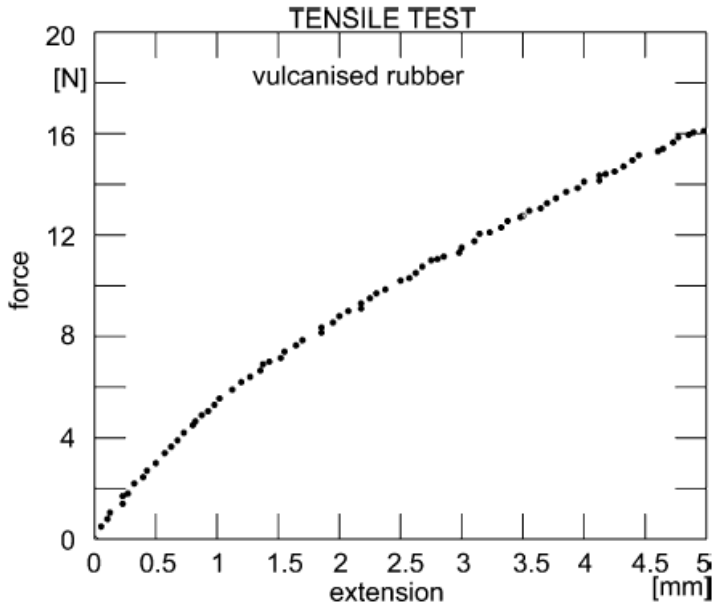


Figure 2.3 Force-extension dependence to 20% strain of tested specimen (Courtesy of Jiri Malac, 2005).

As the need of alternative fuel grows bigger, more studies are to be conducted. An interesting research was done about effect of biodiesel blend on elastomer properties. Diesel was used as a baseline fuel and biodiesel, B10 prepared from palm oil, was the candidate fuel. There were bunch of elastomers to be tested; NBR, HNBR, NBR/PVC, acrylic rubber, co-polymer FKM, and terpolymer FKM. The test materials were immersed in B10 (10 % biodiesel) for 22, 670, and 1008 hours at 100 C. And then ASTM D471, D2240, and D412 were applied. The result of this research was pretty satisfying that B10 demonstrated little impact on the properties of elastomers. (Trakarnpruk and Porntangjitlikit, 2007)

Another review is about the experimental research on the resistance of rubber materials to dimethyl ether. 20 % DME (Dimethyl Ether) blended in diesel, known as D20 was used as a fuel. There were 5 different types of materials to be tested; Chloroprene rubber, acrylate rubber, fluorosilicone rubber, ethylene-propylene-diene monomer rubber, nitrile-butadiene rubber, and fluorocarbon rubber. Samples were incubated in D20 for 1, 7, and 30 days and then ASTM

D412, D471, and D2240 were applied. The results derived from that research speaks in favour of only nitrile-butadiene rubber which was found to be the least susceptible to the presence of DME in diesel and appears to have the best chance of working in a practical application. (Li and Zhou, 2008)

Another work was carried out to exhibit high-performance nano-adhesive bonding of titanium for aerospace and space applications. The high-performance nano-adhesive is prepared by dispersing silicate nanoparticles into the ultra-high-temperature-resistant epoxy adhesive at 10 % weight ratio with the matrix adhesive followed by modification of the nano-adhesive after curing under high-energy radiation for 6 h in the pool of SLOWPOKE-2 nuclear reactor to promote crosslink into the adhesive. As a result, a significant increase in lap shear strength was obtained. In Fig 2.4 comparison between the adhesives is shown. (Bhowmik et all, 2008)

Another experimental research was done over the swell behaviours of O-rings with different test fuels. The tested materials were including; VMQ (silicone), CR (chloroprene), NBR (nitrile), FVMQ (fluorosilicone), FKM (fluorocarbon), and EPDM (ethylene-propylene). As for test fluids high-aromatic gasoline, jet-turbine lubricant, phosphate-ester hydraulic fluid, and standard reference test oils were utilized. (Keller, 2009)

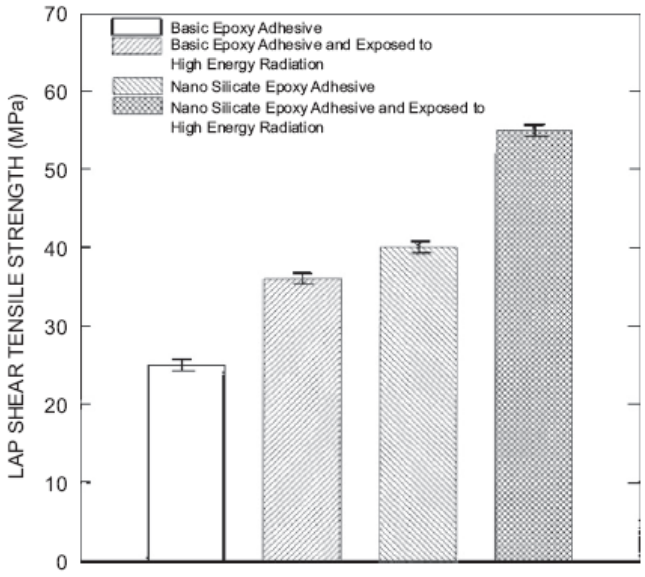


Figure 2.4 Tensile lap shear strength of adhesive joint of plasma-nitrided titanium (Courtesy of Bhowmik et all, 2008).

For more than 60 years, engineers specifying seals and customers using them have accepted the arbitrary rule that the maximum amount O-rings will swell in most applications is a 25% change in volume. Results showed that the maximum volume change for O-rings in most applications is actually 40%, not 25%. (Keller, 2009).

2.5 Concluding Remarks

This chapter reviewed previously done research studies on compatibility of materials with alternative fuels. However, material-fuel compatibility research studies are not revealed fully due to proprietary concerns and nature of the studies is partially explained. Chiefly, duration of soaking, temperature, and the type of fuel have an influence on mechanical properties of materials, and have to be considered when characterizing the materials.

Chapter 3 Evaluating Compatibility of Additives or Fuels with Fuel System Materials

3.1 Introduction

The information included in this chapter is obtained from ASTM standard practice D4054-09 titled: *Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives*. According to section A3 of this standard; this practice covers and provides a framework for the qualification and approval of new fuels and new fuel additives for use in commercial and military aviation gas turbine engines. The practice was developed as a guide by the aviation gas-turbine engine Original Equipment Manufacturers (OEMs) with ASTM International member support. The OEMs are solely responsible for approval of a fuel or additive in their respective engines and airframes. For the purpose of this guide, "approval" means "permission to use;" it is not an endorsement of any kind. Standards organizations such as ASTM International, United Kingdom Ministry of Defence, and the U.S. military list only those fuels and additives that are mutually acceptable to all OEMs. ASTM International and OEM participation in the evaluation or approval procedure does not constitute an endorsement of the fuel or additive.

3.2 Test Program

3.2.2 Test Materials

Tables 3.2 and 3.4, collectively, are referred to as the "short list" by the engine and aircraft OEMs and DOD. Table 3.2 is a list of representative non-metallic materials used in gas turbine

engine and airframe fuel systems. Table 3.4 is a list of representative metals used in gas turbine engine and airframe fuel systems. The engine manufacturers, airplane manufacturers, and DOD have agreed to these generic classes of materials for the purpose of evaluating compatibility with fuels and fuel additives. The list of materials to be tested in Tables 3.2 and 3.4 include 15 non-metallics and 15 metals, respectively.

3.2.3 Test Temperatures

Materials are to be tested at the highest temperature to which it will be subjected for its specific application within an aircraft and engine fuel system. Testing at temperatures beyond these maximums result in diminished baseline material performance and significantly reduces test sensitivity. The appropriate test temperature for each material is shown in Tables 3.2 and 3.4 along with the standard test procedure. Since 93 and 163 C are the most prevalent temperatures, materials are soaked in these two temperatures.

3.2.4 Screening Tests

If the OEMs determine that material compatibility testing is required, laboratory-scale soak tests shall be performed on the short list of materials compiled in Tables 3.2 and 3.4. Soak temperatures, test methods, and acceptance criteria are called out in Table 3.3. The soak period is 28 days and the test fluid shall be changed out every 14 days with fresh test fluid. The tests called out in Tables 3.2 and 3.3 compare changes in properties. For example; tensile strength, of materials soaked in the new fuel (or new fuel additive blend) to that of materials soaked in a baseline reference fuel(s). The tests are intended to be a first level screening to identify potential compatibility problems. If tests results are within allowable variation as defined in the evaluation

criteria for each material, then the risk level of the new fuel or fuel additive is considered minimal.

TABLE 3.2 Non-Metallic Materials

Material	Description	Specification	Test Procedure	Test Protocol	Qualified Product
Adhesive	Epoxy Paste	MMM-A-132 Type I, Class 3	ASTM D 1002	Lap Shear	Hysol EA 9394
	Methacrylate	ASTM D 5363 Group 4, Class I, Grade I	MIL-R-46082, Method A = ASTM D 4562	Static Shear	Loctite 609
Coating	Nitrile	SAE-AMS-S-4383	ASTM D 3363 ASTM D 3359	Hardness(Pencil) Tape Adhesion	EC 776 SR
	Polyurethane	SAE-AMS-C-27725 Type II			825 x 309
Film	Kapton	~	ASTM D 412 ASTM D 412	Tensile Strength Elongation	Upilex-S
Foam	Polyurethane	MIL-PRF-87260	ASTM D 412 ASTM D 412	Tensile Strength Elongation	CrestFoam
Gasket, O-Ring	Low Temperature Fluorocarbon	SAE-AMS-R-83485, Type I	ASTM D 2240 ASTM D 1414 ASTM D 1414 ASTM D 471	Hardness, Shore M Tensile Strength Elongation Volume Swell	Parker VM 128
Sealant	Polysulfide Dichromate Cured	SAE-AMS-S-8802 Type I, Class B-2	ASTM D 2240 ASTM D 412 ASTM D 412 ASTM D 471	Hardness, Shore A Tensile Strength Elongation Volume Swell	PR 1422
	Polysulfide Manganese Cured	SAE-AMS-S-8802 Type II, Class B-2			PS 890
	Fluorosilicone	SAE-AMS-S-3375			Q4-2817
	Polythioether	SAE-AMS-S-3277 Class B-2			PR 1828
	Polysulfide Lightweight	SAE-AMS-S-3281			PR 1776

3.2.5 Procedure for Soaking (Aging) Test Materials in Fuel

3.2.5.1 Material Procurement for the Soak Procedure

(1) Sealant, coating, and adhesive materials are typically procured in their raw (uncured) form. This often consists of a two-part mixture, pre-preg, or film. The integrity of the work relies on fabricating and testing equipment on facility. For example, once prepared, sealant specimens are required to be cured in environmentally controlled rooms (75°F and 50 % relative humidity).

(2) Adhesive lap shear testing is done using aluminum adherents with the manufacturer's recommended surface preparation and cure cycle.

(3) Foam materials are procured as a sheet of the material from the applicable vendor. These sheets are then utilized to die-out (cut out) the specimens required for the testing.

(4) O-rings are also obtained directly from the vendors which manufacture materials meeting the various specifications.

(5) Metallic specimens are obtained from various sources who can certify the materials to meet the applicable specifications. Typically, three specimens of each material are utilized in the aging of the metallic specimens. These specimens are roughly one inch by two inches. Thickness is not relevant as we are only looking at surface effects.

While all the materials were being procured, there were few issues encountered. One of the issues was about US-Canada border customs; some of the materials needed over-protection for safety reasons. Another setback was the cost of materials. Since a small amount of material was needed, most vendors were not willing to sell their products in small quantities. Hence that generated a cost issue for the materials to be purchased in bulk.

3.2.5.2 Fuel Soak

(1) Materials are typically exposed to the fuel in separate glass mason jars (quart-size). Specimens of different materials are not aged in the same container because it is possible that components may leach out into the fuel and react with other material specimens or components. For example, the tensile & elongation and volume swell specimens of the AMS-S-8802 polysulfide sealant are aged in a separate jar from the AMS-3281 lightweight polysulfide tensile & elongation and volume swell specimens.

(2) Tensile and elongation; volume swell; and hardness specimens must be suspended in the fuel and not just laid in the bottom of the jar. This can be done by using a rack and wires to hang the specimens, which can then be placed in the jar.

(3) A piece of foil is placed over the mouth of the jar and then the lid is screwed into place to prevent evaporation of the fuel while aging. The foil should extend roughly one inch over all sides of the mouth of the jar. The heating of the quart-jars is done using explosion-proof ovens. These ovens can hold a large number of jars, so many specimens which require the same temperature can be aged simultaneously.

(4) Fuel change out, that is, replacement of old fuel with fresh fuel, must be performed after 14 days for the 28-day aging of non-metallic specimens and after 7 days for the metallic specimens. Change out of the fuel is necessary because properties of the fuel can change significantly when exposed to high temperatures for an extended period of time.

3.2.7 Types of Tests to be performed after 28-Day Soak Period

3.2.7.1 Non-Metallic Materials

Examples of the tests to be performed on the non-metallic materials listed in Table A3.2 include the following:

(1) Single Lap and Static Shear

(2) Volume Swell

(3) Tensile

(4) Elongation

(5) Tape Adhesion

(6) Hardness

The test results of each material shall conform to the requirements by ASTM 4054. Following table illustrates the requirements being sought.

3.2.7.2 Metals

Surface Evaluation—at the conclusion of the 28-day soak, the metal test specimens shall be removed from the test fluid, air dried, and examined visually and under low power of less than 50 times optical magnification. The objective is to inspect for evidence of staining, deposits, surface pits, or gross corrosion. Staining is considered a benign surface phenomenon. Staining results in no appreciable weight loss or gain and indicates the formation of a passive layer that inhibits corrosion. Subsequent to the initial examination, the metal surfaces shall be cleaned using acetone or alcohol and re-examined for surface pits. If desired, deposits can be preserved by evaporating the solvents and then storing in desiccators for future analysis.

TABLE 3.3 Test Requirements

Material	Product	Test Protocol	Test Requirements
Sealants	PR-1422	ASTM D412 ASTM D471 ASTM D2240, A	>200 psi, > 150 % 0-20 % > 35
	PS-890		
	PR-1828		
	PR-1776		
	Q4-2817		
Coatings	EC 776	ASTM D3359 ASTM D3363	Pass ≥ unaged
	825X309		
Adhesives	EA 9394	ASTM D1002	> 1500 psi
	Loctite 609	ASTM D4562	> 1200 psi
O-Rings	VM128	ASTM D471 ASTM D1414 ASTM D2240, M	0-10 % >1000 psi, >150 % ± 5 points from unaged
Film	Upilex-S	ASTM D412	>500 psi, >25 %
Foam	SafeCrest G-15M, Grade 2	ASTM 412	>10 psi, >100 %

3.2.8 Evaluation Criteria

The evaluation criterion for non-metallic materials is shown in Table 3.2. The approach is to look for significant variations in test values between the dry state and the candidate fuel. The allowable variations from the baseline fuel for Non-metallic materials are based on the precision and bias of the test method. Most of the materials have test requirements expressed as maximum or minimum values. These values are drawn from the material specification when applicable. If

there is no material specification or the specification does not have a fuel-soak requirement, then pass/fail criteria is gleaned from experience gained in previous investigations performed on similar materials.

TABLE 3.4 Metallic Materials

Material	Material Specification	Caoting Specification	SOAK Duration/Temperature
7075-T6 Aluminum Chromic Acid Anodize Type I	SAE-AMS-QQ-A-250/12	MIL-A-8625, Type I	28 days/93 C
7075-T6 Sulfuric Acid Anodize Type IIB		MIL-A-8625, Type II B	
7075-T6 Chromate Coversion Coated Class IA		MIL-DTL-5541, Class I A	
2024-T3 Bare	SAE-AMS-4037	N/A	
6061-T6 Bare	SAE-AMS-4027	N/A	
304 SS	ASTM A240	N/A	28 days/163 C
17-4 pH	SAE-AMS-5604	N/A	
TI 8A1-1V-1MO	SAE-AMS-T-9046	N/A	
TI CP 70	SAE-AMS-T-9046	N/A	
TI 3AL-2.5V	SAE-AMS-T-9046	N/A	
INCO 625		N/A	
INCO 718		N/A	
IN 200 Ni		N/A	
Monel 400		N/A	
Waspalloy		N/A	

Chapter 4 Materials and Methodology

4.1 Introduction

This chapter describes the physical properties of each material in details, and the equipments utilized for soaking based on products' Technical Data Sheet. As mentioned previously in Chapter 3, some of the materials are procured in raw form. Hence this chapter will also focus on the preparation of samples from those materials. The materials, utilized in this research, can be grouped in two categories: non-metallic and metallic.

4.2 Non-Metallic Materials

Non-metallic materials are categorized in 6 different types; adhesives, coating materials, films, foams, o-rings, and sealants.

4.2.1 Adhesives

Hysol EA 9394

Hysol EA 9394 is a structural paste adhesive formed of two parts and qualified to MMM-A-132 Rev A, Type I, Class 3. It cures at room temperature and possesses high strength to 350°F/177°C and higher. Its thixotropic nature and high temperature compressive strength also make it ideal for pottings, fillings, and liquid shim applications

Loctite 609

Loctite 609 is designed for the bonding of cylindrical fitting parts and meets the requirements of Military Specification Mil-R-46082B. The product cures when confined in the absence of air

between close fitting metal surfaces and prevents loosening and leakage from shock and vibration.

4.2.2 Coating Materials

EC 776SR

EC 776SR is a general purpose, solvent-based adhesive/coating with good adhesion to synthetic rubber, metal, glass, and many plastics. Since EC 776 and EC 776SR show very close physical characteristics, EC 776SR includes a red dye for identification purposes.

825X309

825X309 is a chemically cured acid and fluid resistant urethane coating intended for the protection against fuel contaminants. It provides protection for non-ferrous metals, against fresh or salt water, aircraft fuels, hydraulic fluids, engine oils and dilute acid solutions. It offers good adhesion to chemically treated surfaces and is unique in having good adhesion to titanium and stainless steel. It exhibits very good intercoat compatibility with sealants and touch-up materials when properly cleaned, even after long term exposure to fuel.

825X309 is used to protect the inside of an aircraft's fuel tank against corrosion from fuel contaminants. It is compatible with all current spray equipment, is easy to apply in a variety of environmental conditions, and meets the specification AMS-C-27725 Type II.

4.2.3 Foams

Crestfoam

Crest SafeCrest reticulated polyurethane foams are suitable for explosion suppression and surge/noise mitigation and environmentally-friendly materials for use in fuel tanks of aircraft, boats, military vehicles, competition and emergency vehicles, automobiles and trucks- virtually

any vehicle where the possibility of fuel tank explosion exists, or where surge/noise mitigation is required.

4.2.4 O-Rings

Parker VM 128

VM128 is made of a low-temperature fluorocarbon polymer that results in functional seal performance down to -40°F (-40°C). Like other fluorocarbon compounds, VM128 has a +400°F (+200°C) upper temperature limit with very good compression set resistance. As application temperatures continue to climb, nitrile materials may no longer perform adequately. VM128 offers a substantial improvement in high temperature performance over these other seal material options. Fluorocarbon rubber as a polymer family has great chemical resistance. VM128 is fully compatible with all aerospace jet fuels and hydrocarbon-based hydraulic oils.

Figure 4.1 O-Ring Specimen

4.2.5 Sealants

There are 5 types of sealants to be tested in this work and the properties of each material are described in details below.

PR 1422-B

PR-1422 Class B is a two-part aircraft integral fuel tank sealant, which has a service temperature range from -65°F (-54°C) to 250°F (121°C), with intermittent excursions up to 275°F (135°C). This material is designed for fillet sealing of fuel tanks and other aircraft fuselage sealing applications. The cured sealant maintains very good elastomeric properties after prolonged exposure to both jet fuel and aviation gas. It cures at room temperature to form a resilient sealant having excellent adhesion to common aircraft substrates. It meets the specification MIL-S-8802.

PS 890

P/S 890 Class B, like PR 1422, is a two-part aircraft integral fuel tank sealant, which has a service temperature range from -65°F (-54°C) to 250°F (121°C), with intermittent excursions up to 275°F (135°C). This material is designed for fillet sealing of fuel tanks and other aircraft fuselage sealing applications. The cured sealant maintains very good elastomeric properties after prolonged exposure to both jet fuel and aviation gas. It cures at room temperature to form a resilient sealant having very good adhesion to common aircraft substrates. It meets the specification MIL-S-8802.

Q4 2817

Q4-2817 is a one-part, ready to use, high strength solvent-free fluorosilicone elastomer paste. It retains its properties under exposure to fuels, oils and solvents, exhibits very good adhesion and

bond strength to most materials. It is resistant to weathering, moisture and ozone and cures at room temperature to form a tough, rubbery solid.

PR 1828

PR-1828 Class B is a two-part rapid curing, primer-free to most common substrates, aircraft integral fuel tank sealant. It has a service temperature range from -80°F (-62°C) to 320°F (160°C), with intermittent excursions up to 420°F (216°C). This material is designed for fillet sealing of fuel tanks and other aircraft fuselage sealing applications. The cured sealant maintains very good elastomeric properties after prolonged exposure to both jet fuel and aviation gas. Unlike standard polysulfide fuel tank sealants, it can cure at low temperatures and is unaffected by changes in relative humidity. It has very good adhesion to common aircraft substrates and meets the specification AMS 3277.

PR 1776

PR 1776 is a two-part, high temperature resistant low gravity, fuel tank and fuselage sealant, based on Permapol P-5 liquid polymers, a chemically modified improved class of polysulfide polymers. The mixed compound is a thixotropic paste, readily applied by extrusion or injection gun, which does not flow from vertical or overhead surfaces. Sealant has very good adhesion to aluminium, titanium, stainless steel, and other metals.

4.2.6 Films

Upilex-S

UPILEX, ultra-high heat-resistant polyamide film, is the product of the polycondensation reaction between biphenyltetracarboxylic dianhydride (BPDA), of which process UBE Industries

originally developed. Most notable of its characteristics is physical, mechanical, electrical, and chemical properties under high-temperature conditions

4.3 Metallic Materials

4.3.1 Aluminum 7075-T6, 2024-T3, 6061-T6

Aluminum 7075-T6 specimens are anodized with chromic, and sulpuric acid and coated with chromate conversion. Aluminum 2024-T3 and 6061-T6 are in bare form.

4.3.2 Titanium 8A1-1V-1MO, CP 70, 3Al-2.5V

Titanium is a chemical element with the symbol Ti and atomic number 22. Sometimes called the "space age metal", it has a low density and is a strong, lustrous, corrosion-resistant (including sea water, aqua regia and chlorine) transition metal with a silver color.

4.3.3 Inconel

Inconel is a registered trademark of Special Metals Corporation that refers to a family of austenitic nickel-chromium-based superalloys. Inconel alloys are typically used in high temperature applications. It is often referred to in English as "Inco" (or occasionally "Inconel"). Inconel 625 and 718 are to be used in this research.

4.3.4 Monel

Monel is a trademark of Special Metals Corporation for a series of nickel alloys, primarily composed of nickel (up to 67%) and copper, with some iron and other trace elements. Monel was created by David H. Browne, chief metallurgist for International Nickel Co. Monel alloy 400 is binary alloy of the same proportions of nickel and copper as is found naturally in the nickel ore from the Sudbury (Ontario) mines. Monel was named for company president Ambrose Monell,

and patented in 1906. One L was dropped, because family names were not allowed as trademarks at that time. Monel 400 is to be utilized in this research.

4.3.5 Waspaloy

Waspaloy is a registered trademark of United Technology Corp that refers to an age hardening austenitic nickel-based super-alloy. Waspaloy is typically used in high temperature applications, particularly in gas turbines. Nominal composition:

Nickel 58%, chromium 19%, cobalt 13%, molybdenum 4%, titanium 3%, and aluminum 1.4%.

4.3.6 Nickel

Nickel is a chemical element, with the chemical symbol Ni and atomic number 28. It is a silvery-white lustrous metal with a slight golden tinge. It is one of the four elements that are ferromagnetic around room temperature, the other three being iron, cobalt and gadolinium. Nickel 400 is to be tested.

4.3.7 Stainless Steel

In metallurgy stainless steel, also known as inox steel or inox from French "inoxydable", is defined as a steel alloy with a minimum of 10.5 or 11% chromium content by mass. Stainless steel does not stain, corrode, or rust as easily as ordinary steel, but it is not stain-proof. It is also called corrosion-resistant steel or CRES when the alloy type and grade are not detailed, particularly in the aviation industry. There are different grades and surface finishes of stainless steel to suit the environment the alloy must endure. Stainless steel is used where both the properties of steel and resistance to corrosion are required. 304 and 17-4 pH are to be tested.

4.2 Equipments

4.2.1 Jars

Depending on the specimen size there are 2 types of jars to be used; Ball 67000 quart size wide mouth mason jars with 3.5" x 3.5" x 6.9" and Ball 68100 half gallon wide mouth mason jars with 4.5" x 4.5" x 9". And they are made sure to withstand the sought soak temperature and pressure forming inside.

Figure 4.2 Ball 68100 and 67000 Jars

4.2.2 Oven

Two indentical HS 3804 E series explosion-proof ovens are to be used for this experimental work. HS 3804 E contains friction-aired chamber, which can be used for a number of hazardous

work applications due to the unique operating concept of providing controlled heat without heating elements. This characteristic helps solve the problem of operational safety when operating in a Class 1, Group D processing environment by removing an ignition source.

Figure 4.3 Explosion-proof ovens

4.3 Specimen Preparation

4.3.1 Adhesives

Hysol EA 9394

Hysol EA 9394, as stated in Table 3.2, is to be tested to evaluate lap shear strength with reference to ASTM D1002. Since the method being used is single lap shear, two aluminum 2024-T3 strips are employed. Since it is undesirable to exceed the yield point of the metal in tension during test, the permissible length of overlap in the specimen will vary with the thickness and type of metal, and on the general level of strength of the adhesive being investigated. As recommended by ASTM D1002 the overlap length, 12.7 mm (0.5 in).

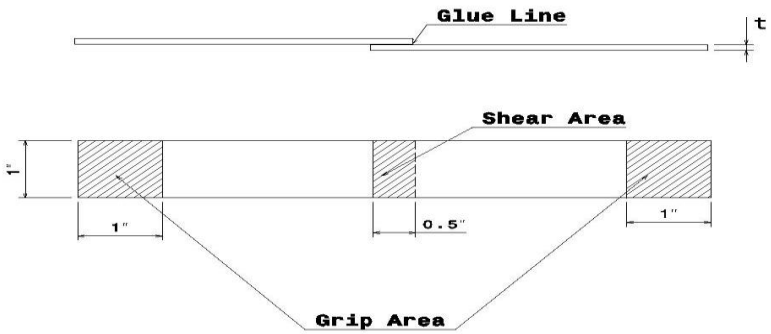


Figure 4.4 Single Lap Shear Specimen

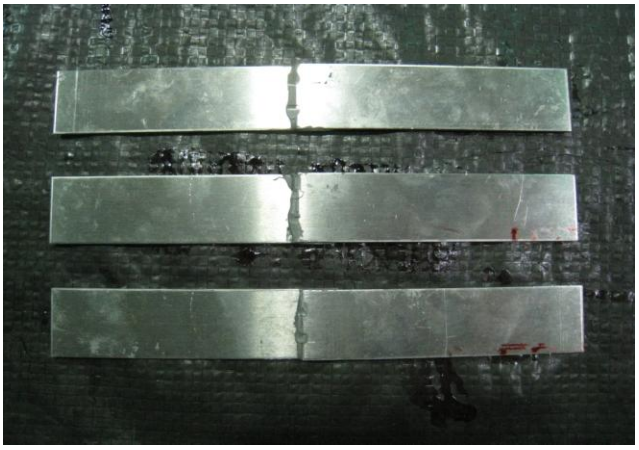


Figure 4.5 Prepared Lap Shear Specimens

.

The thickness of aluminum strips for EA 9394 is 0.063 in. Before bonding process, the contact areas are to be cleaned with acetone. And the surfaces stand several minutes while the chemical evaporates. Since Hysol EA 9394 consists of two parts, Part A and B, there is a mix ratio: by weight 100 Part A and 17 Part B. Metal strips are bonded together with 20 lb clamps and cured in an air circulating oven for 1 hour at 66 C.

Loctite 609

Loctite 609, as indicated in Table 3.2, is to be tested to evaluate its static shear strength with reference to ASTM D4562. Prior to bonding, all surfaces (internal and external) are to be cleaned with a Loctite Solvent and allowed to dry. After cleaning process, Loctite 609 is applied around the leading edge of the pin and inside of the collar, and rotation motion during assembly is to be used for good coverage. Subsequent to bonding process the specimens are allowed to cure on a curing rack for 6 hours at room temperature.

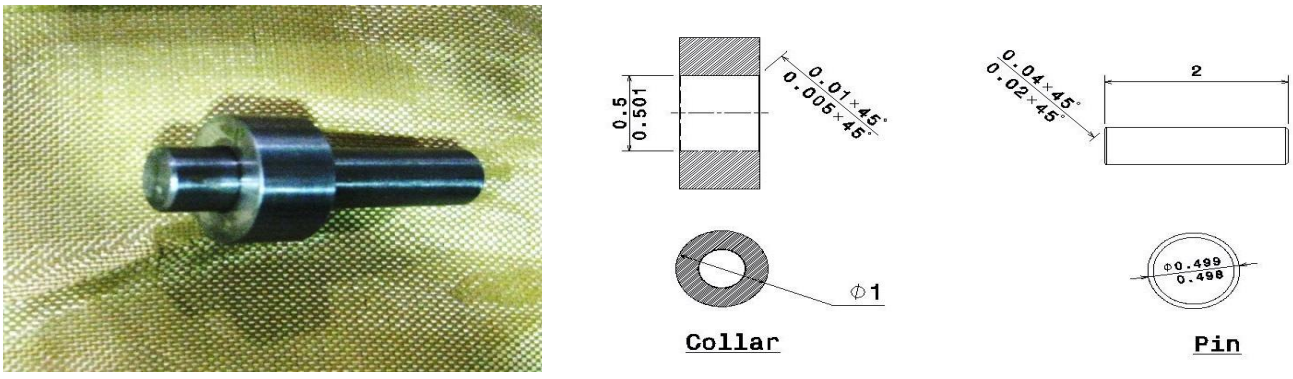


Figure 4.6 Static Shear Specimen

4.3.2 Coatings

EC 776 SR and 825X309

EC 776 SR, as indicated in Table 3.2, is to be tested to evaluate pencil hardness and tape adhesion in accordance with ASTM D3363 and D3359 respectively. Prior to the application of the coating, all surfaces (internal and external) are to be clean, dry and free from oil and grease. After cleaning process, the coatings are applied through dip-coating process in order to obtain

the thickness recommended by vendors. Metal plates are Aluminum 6061-T3 with 2x5x0.125 in. dimensions. EC 776, under atmospheric conditions, becomes tack free in 20 min and should thoroughly dry in approximately 24 hours. 825X309 consists of 4 parts; base, 1 part activator and 4 parts thinner. It is to be dried hard for either 14 days at 25 C, 50% RH or 3 days at 60 C, 10-20%. The coating thickness for EC 776SR is 0.002 in. and for 825x309 is 0.004 in.

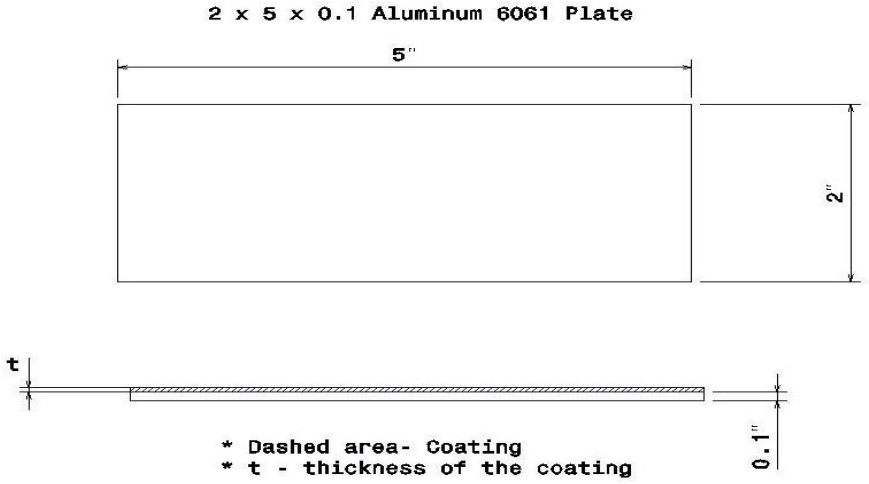


Figure 4.7 Dimension of Coating Specimen.

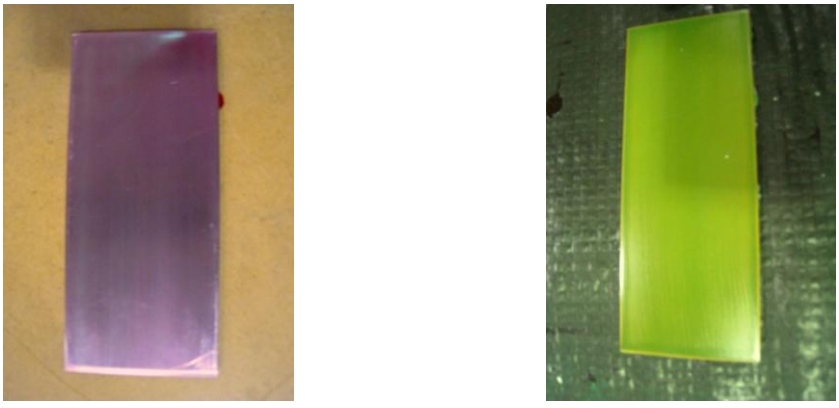


Figure 4.8 EC 776SR (left) and 825x309 (right) Specimens.

4.3.3 Foams

Crestfoam

Crestfoam, as indicated in Table 3.2, is to be tested to evaluate its tensile strength and elongation in accordance with ASTM D412. For tensile and elongation, foam is cut in straight specimen form with 1 inch thickness and width, and 5 inch length.

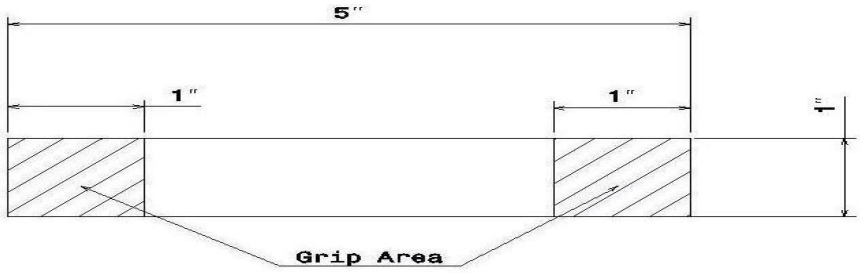
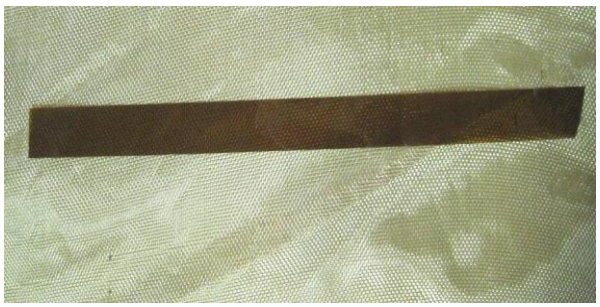


Figure 4.9 Foam Tensile Test Specimen.

4.3.4 Films

Upilex-S

Upilex-S, as indicated in Table 3.2, is to be tested to evaluate its tensile strength and elongation with reference to ASTM D412. Specimens are cut in straight shape with 0.00197 inch (50 microns) thickness.



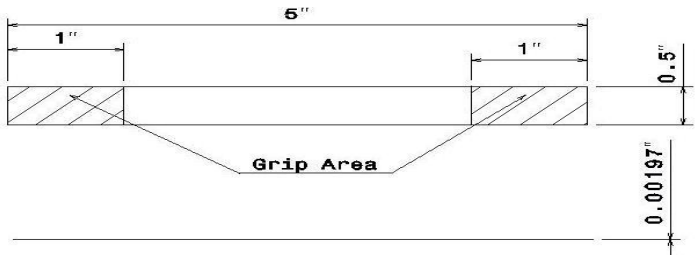


Figure 4.10 Upilex Tensile Test Specimen

4.3.5 Sealants

Sealants, as indicated in Table 3.2, is to be tested to evaluate its tensile strength and elongation, hardness, and volume swell according to ASTM D412, D 2240, and D471 respectively. Since the nature of stated ASTM standards requires no substrate, there is no surface preparation. Uncured materials are to be moulded in order to obtain the shapes recommended by ASTM as shown in the following figure. Before pouring the material into the pockets, surfaces are degreased and cleaned thoroughly. Then, since the mould is made of aluminum, all the contact areas are sprayed with release agent prior to the moulding process in order to prevent sealants from sticking to the surface.

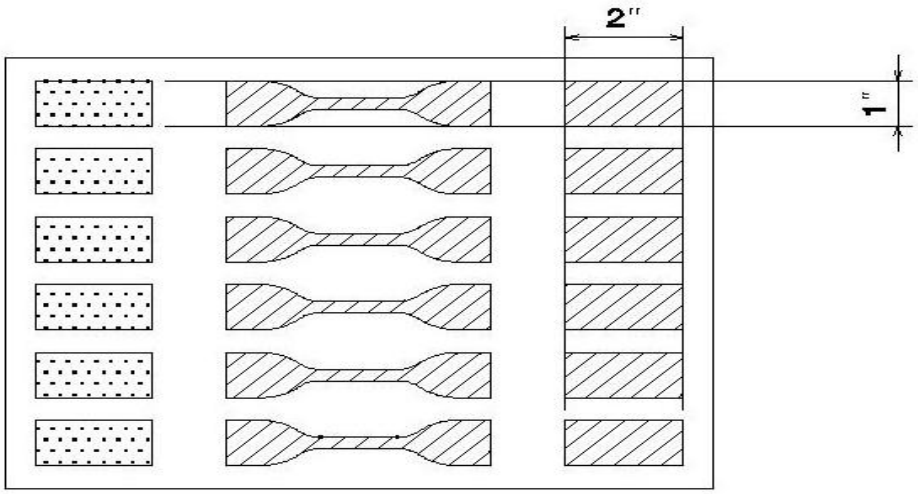


Figure 4.11 Sealant Tensile, Volume Swell, and Hardness Test Specimen Mould.

As seen in Figure specimens are made in shapes of dumbbell and rectangular. Dumbbell specimens are moulded in accordance with ASTM D412 Die C. Hardness and volume swell specimens are represented by dotted and dashed areas respectively. The thickness of dumbbell and volume swell specimens is 2 mm. Hardness specimens are 6 mm thick. Figure 4.12 shows the examples of cured sealant specimens.

- PR-1422 Class B is a two part sealant consists of Part A and B. It is to be the mixture of 13.3 Part A and 100 part B by weight. It cures at room temperature for 14 days.
- PS 890 Class B is a two part sealant consists of Part A and B. It is to be the mixture of 10 Part A and 100 part B by weight. It cures at room temperature for 14 days.
- Q4-2817 is a one part, ready to use, sealant. It cures at room temperature for 5 days.
- PR-1828 Class B is a two-part sealant consists of Part A and B. It is to be the mixture of 12 Part A and 100 part B by weight. It cures at room temperature, 50% relative humidity for 7 days.
- PR 1776 is a two part sealant consists of Part A and B. It is to be the mixture of 10 Part A and 100 part B by weight. It cures at room temperature for 14 days.

Figure 4.12 PR 1422 Class B Hardness, Tensile, and Volume Swell Specimens

Chapter 5 Results and Discussions

In this chapter, after 28-day soak period, the results of experimental work for each material are shown. Some results are depicted in graphic form in order to show the mechanical responses of elastomers under whether tensile or compressive force. As for metallic materials, results will be shown in pictorial form in Appendix section.

5.1 Test Results of Elastomers

5.1.1 Lap Shear Test Results

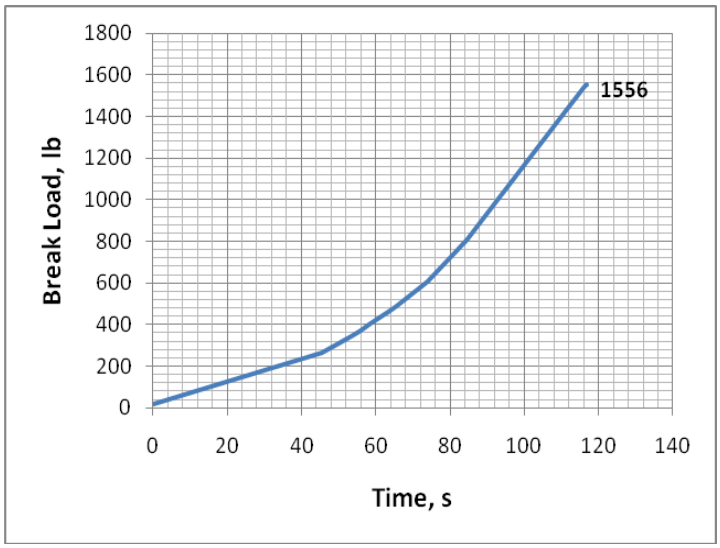
As stated in Table 3.2 Hysol product is subject to ASTM D1002 single lap shear test and 3 samples of each material are tested. After being soaked for 28 days in Jet A fuel, samples are taken out of the jars and tested in accordance with ASTM D1002.

The testing machine, as suggested, is capable of maintaining a rate of loading of 0.05 in. /min. It is provided with a suitable pair of self-aligning grips to hold the specimen. Specimens are placed in the grips of the testing machine so that the outer 25 mm (1 in.) of each end are in contact with the jaws and so that the long axis of the test specimen coincides with the direction of applied pull through the center line of the grip assembly. Subsequent to specimen mounting, load is applied at the rate of 0.05 in. /min as mentioned above. The following data is the results obtained from the computer.(**ASTM D1002-01**, *Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal), Section 5 & 6*).

Hysol EA 9394

Dry Test Results

Three non-aged specimens are tested for dry test results of lap shear strength (LSS).



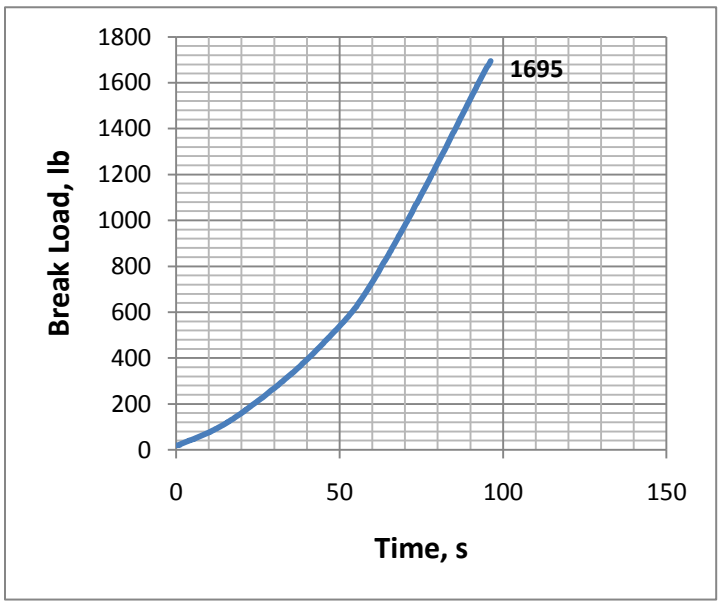
Specimen 1 fails at 1556 lb.

=>

LSS1 = F/A= 1556{lb.}/0.5 {in^2}

LSS1 = 3112 psi

Figure 5.1 Hysol EA 9394 Single Lap Shear Dry Test Specimen 1



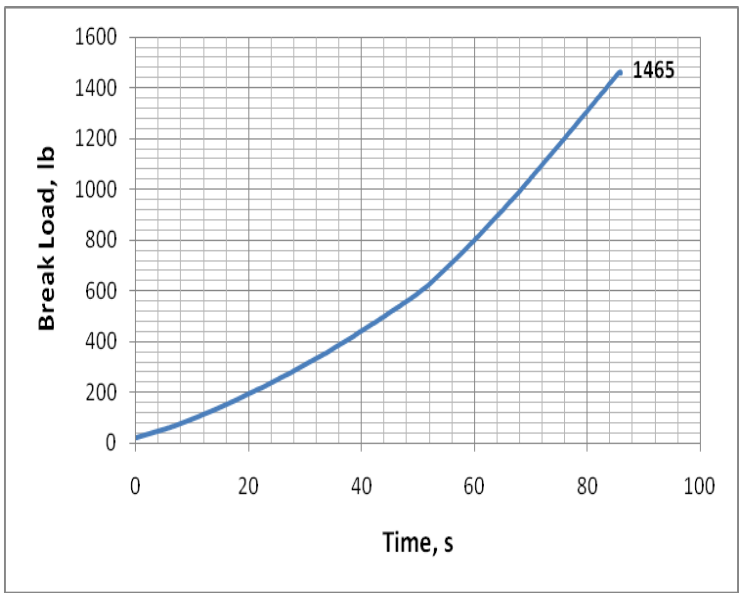
Specimen 2 fails at 1695 lb.

=>

LSS2 = F/A= 1695{lb.}/0.5 {in^2}

LSS2 = 3390 psi

Figure 5.2 Hysol EA 9394 Single Lap Shear Dry Test Specimen 2



Specimen 3 fails at 1465 lb.

=>

LSS3 = F/A= 1460{lb.}/0.5 {in^2}

LSS3 = 2930 psi

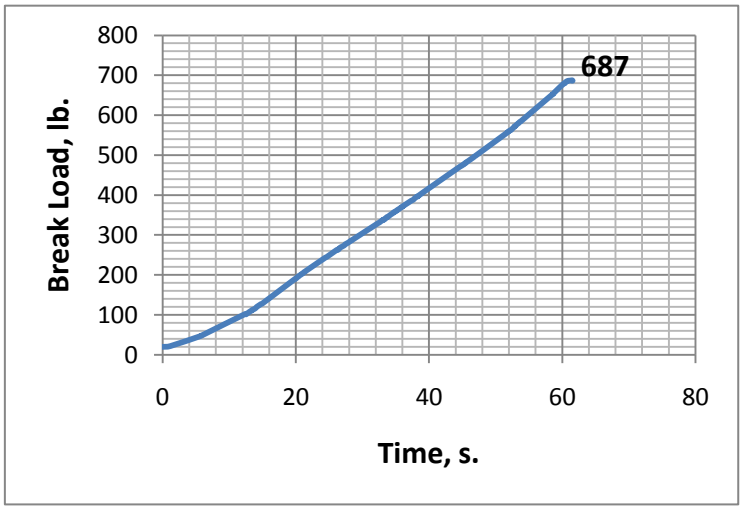
Figure 5.3 Hysol EA 9394 Single Lap Shear Dry Test Specimen 3

Taking the average value of 3 specimens;

LSS = 3144 psi

Post-Soak Test Results

As for dry test results three specimens are tested after 28 days soak period.



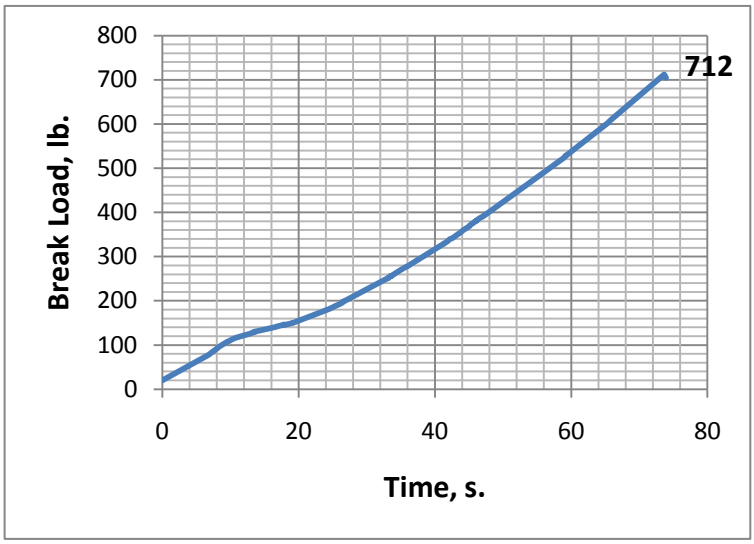
Specimen 1 fails at 687 lb.

=>

LSS1 = F/A= 687{lb.}/0.5 {in^2}

LSS1 = 1374 psi

Figure 5.4 Hysol EA 9394 Single Lap Shear Post-Soak Specimen 1



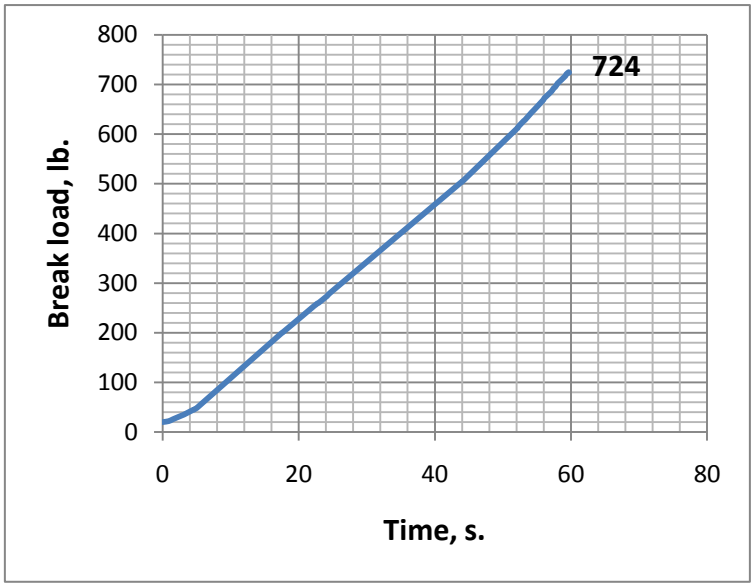
Specimen 2 fails at 712 lb.

=>

LSS2 = F/A= 712{lb.}/0.5 {in^2}

LSS2 = 1424 psi

Figure 5.5 Hysol EA 9394 Single Lap Shear Post-Soak Specimen 2



Specimen 3 fails at 724 lb.

=>

LSS3 = F/A= 724{lb.}/0.5 {in^2}

LSS3 = 1448 psi

Figure 5.6 Hysol EA 9394 Single Lap Shear Post-Soak Specimen 3

Taking the average value of 3 specimens;

LSS = 1415psi

5.1.2 Static Shear Test Results

After the static shear specimens removed from the jar, they are conditioned at room temperature for a while. Once they are ready, they are placed, as instructed in ASTM D4562, on the universal test machine as shown in Fig. 3 and loaded smoothly at about 500 lb./s (2200 N/s) using a free crosshead speed of 0.05 in./min (1.3 mm/min). (**ASTM D4562-01,** *Standard Test Method for Shear Strength of Adhesives Using Pin-and-Collar Specimen*, **ASTM D5363,** *Standard Specification for Anaerobic Single-Component Adhesives, and* **MIL-R-46082**, *Retaining Compounds, Single Component, Anaerobic.*).

The static shear strength is calculated by dividing the breakaway load by the bond area as follows:

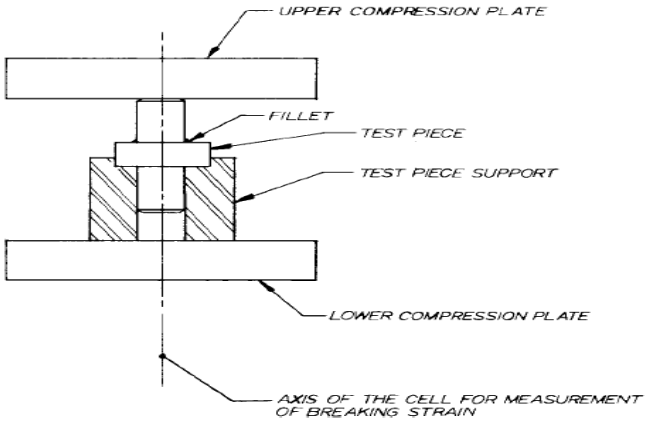


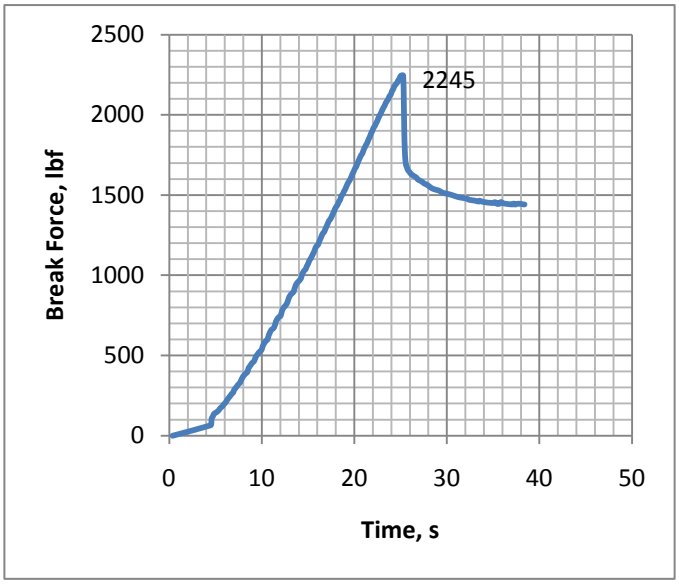
Figure 5.7 Static Shear Test Device

Shear Strength = Maximum Load / (Diameter x 3.14 x width) = 0.69 in^2

Loctite 609

Dry Test Results

Three non-aged specimens are tested in order to obtain static shear strength (SSS)



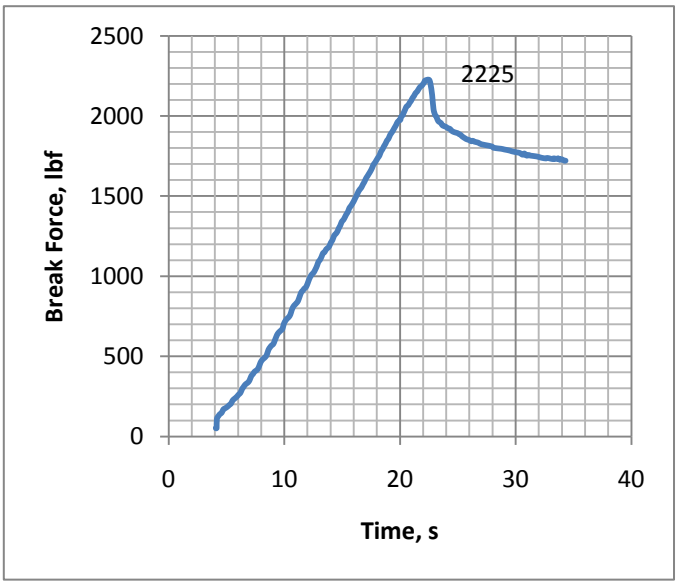
Specimen 1 fails at 2245 lb.

=>

SSS1 = F/A= 2245{lb.}/0.69 {in^2}

SSS1 = 3254 psi

Figure 5.8 Loctite 609 Static Shear Dry Test Specimen 1



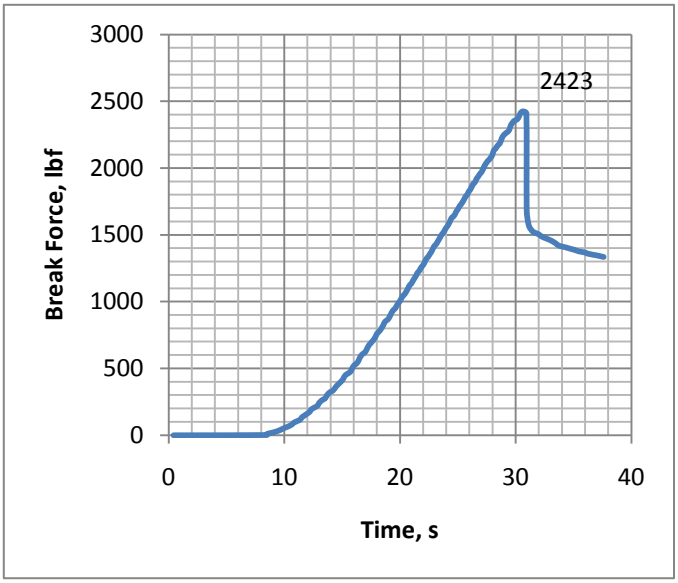
Specimen 2 fails at 2225 lb.

=>

SSS2 = F/A= 2245{lb.}/0.69 {in^2}

SSS2 = 3225 psi

Figure 5.9 Loctite 609 Static Shear Dry Test Specimen 2



Specimen 3 fails at 2225 lb.

=>

SSS3 = F/A= 2423{lb.}/0.69 {in^2}

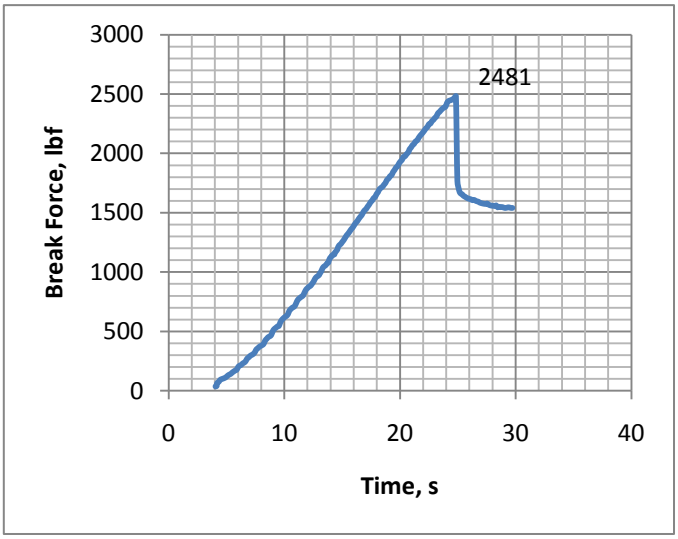
SSS3 = 3511 psi

Figure 5.10 Loctite 609 Static Shear Dry Test Specimen 3

Taking the average value of 3 specimens;

SSS = 3330 psi

Post-Soak Test Results



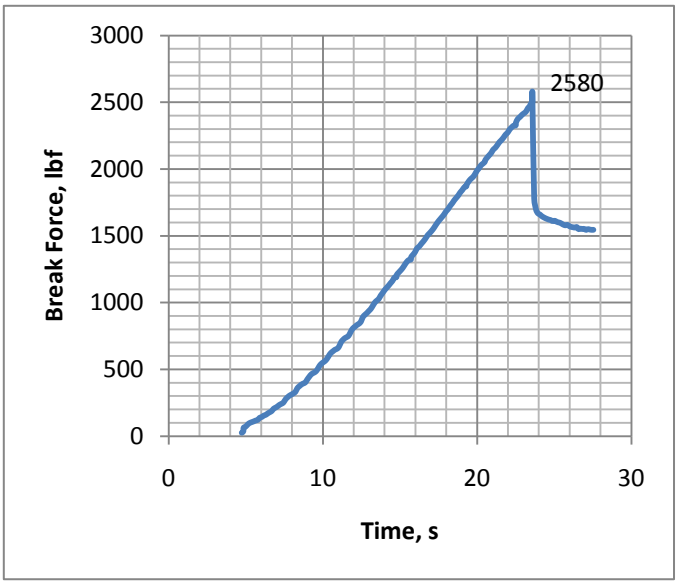
Specimen 1 fails at 2481 lb.

=>

SSS1 = F/A= 2481{lb.}/0.69 {in^2}

SSS1 = 3596 psi

Figure 5.11 Loctite 609 Static Shear Post-Soak Specimen 1



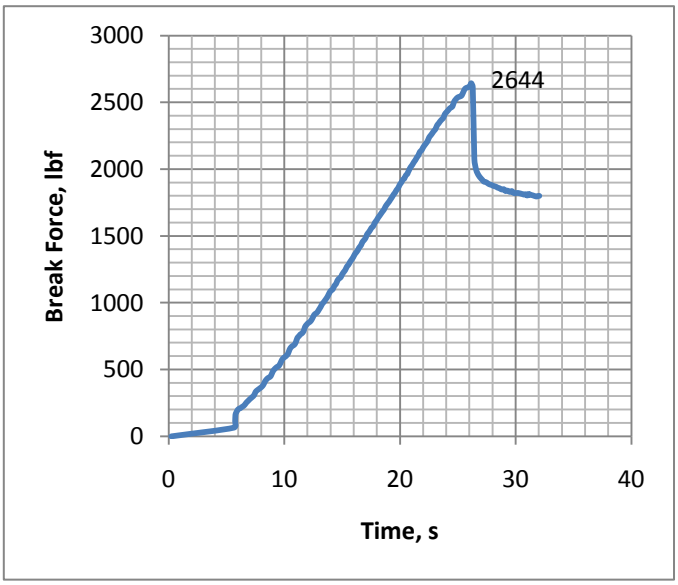
Specimen 2 fails at 2580 lb.

=>

SSS2 = F/A= 2580{lb.}/0.69 {in^2}

SSS2 = 3740 psi

Figure 5.12 Loctite 609 Static Shear Post-Soak Specimen 2



Specimen 3 fails at 2580 lb.

=>

SSS3 = F/A= 2644{lb.}/0.69 {in^2}

SSS3 = 3832 psi

Figure 5.13 Loctite 609 Static Shear Post-Soak Specimen 3

Taking the average value of 3 specimens;

SSS = 3723 psi

5.1.3 Tape Adhesion Test Results

EC 776SR and 825x309

As stated in ASTM 4054 both materials are subject to ASTM D3359 tape adhesion. For tape adhesion, there are two methods of testing recommended but Method A is the procedure to be followed. For tape adhesion there are few apparatus needed such as sharp razor blade, cutting guide, 1in. wide semitransparent pressure-sensitive tape, rubber eraser on the end of a pencil and a good source of light. An area clean, dry and free of blemishes is selected. Then two cuts, which intersect in the middle with 40 degree angle, of 1.5 in. length are made in the film with one steady motion. A piece of about 3 in. (75 mm) long tape is cut and the center of the tape is placed at the intersection of the cuts with the tape running in the same direction as the smaller angles. The tape by finger is placed in the area of the incisions and then is rubbed firmly with the eraser on the end of a pencil. Within 90 ± 30 s of application, remove the tape is removed by seizing the free end and pulling it off rapidly (not jerked) back upon itself at as close to an angle of 180° as possible. The test is repeated in two other locations on each test panel. Two specimens are tested from each material and the adhesion is rated in accordance with the following scale:

5A No peeling or removal,

4A Trace peeling or removal along incisions or at their intersection,

3A Jagged removal along incisions up to 1⁄16 in. (1.6 mm) on either side,

2A Jagged removal along most of incisions up to 1⁄8 in. (3.2 mm) on either side,

1A Removal from most of the area of the X under the tape,

0A Removal beyond the area of the X

(ASTM D3359-02, *Standard Test Methods for Measuring Adhesion by Tape Test.*)

Dry Test results;

Since there is not any trace of removal observed on both specimens for EC 776 SR and 825x309, they are rated 5A according to the scale given above.

Post-Soak Test results;

After the soak period, the same method is applied to specimens and there is no any trace of removal observed. Hence, both EC 776 SR and 825x309 are rated 5A.

5.1.4 Pencil Hardness Test Results

EC 776SR and 825x309

For pencil hardness a set of calibrated wood pencils, pencil holder cart with 45 degree angle, pencil sharpener, and abrasive paper with grit No. 400 are needed. Pencil tips are made sure to be smooth and flat by rubbing the pencil against the abrasive paper at 90 degree. The coated panel is placed to be tested on a level, firm horizontal surface. Pencil is placed in the scratcher cart and positioned at a 45 degree angle to the test panel. Starting with hardest lead cart is pushed away exerting enough force to either crush the lead edge or scratch/mar the paint. Length of the strokes is ¼ in. minimum. Process is repeated by selecting and testing the leads (going from harder to softer) until a lead is tested that will not mar or scratch the coated surface. The materials are rated in accordance with the following scale:

6H-5H-4H-3H-2H-H-F-HB-B-2B-3B-4B-5B-6B

(ASTM D3363-05, Standard *Test Method for Film Hardness by Pencil Test*.)

Dry Test results;

Starting from the softest one, it is found out that EC 776SR is rated 3H and 825x309 is rated higher than 6H.

Post-Soak Test results;

At the end of soak period, starting from the softest one, it is found out that EC 776SR is rated H and 825x309 is rated, as dry try test results, higher than 6H.

5.1.5 Tensile and Elongation Test Results

Referring to Table 3.2 O ring, sealant, foam, and film specimens are subject to tensile and elongation test.As mention in Chapter 3 test procedure will be in compliance with ASTM D412 and D1414. Both test standards require a universal tensile machine with 500 mm/min grip separation rate is used. Since ASTM D1414 is designated for O-rings, grips for testing consist of ball-bearing spools 9 mm diameter, and is capable of being brought within 19 mm center to center distance at closest approach. With this method materials tensile strenght and ultimate elongation rate are evaluated.(**ASTM D412-98a**, *Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers-Tension and* **ASTM D1414-94**, *Standard Test Methods for Rubber O-Rings.*)

Tensile Strength (TS) = F/A

F = Breakforce

A = twice the cross-sectional area calculated from actual thickness, W= 0.07 in, as follows:

= pi*W^2*2 = 1.57* W^2

=> TS= F/ (1.57* W^2)

Ultimate elongation, % = [2D + G -C] x 100

D = distance between centers of the spool grips at the time of rupture of specimen,

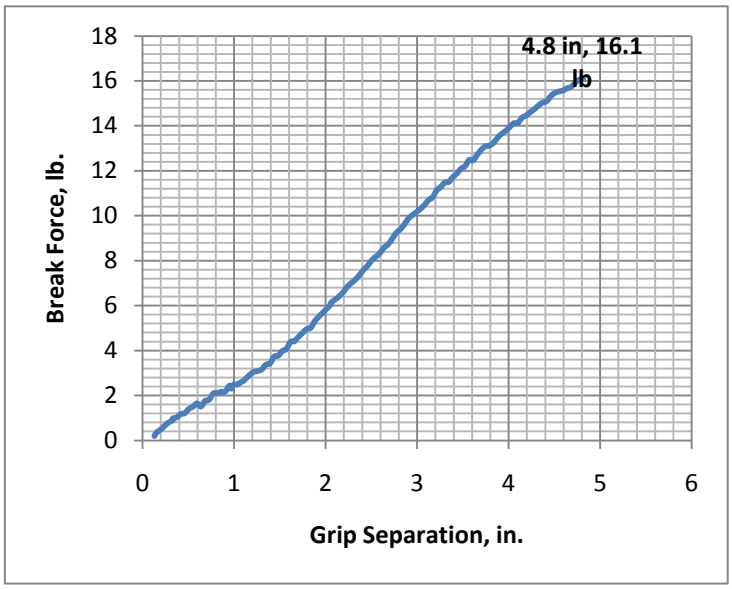
G = circumference of one spool (spool diameter x 3.14) = 0.2 x 3.14 = 0.628 in.

C = inside circumference of the specimen (or inside diameter x 3.14)

= (1.239-014) x 3.14 = 3.45 in

Parker VM 128 O-Ring

Dry Test results;



Specimen 1 fails at 16.1 lb. and grip separation of 3.1 in.

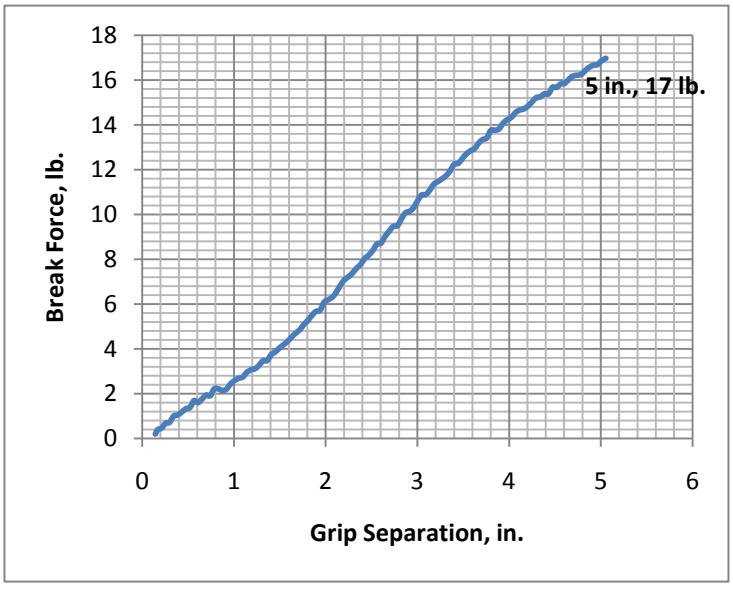
=>

TS1= 16.1/(1.57*0.07^2) = 2093 psi

E1 = (2x3.1+0.628-3.45)x100

= % 338

Figure 5.14 O-Ring Pre-Soak Tensile Test Specimen 1



Specimen 2 fails at 17 lb. and grip separation of 3.3 in.

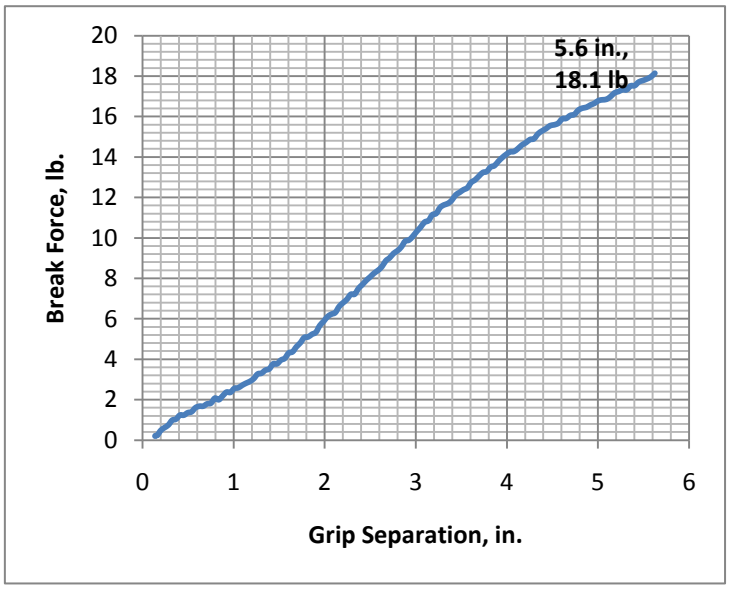
=>

TS2= 17/(1.57*0.07^2) = 2210 psi

E2 = (2x3.3+0.628-3.45)x100

= % 378

Figure 5.15 O-Ring Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 18.1 lb. and grip separation of 3.9 in.

=>

TS3= 18.1/(1.57*0.07^2) = 2353 psi

E3 = (2x3.9+0.628-3.45)x100

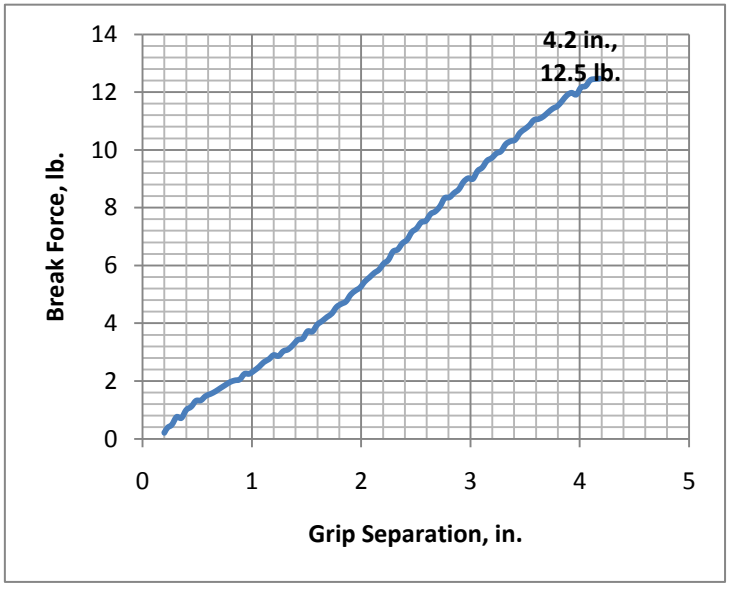
= % 498

Figure 5.16 O-Ring Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 2218 psi	E % = 405

Post-Soak Test results;



Specimen 1 fails at 12.5 lb. and grip separation of 2.5 in.

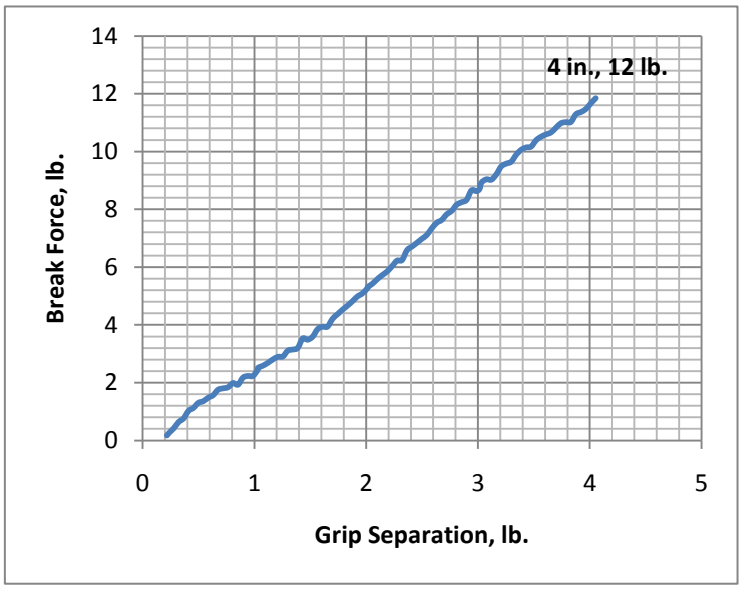
=>

TS1= 12.5/(1.57*0.07^2) = 1625 psi

E1 = (2x2.5+0.628-3.45)x100

= % 218

Figure 5.17 O-Ring Post-Soak Tensile Test Specimen 1



Specimen 2 fails at 12 lb. and grip separation of 2.3 in.

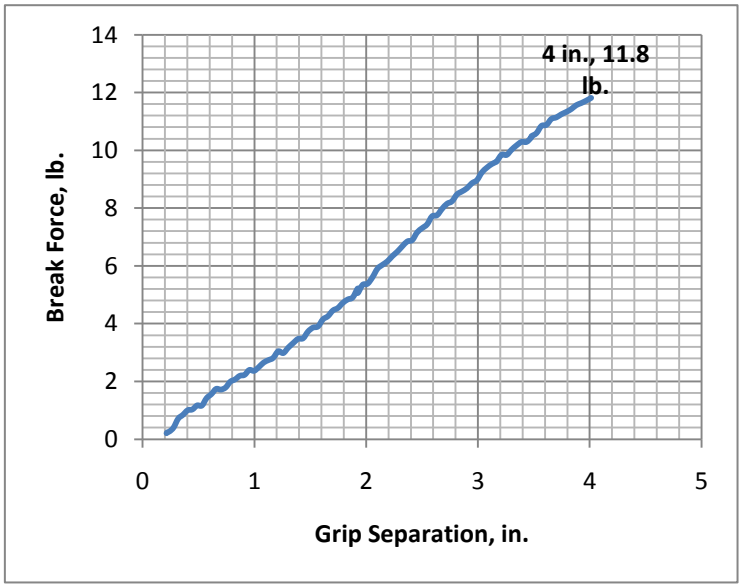
=>

TS2= 12/(1.57*0.07^2) = 1560 psi

E2 = (2x2.3+0.628-3.45)x100

= % 178

Figure 5.18 O-Ring Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 11.8 lb. and grip separation of 2.3 in.

=>

TS3= 11.8/(1.57*0.07^2) = 1534 psi

E3 = (2x2.3+0.628-3.45)x100

= % 178

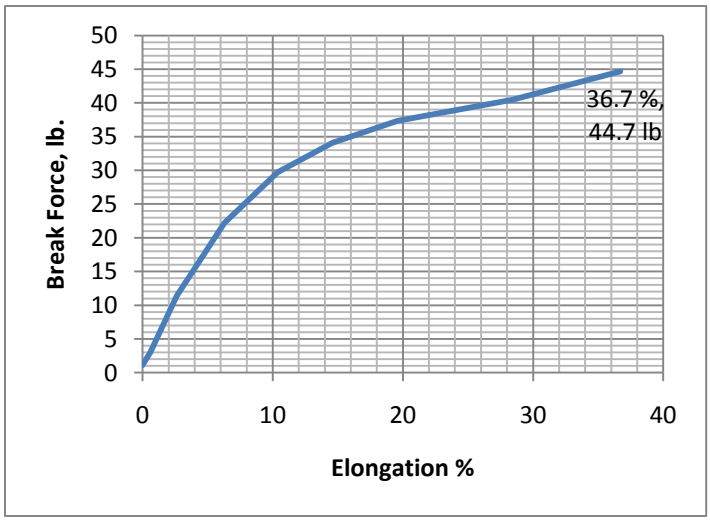
Figure 5.19 O-Ring Post-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 1573 psi	E % = 192

Upilex-S Film

Dry Test results;



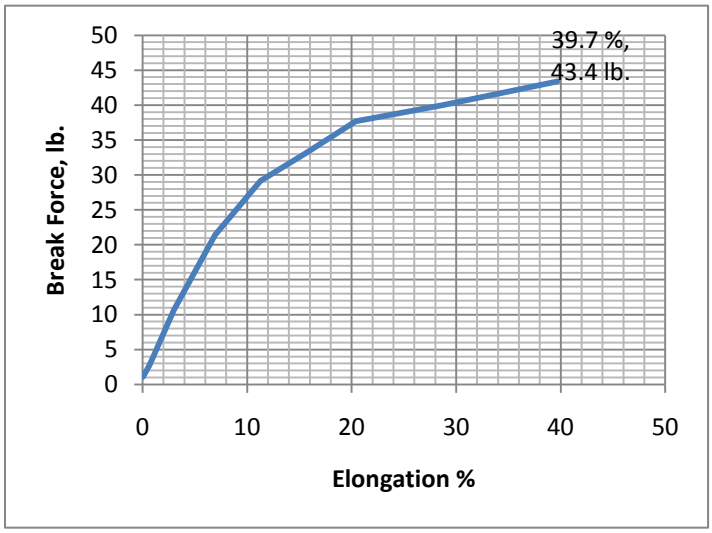
Specimen 1 fails at 44.7 lb. and 36.7 % extension

=>

TS1 = F/A= 44.7{lb.}/0.0025 {in^2}

TS1 = 17880 psi

Figure 5.20 Upilex-S Pre-Soak Tensile Test Specimen 1



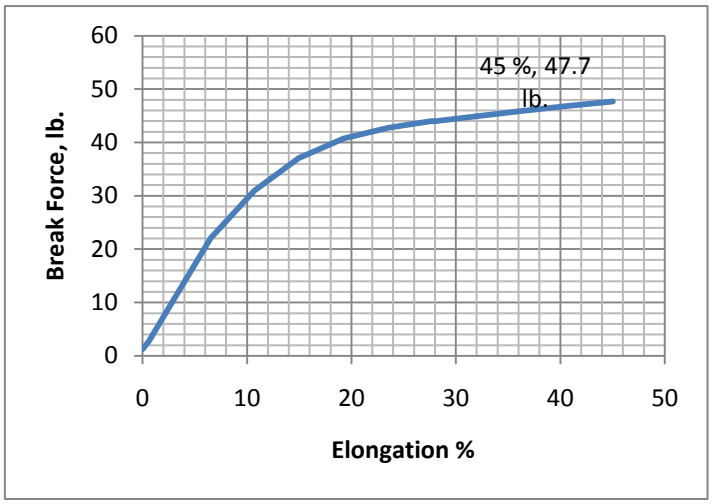
Specimen 2 fails at 43.4 lb. and 39.7 % extension

=>

TS2 = F/A= 43.4{lb.}/0.0025 {in^2}

TS2 = 17360 psi

Figure 5.21 Upilex-S Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 47.7 lb. and 45 % extension

=>

TS3 = F/A= 47.7{lb.}/0.0025 {in^2}

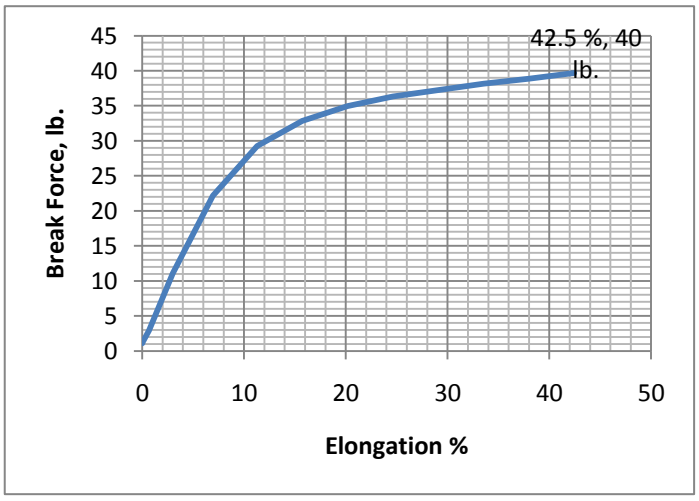
TS3 = 19080 psi

Figure 5.22 Upilex-S Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 18107 psi E % = 40.5

Post-Soak Test results;



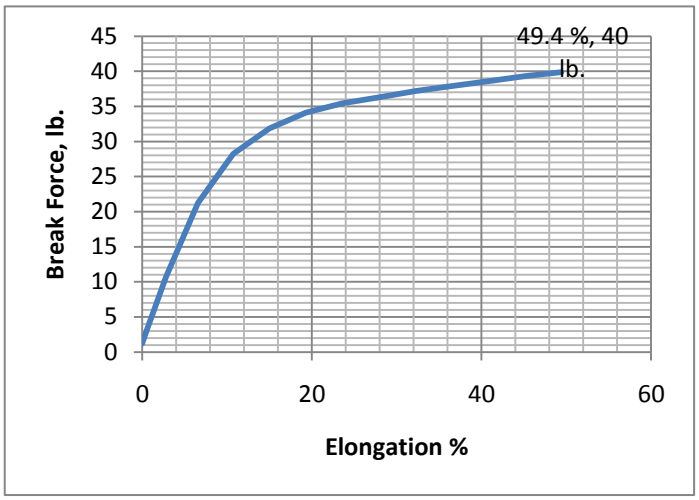
Specimen 1 fails at 40 lb. and 42.5 % extension

=>

TS1 = F/A= 40{lb.}/0.0025 {in^2}

TS1 = 16000 psi

Figure 5.23 Upilex-S Post-Soak Tensile Test Specimen 1



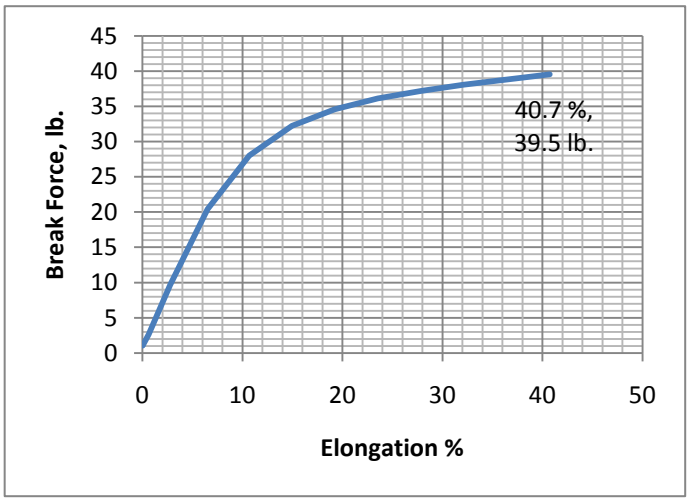
Specimen 2 fails at 40 lb. and 49.4 % extension

=>

TS2 = F/A= 40{lb.}/0.0025 {in^2}

TS2 = 16000 psi

Figure 5.24 Upilex-S Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 39.5 lb. and 40.7 % extension

=>

TS3 = F/A= 40{lb.}/0.0025 {in^2}

TS3 = 15800 psi

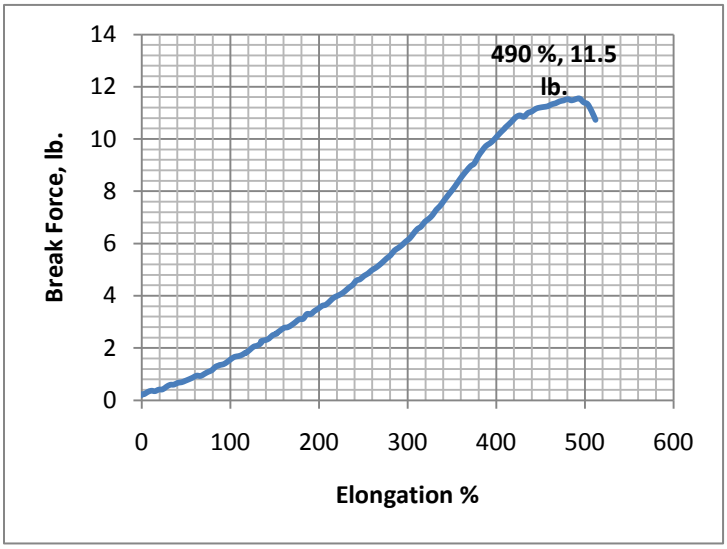
Figure 5.25 Upilex-S Post-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 15934 psi E % = 44.2

Crest Foam

Dry Test results;



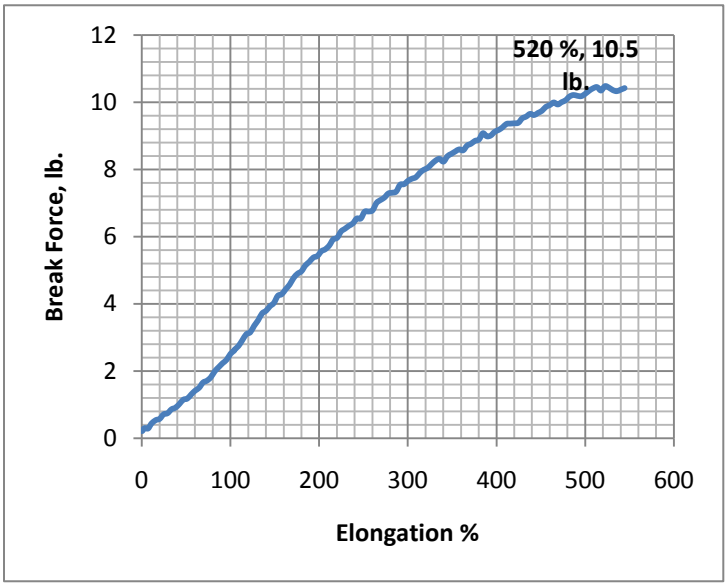
Specimen 1 fails at 11.5 lb. and 490 % extension

=>

TS1 = F/A= 11.5{lb.}/1 {in^2}

TS1 = 11.5 psi

Figure 5.26 CrestFoam Pre-Soak Tensile Test Specimen 1



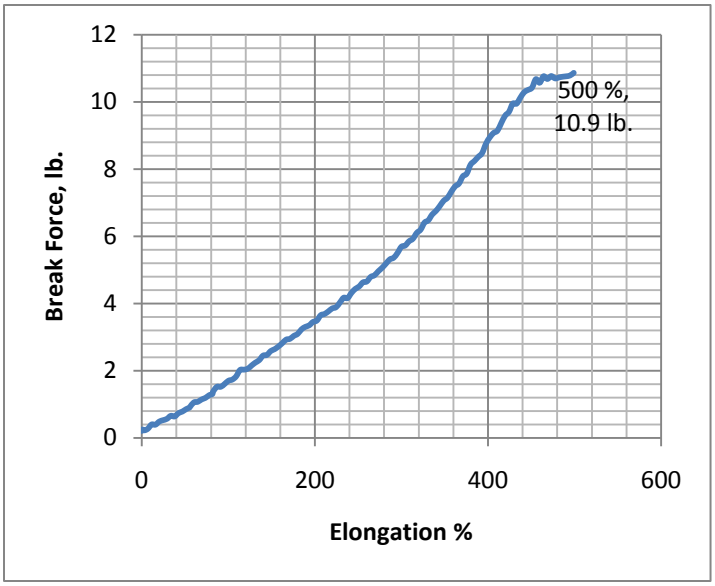
Specimen 2 fails at 10.5 lb. and 520 % extension

=>

TS2 = F/A= 10.5{lb.}/1 {in^2}

TS2 = 10.5 psi

Figure 5.27 CrestFoam Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 10.9 lb. and 500 % extension

=>

TS3 = F/A= 10.9{lb.}/1 {in^2}

TS3 = 10.9psi

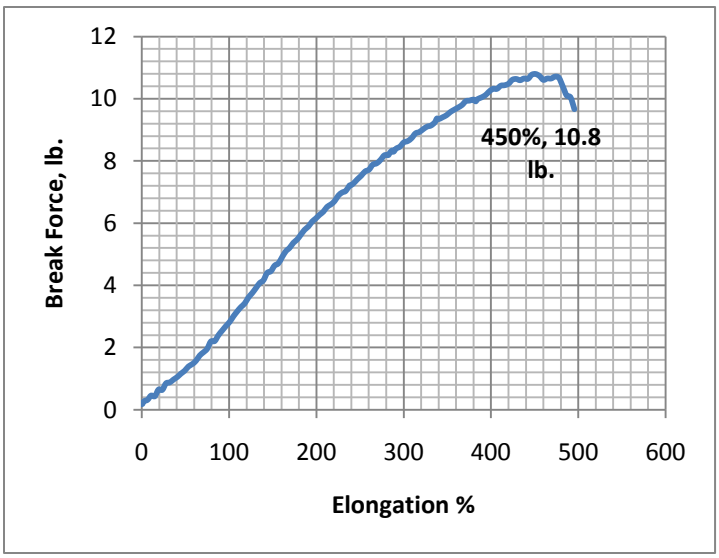
Figure 5.28 CrestFoam Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 11 psi

E % = 504

Post-Soak Test results;



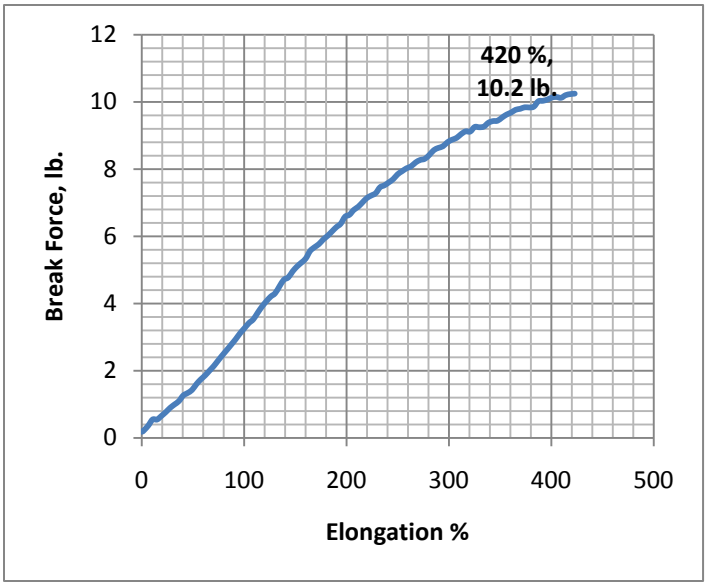
Specimen 1 fails at 10.8 lb. and 450 % extension

=>

TS1 = F/A= 10.9{lb.}/1 {in^2}

TS1 = 10.8psi

Figure 5.29 CrestFoam Post-Soak Tensile Test Specimen 1



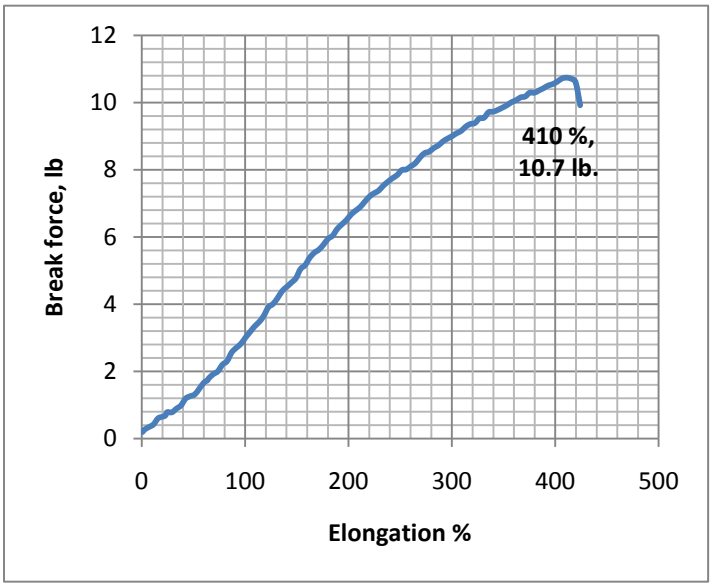
Specimen 2 fails at 10.2 lb. and 420 % extension

=>

TS2 = F/A= 10.2{lb.}/1 {in^2}

TS2 = 10.2psi

Figure 5.30 CrestFoam Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 10.7 lb. and 410 % extension

=>

TS3 = F/A= 10.7{lb.}/1 {in^2}

TS3 = 10.7psi

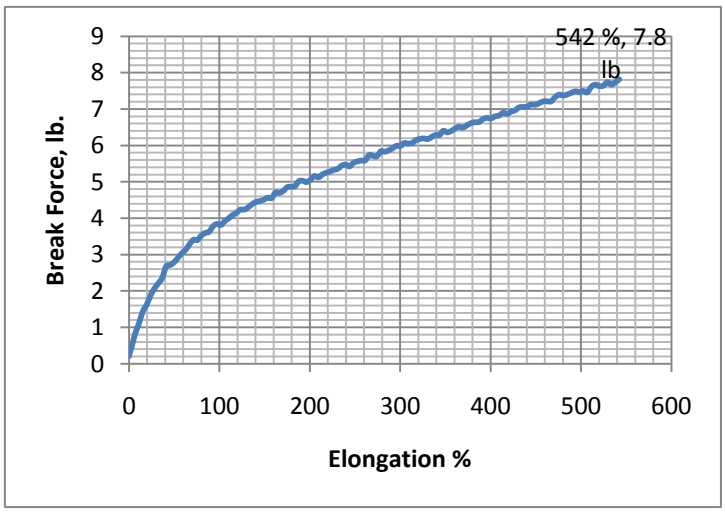
Figure 5.31 CrestFoam Post-Soak Tensile Test Specimen 2

Taking the average value of 3 specimens;

TS = 10.6 psi E % = 427

PR 1422 Sealant

Dry Test Results;



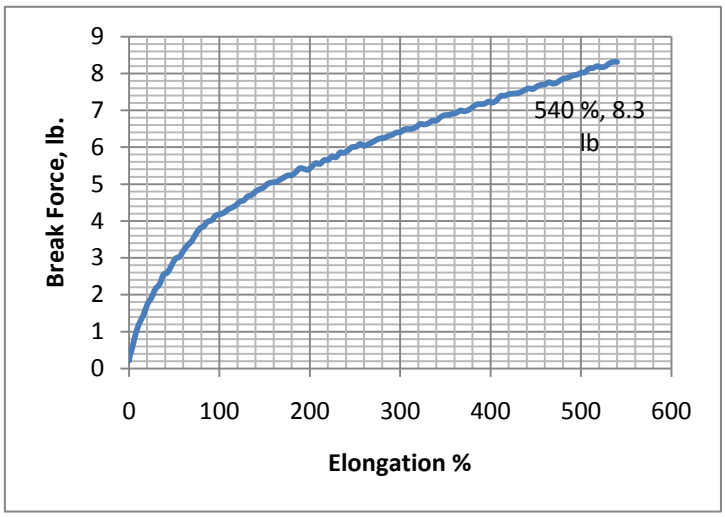
Specimen 1 fails at 7.8 lb. and 542 % extension

=>

TS1 = F/A= 7.8{lb.}/0.01536 {in^2}

TS1 = 508 psi

Figure 5.32 PR 1422 Pre-Soak Tensile Test Specimen 1



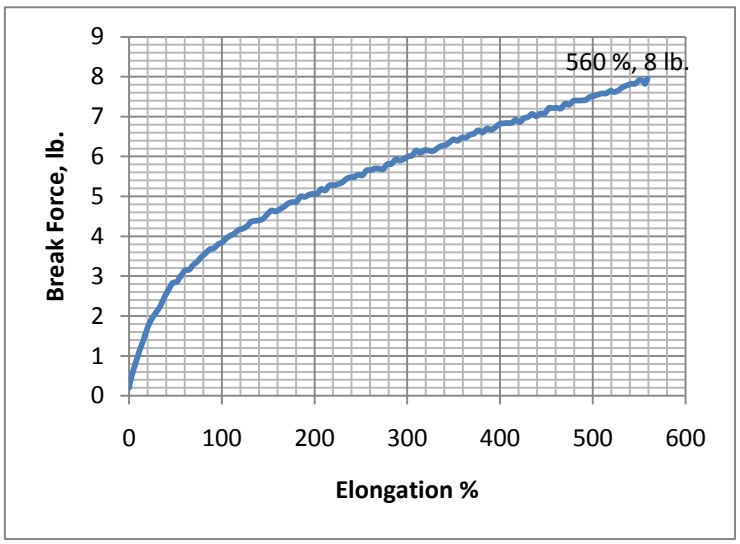
Specimen 2 fails at 8.3 lb. and 540 % extension

=>

TS2 = F/A= 8.3{lb.}/0.01536 {in^2}

TS2 = 540 psi

Figure 5.33 PR 1422 Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 8 lb. and 560 % extension

=>

TS3 = F/A= 8{lb.}/0.01536 {in^2}

TS3 = 520 psi

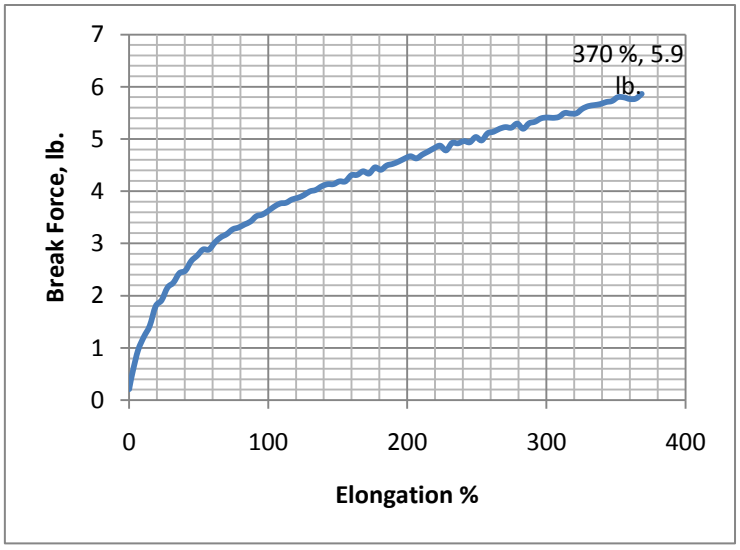
Figure 5.34PR 1422 Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 523 psi

E % = 547

Post-Soak Test Results;



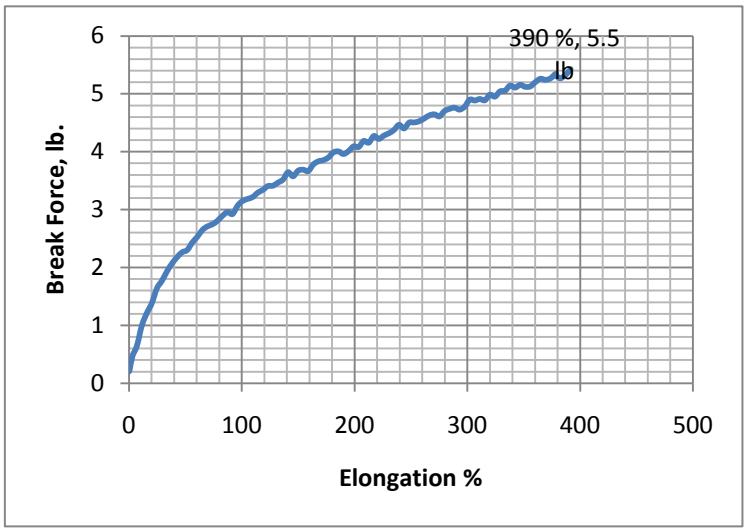
Specimen 1 fails at 5.9 lb. and 370 % extension

=>

TS1 = F/A= 5.9{lb.}/0.01536 {in^2}

TS1 = 384 psi

Figure 5.35 PR 1422 Post-Soak Tensile Test Specimen 1



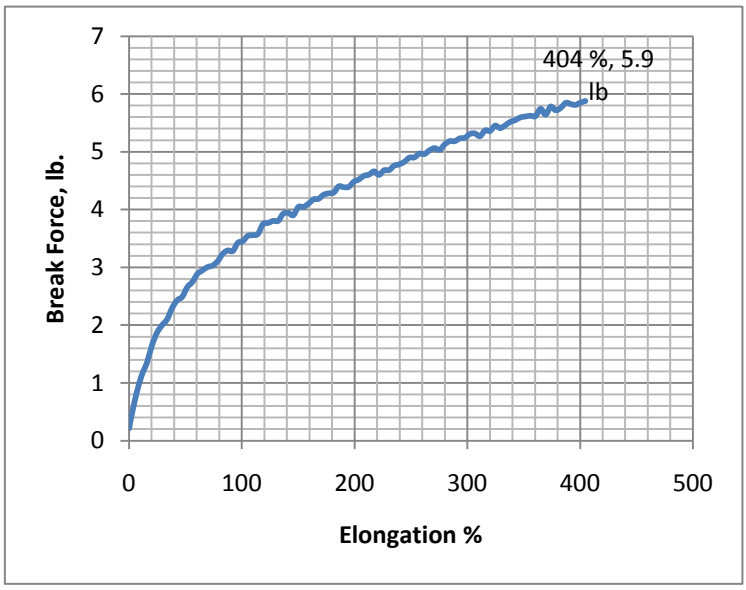
Specimen 2 fails at 5.5 lb. and 390 % extension

=>

TS2 = F/A= 5.5{lb.}/0.01536 {in^2}

TS2 = 358 psi

Figure 5.36 PR 1422 Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 5.9 lb. and 404 % extension

=>

TS3 = F/A= 5.9{lb.}/0.01536 {in^2}

TS3 = 384 psi

Figure 5.37 PR 1422 Post-Soak Tensile Test Specimen 3

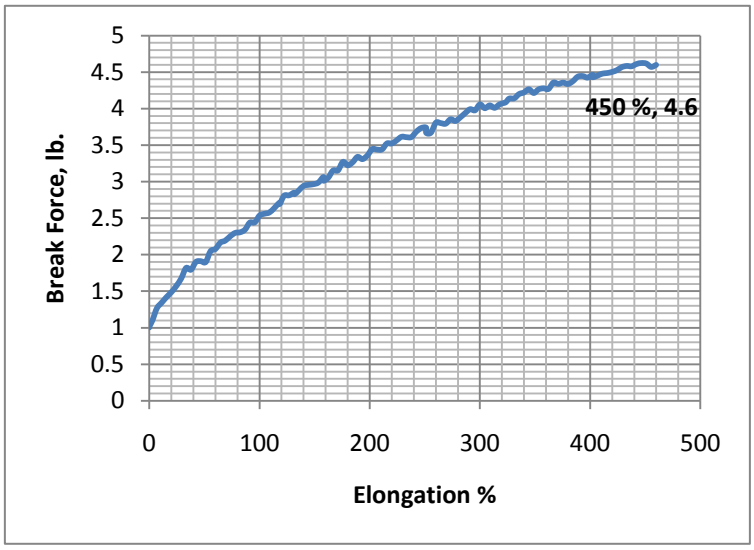
Taking the average value of 3 specimens;

TS = 375 psi

E % = 388

PS 890 Sealant

Dry Test Results;



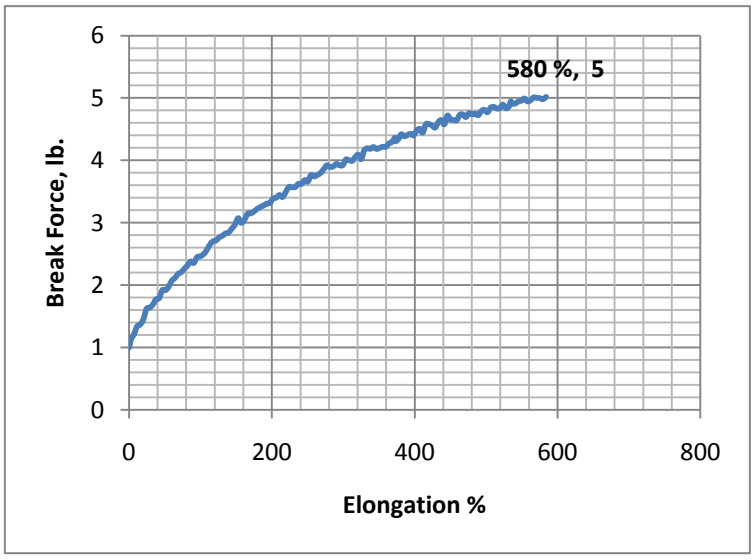
Specimen 1 fails at 4.6 lb. and 450 % extension

=>

TS1 = F/A= 4.6{lb.}/0.01536 {in^2}

TS1 = 300 psi

Figure 5.38 PS 890 Pre-Soak Tensile Test Specimen 1



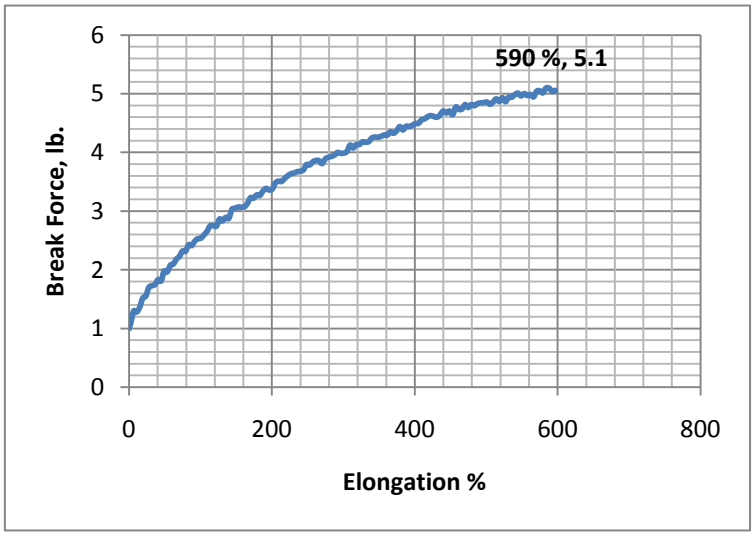
Specimen 2 fails at 5 lb. and 580 % extension

=>

TS2 = F/A= 5{lb.}/0.01536 {in^2}

TS2 = 325 psi

Figure 5.39 PS 890 Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 5.1 lb. and 590 % extension

=>

TS3= F/A= 5.1{lb.}/0.01536 {in^2}

TS3 = 332 psi

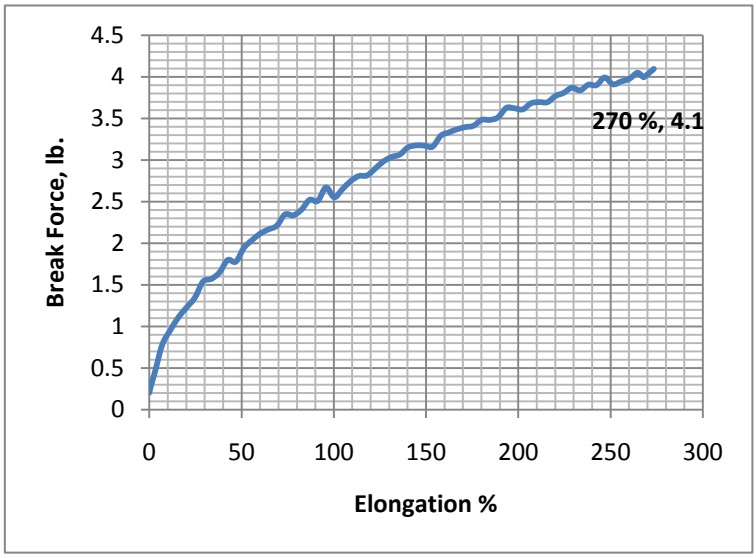
Figure 5.40 PS 890 Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 320 psi

E % = 540

Post-Soak Test Results;



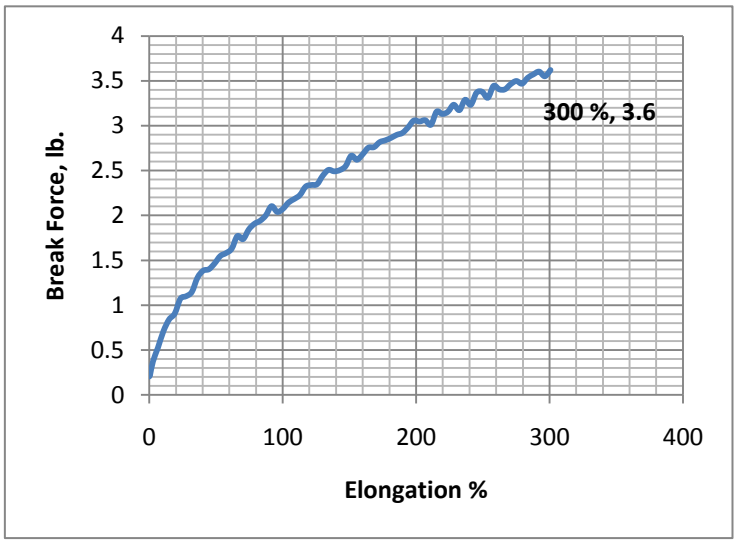
Specimen 1 fails at 4.1 lb. and 270 % extension

=>

TS1= F/A= 4.1{lb.}/0.01536 {in^2}

TS1 = 267 psi

Figure 5.41 PS 890 Post-Soak Tensile Test Specimen 1



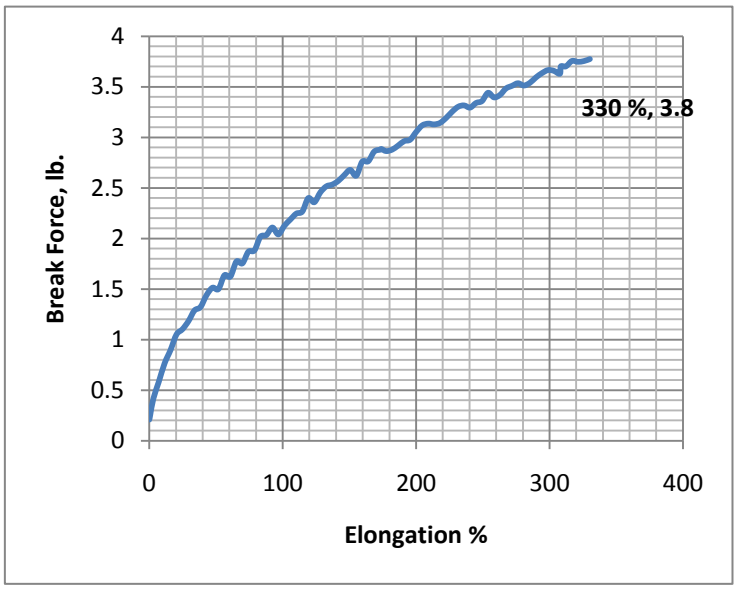
Specimen 2 fails at 3.6 lb. and 300 % extension

=>

TS2 = F/A= 3.6{lb.}/0.01536 {in^2}

TS2 = 235 psi

Figure 5.42 PS 890 Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 3.8 lb. and 330 % extension

=>

TS3 = F/A= 3.8{lb.}/0.01536 {in^2}

TS3 = 248 psi

Figure 5.43 PS 890 Post-Soak Tensile Test Specimen 3

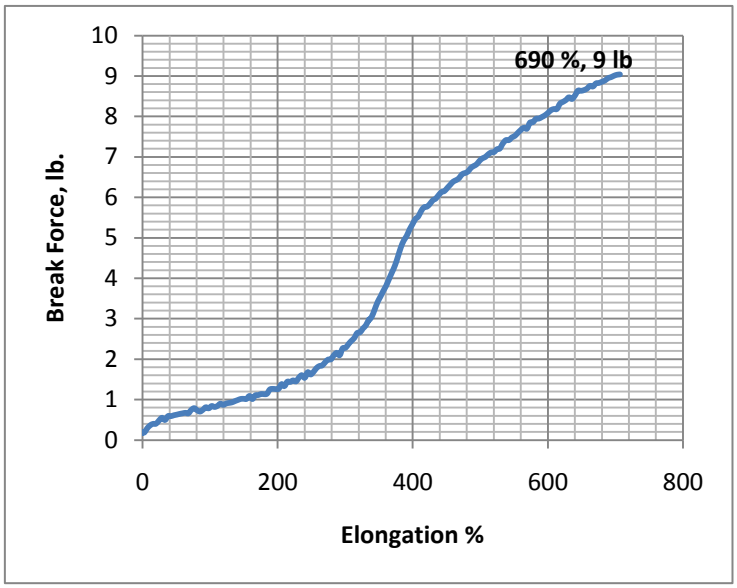
Taking the average value of 3 specimens;

TS = 250 psi

E % = 300

Q4 2817 Sealant

Dry Test Results;



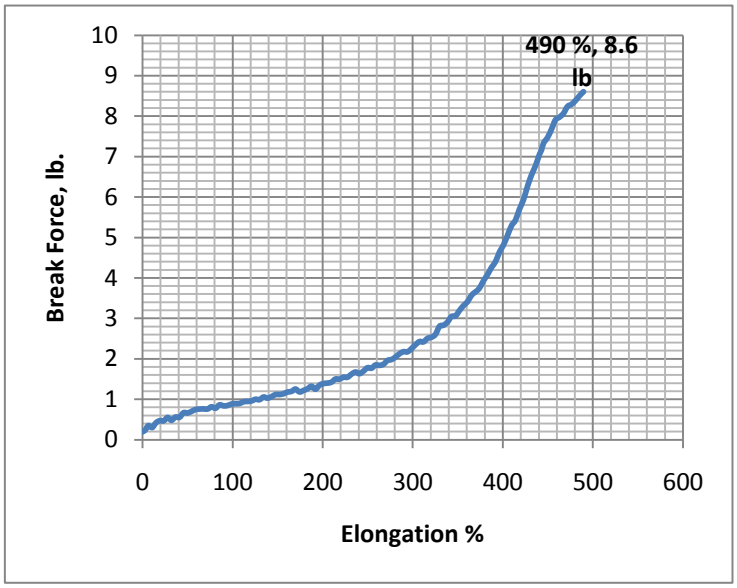
Specimen 1 fails at 9 lb. and 690 % extension

=>

TS1 = F/A= 9{lb.}/0.01536 {in^2}

TS1 = 586 psi

Figure 5.44 Q4-2817 Pre-Soak Tensile Test Specimen 1



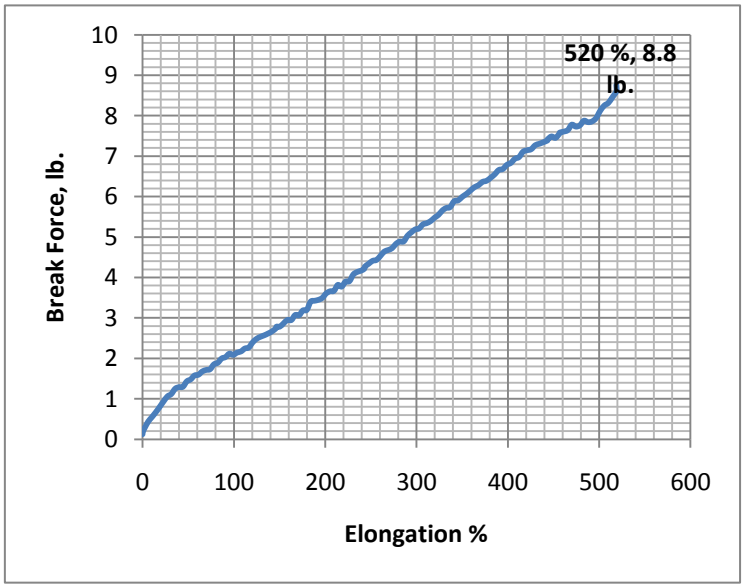
Specimen 2 fails at 8.6 lb. and 490 % extension

=>

TS2 = F/A= 8.6{lb.}/0.01536 {in^2}

TS2 = 560 psi

Figure 5.45 Q4-2817 Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 8.8 lb. and 520 % extension

=>

TS3 = F/A= 8.8{lb.}/0.01536 {in^2}

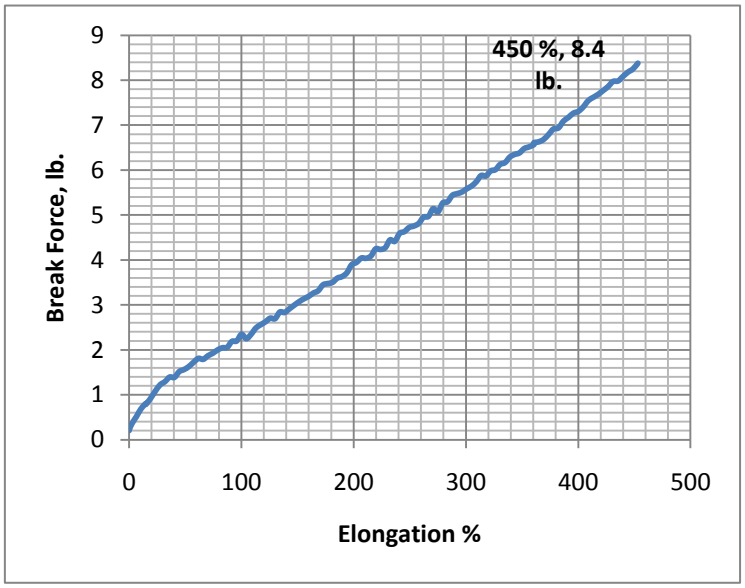
TS3 = 573 psi

Figure 5.46 Q4-2817 Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 573 psi E % = 567

Post-Soak Test Results;



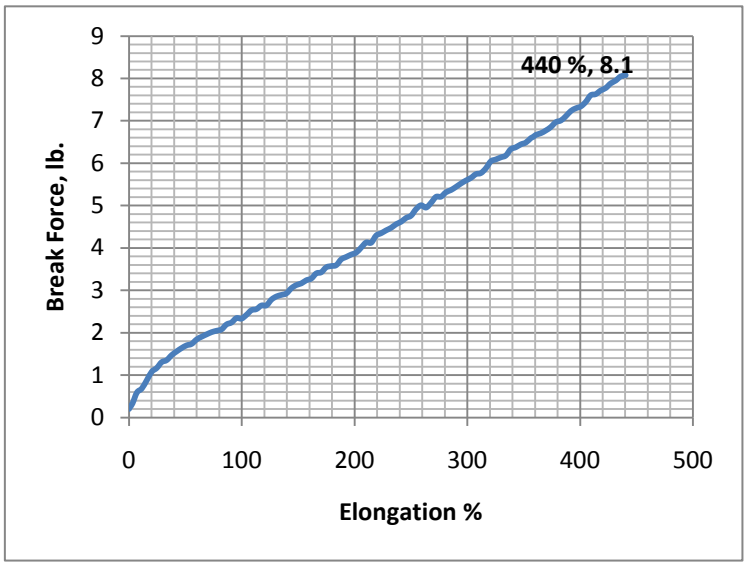
Specimen 1 fails at 8.4 lb. and 450 % extension

=>

TS1 = F/A= 8.4{lb.}/0.01536 {in^2}

TS1 = 547 psi

Figure 5.47 Q4-2817 Post-Soak Tensile Test Specimen 1



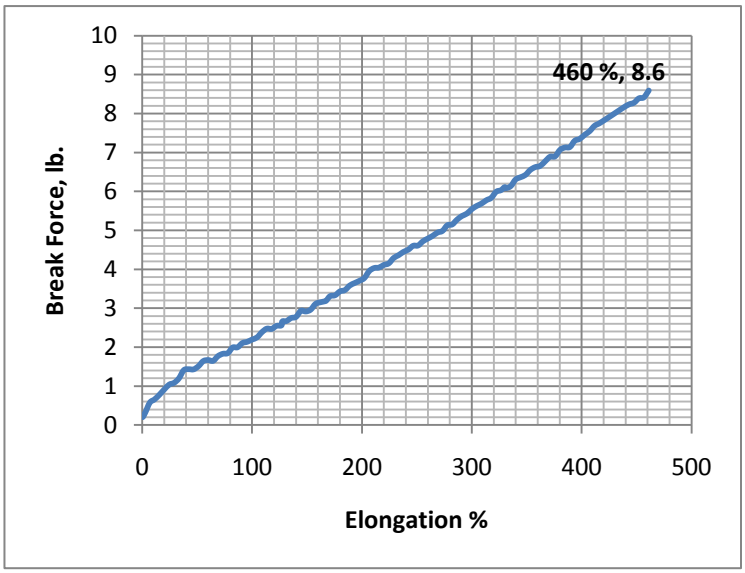
Specimen 2 fails at 8.1 lb. and 440 % extension

=>

TS2 = F/A= 8.1{lb.}/0.01536 {in^2}

TS2 = 527 psi

Figure 5.48 Q4-2817 Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 8.6 lb. and 460 % extension

=>

TS3 = F/A= 8.6{lb.}/0.01536 {in^2}

TS3 = 560 psi

Figure 5.49 Q4-2817 Post-Soak Tensile Test Specimen 3

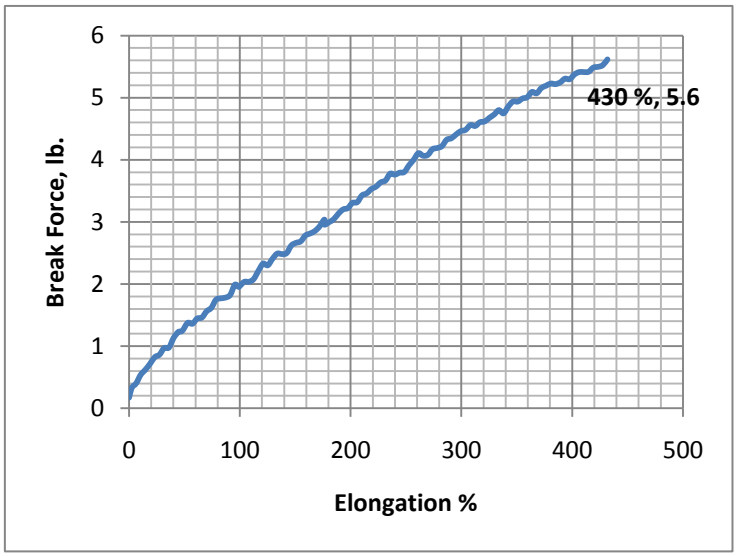
Taking the average value of 3 specimens;

TS = 545 psi

E % = 450

PR 1776 Sealant

Dry Test Results;



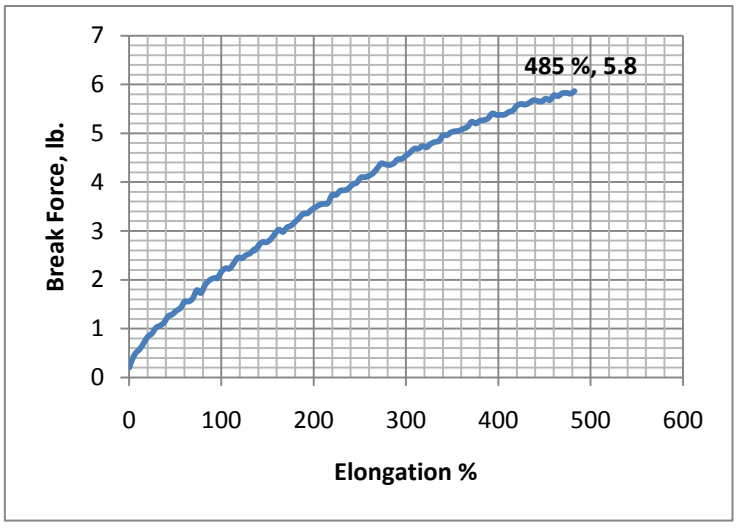
Specimen 1 fails at 5.6 lb. and 430 % extension

=>

TS1 = F/A= 5.6{lb.}/0.01536 {in^2}

TS1 = 365 psi

Figure 5.50 PR 1776 Pre-Soak Tensile Test Specimen 1



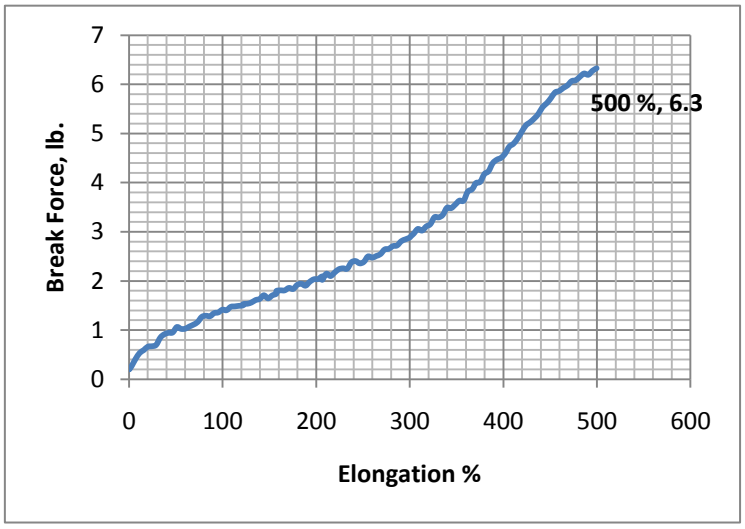
Specimen 2 fails at 5.8 lb. and 485 % extension

=>

TS2 = F/A= 5.8{lb.}/0.01536 {in^2}

TS2 = 378 psi

Figure 5.51 PR 1776 Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 6.3 lb. and 500 % extension

=>

TS3 = F/A= 6.3{lb.}/0.01536 {in^2}

TS3 = 410 psi

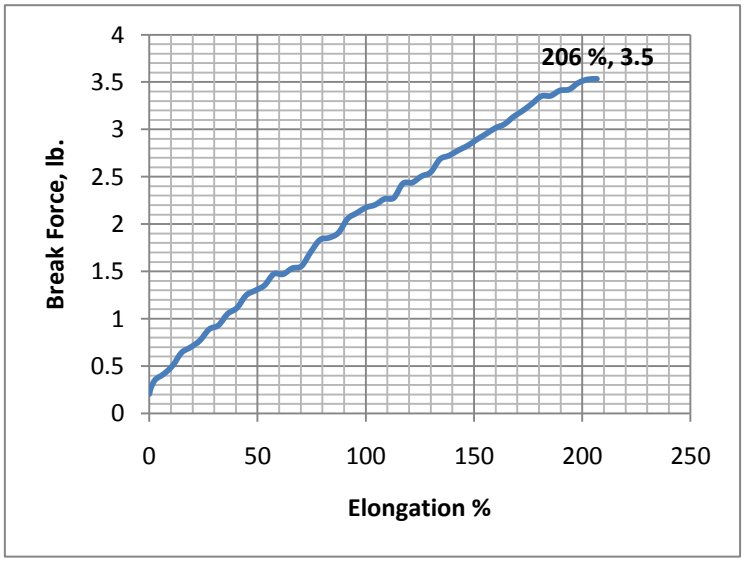
Figure 5.52 PR 1776 Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 384 psi

E % = 471

Post-Soak Test Results;



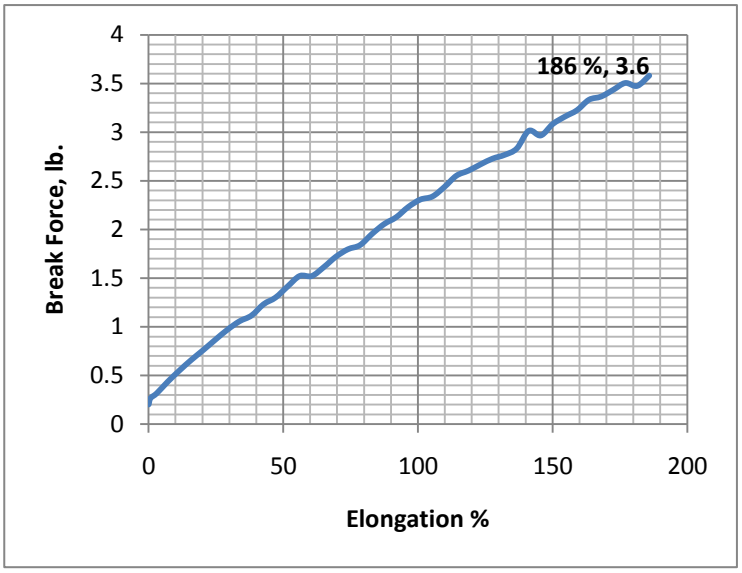
Specimen 1 fails at 3.5 lb. and 206 % extension

=>

TS1 = F/A= 3.5{lb.}/0.01536 {in^2}

TS1 = 228 psi

Figure 5.53 PR 1776 Post-Soak Tensile Test Specimen 1



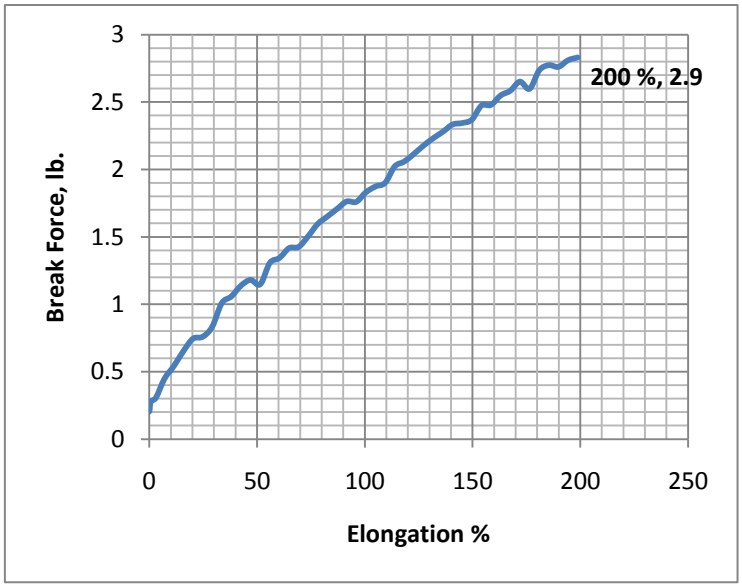
Specimen 2 fails at 3.6 lb. and 186 % extension

=>

TS2 = F/A= 3.6{lb.}/0.01536 {in^2}

TS2 = 234 psi

Figure 5.54 PR 1776 Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 2.9 lb. and 200 % extension

=>

TS3 = F/A= 2.9{lb.}/0.01536 {in^2}

TS3 = 189 psi

Figure 5.55 PR 1776 Post-Soak Tensile Test Specimen 3

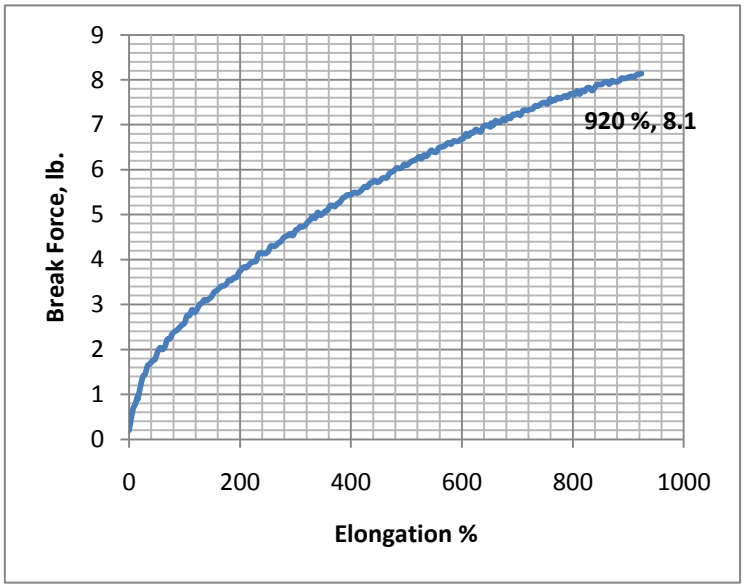
Taking the average value of 3 specimens;

TS = 217 psi

E % = 197

PR 1828 Sealant

Dry Test Results;



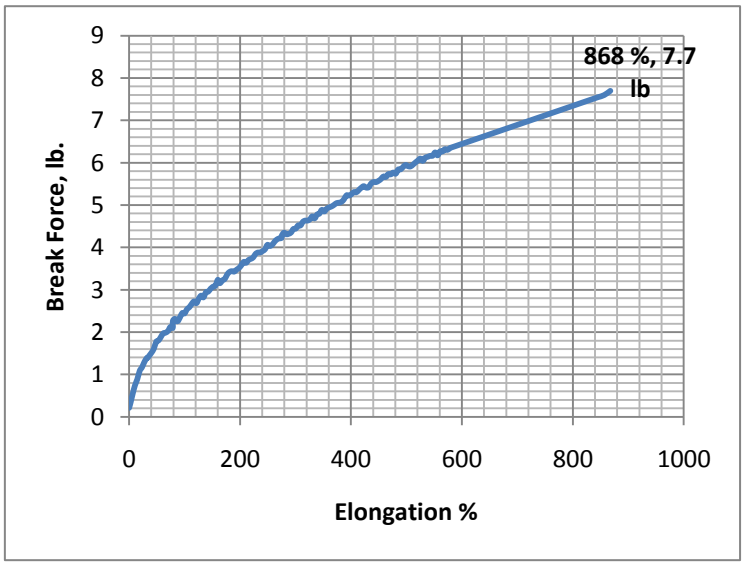
Specimen 1 fails at 8.1lb. and 920 % extension

=>

TS1 = F/A= 8.1{lb.}/0.01536 {in^2}

TS1 = 527 psi

Figure 5.56 PR 1828 Pre-Soak Tensile Test Specimen 1



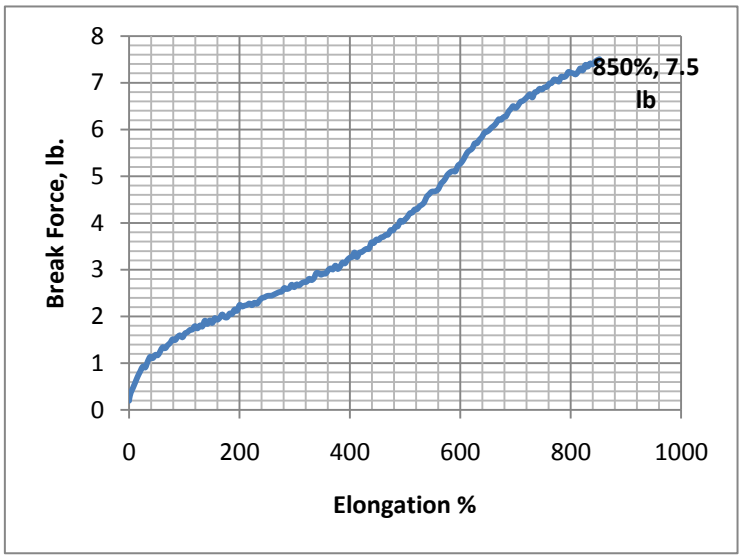
Specimen 2 fails at 7.7 lb. and 868 % extension

=>

TS2 = F/A= 7.7 {lb.}/0.01536 {in^2}

TS2 = 501 psi

Figure 5.57 PR 1828 Pre-Soak Tensile Test Specimen 2



Specimen 3 fails at 7.5 lb. and 850 % extension

=>

TS3 = F/A= 7.5{lb.}/0.01536 {in^2}

TS3 = 488 psi

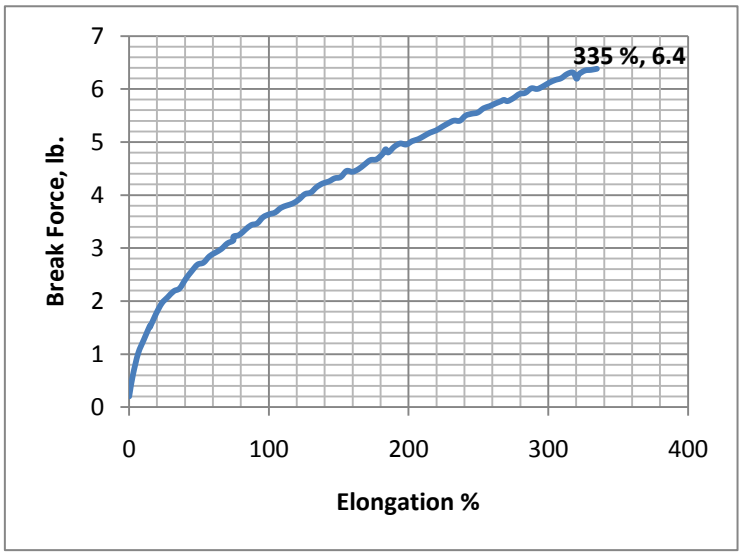
Figure 5.58 PR 1828 Pre-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 505 psi

E % = 880

Post-Soak Test Results;



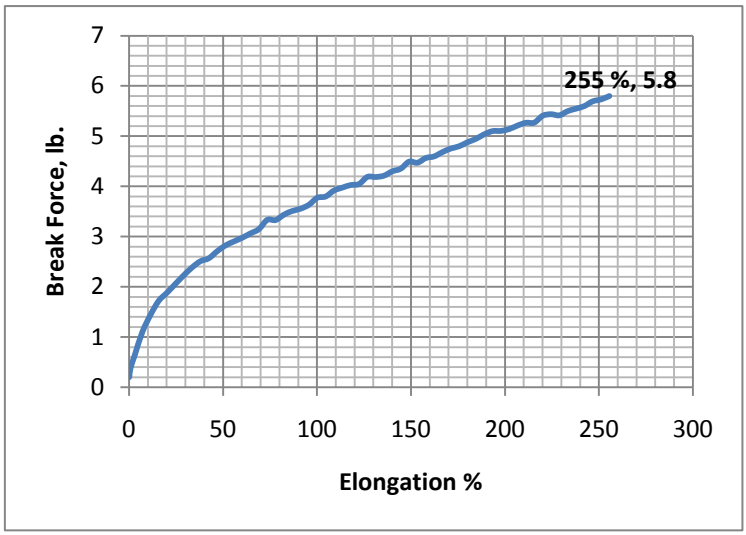
Specimen 1 fails at 6.4 lb. and 335 % extension

=>

TS1 = F/A= 6.4{lb.}/0.01536 {in^2}

TS1 = 416 psi

Figure 5.59 PR 1828 Post-Soak Tensile Test Specimen 1



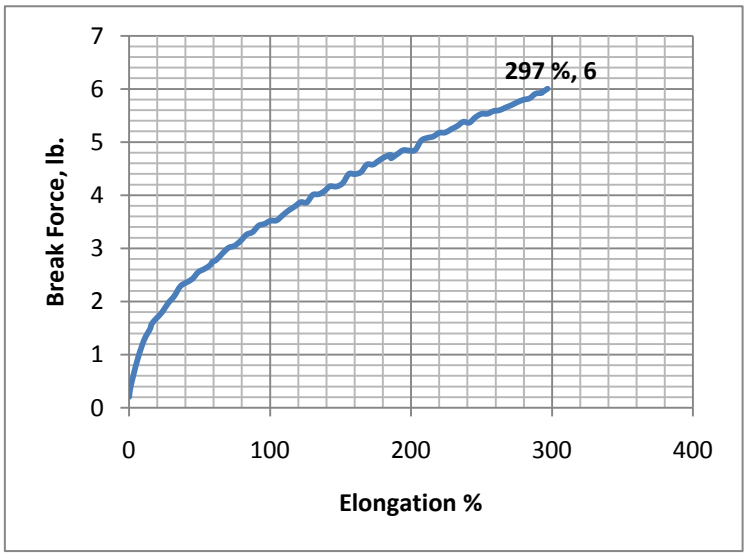
Specimen 2 fails at 5.8 lb. and 255 % extension

=>

TS2 = F/A= 5.8 {lb.}/0.01536 {in^2}

TS2 = 378 psi

Figure 5.60 PR 1828 Post-Soak Tensile Test Specimen 2



Specimen 3 fails at 6 lb. and 297 % extension

=>

TS3 = F/A= 6{lb.}/0.01536 {in^2}

TS3 = 390 psi

Figure 5.61 PR 1828 Post-Soak Tensile Test Specimen 3

Taking the average value of 3 specimens;

TS = 395 psi

E % = 296

5.1.6 Volume Swell Test Results

For volume swell evaluation ASTM D471 is being used. Since Jet A is water-insoluable, water displacement for water-insoluable liquids method is conducted. Three specimens are tested and average result is taken into consideration. The mass M1(g) of each specimen in air is obtained to the nearest 1 mg, and then the mass M2(g) of each specimen is obtained immersed in distilled water at room temperature. Each specimen is dipped in alcohol to remove water, blotted dry with filter paper free of lint and foreign material, and placed in a mason jar to complete the 28-day immersion test at 93 C. At the end of the required immersion period, each specimen is removed from the test tube. The specimens are cooled to room temperature by transferring them to a cool, clean portion of the test liquid for 30 to 60 min, and then dipped quickly in acetone at room temperature, blotted lightly with filter paper free of lint or foreign material, placed in a tarred, stoppered weighing bottle, weighed, and the mass is recorded as M3(g). Each specimen is removed from the bottle, weighed in distilled water, and the mass is recorded as M4(g) in immediate consecutive order to determine the water displacement after immersion. Three specimens are tested and average result is taken into consideration (**ASTM D471-98e1**, *Standard Test Method for Rubber Property-Effect of Liquids*).

Parker VM 128 O-Ring

There specimens, as mentioned above, were tested and the results are shown in the following TABLE 5.1.

TABLE 5.1 O-ring Volume Swell Measurements

Product		Pre-Soak				Post-Soak				Volume
	Specimen	Mass in air, M1 (g)	M1, average	Mass in water, M2(g)	M2, average	Mass in air, M3(g)	M3, average	Mass in water, M4(g)	M4, average	Volume Change, %
VM 126	Specimen 1	0.486	0.4840	0.214	0.2093	0.521	0.5080	0.132	0.1363	35
	Specimen 2	0.484		0.209		0.506		0.125		
	Specimen 3	0.482		0.205		0.497		0.152		

Sealants

At the end of the soak period specimens are taken out if the jars and volume swell application is completed. Following table contains all measurements instructed by ASTM D471.

TABLE 5.2 Sealants Volume Swell Measurements

Product		Pre-Soak				Post-Soak				Volume
	Specimen	Mass in air, M1 (g)	M1, average	Mass in water, M2(g)	M2, average	Mass in air, M3(g)	M3, average	Mass in water, M4(g)	M4, average	Volume Change, %
PR-1422	Specimen 1	2.527	2.7120	0.84	0.8953	2.503	2.7453	0.59	0.6400	16
	Specimen 2	2.902		0.949		3.043		0.65		
	Specimen 3	2.707		0.897		2.69		0.68		
PS 890	Specimen 1	3.06	3.1547	1.237	1.2720	2.975	3.0677	1.043	1.0740	6
	Specimen 2	3.167		1.272		3.073		1.079		
	Specimen 3	3.237		1.307		3.155		1.1		
Q4-2817	Specimen 1	3.964	3.8980	1.811	1.7707	3.991	3.9360	1.675	1.6230	9
	Specimen 2	3.888		1.749		3.942		1.583		
	Specimen 3	3.842		1.752		3.875		1.611		
PR-1776	Specimen 1	2.54	2.6160	0.673	0.6917	2.578	2.6743	0.412	0.4043	18
	Specimen 2	2.595		0.681		2.769		0.408		
	Specimen 3	2.713		0.721		2.676		0.393		
PR-1828	Specimen 1	2.916	2.8820	1.028	1.0297	3.05	3.0020	0.812	0.8090	18
	Specimen 2	2.88		1.038		3.021		0.806		
	Specimen 3	2.85		1.023		2.935		0.809		

5.1.7 Hardness Test Results

Parker VM 128 O-Ring

For hardness test, shore M indentor equipped with digital indicator is used. Each specimen is placed on the support table and recommended procedure is applied. Five measurements are made on each specimen and it is made sure that all measurements are at least 6 mm away from each other (**ASTM D2240-03**, *Standard Test Method for Rubber Property—Durometer Hardness*). Test results are illustrated in the following table

TABLE 5.3 O-Ring Hardness Test Results

State	Specimen	Hardness Point 1	Hardness Point 2	Hardness Point 3	Hardness Point 4	Hardness Point 5	Mean Value	Test Results
VM 126								
Pre-Soak	1	72	71	74	72	73	72	73
	2	74	73	74	72	75	74	
	3	73	75	75	75	74	74	
Post-Soak	1	82	81	83	81	82	82	82
	2	83	84	83	82	83	83	
	3	83	82	82	83	81	82	

Sealants

For hardness evaluation of sealants, shore A indentor equipped with digital indicator is used. Each specimen is placed on the support table and recommended procedure is applied. Five measurements are made on each specimen and it is made sure that all measurements are 6 mm away from each other (**ASTM D2240-03**, *Standard Test Method for Rubber Property—Durometer Hardness*). Test results are illustrated in the following table.

TABLE 5.4 Sealants Hardness Test Results

State	Specimen	Test 1	Test 2	Test 3	Test 4	Test 5	Mean Value	Test Results
Pr 1422 B-2								
Pre-Soak	1	55	58	56	56	57	56	57
	2	59	58	58	58	60	59	
	3	56	53	54	55	56	55	
Post-Soak	1	59	60	55	59	53	57	57
	2	55	57	58	55	59	57	
	3	55	57	55	58	58	57	
PS 890 B-2								
Pre-Soak	1	50	52	50	50	52	51	51
	2	52	53	52	50	53	52	
	3	51	50	51	52	52	51	
Post-Soak	1	57	54	58	57	59	57	58
	2	58	59	57	56	55	57	
	3	59	60	57	58	60	59	
Q4-2817								
Pre-Soak	1	41	46	45	44	47	45	45
	2	45	44	47	48	45	46	
	3	46	47	48	44	45	46	
Post-Soak	1	57	57	52	54	54	55	54
	2	54	53	55	52	51	53	
	3	53	56	54	54	55	54	
PR 1776 B-1/2								
Pre-Soak	1	41	42	42	43	44	42	49
	2	43	41	40	58	60	48	
	3	56	53	54	55	56	55	
Post-Soak	1	49	48	46	47	46	47	48
	2	47	50	47	50	49	49	
	3	50	51	45	48	48	48	
PR 1828 B-2								
Pre-Soak	1	44	45	43	46	46	45	44
	2	45	44	43	43	44	44	
	3	43	45	46	44	46	45	
Post-Soak	1	46	49	48	47	48	48	49
	2	50	51	51	50	50	50	
	3	48	49	47	47	49	48	

5.2 Visual Inspection Results

As mentioned in Chapter 4, metallic specimens are to be inspected visually for both surface and microstructural evaluations. Surface Evaluation—before the 28-day soak period, the metal test specimens are examined visually and under low power (50X) optical magnification. The objective is to compare any surface deformation between pre-soak and post-soak states. After the examination of dry specimens, they are soaked for 28 days. At the end of the 28-day soak period, specimens are inspected for evidence of staining, deposits, surface pits, or gross corrosion. Staining is considered a benign surface phenomenon. Staining results in no appreciable weight loss or gain and indicates the formation of a passive layer that inhibits corrosion. Subsequent to the initial examination, the metal surfaces are cleaned using acetone or alcohol and re-examined for surface pits. Figures illustrated in the Appendix section is the depiction of comparison between pre-soak and post-soak states (**ASTM D4054-09,** *Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives*, *Section A3*).

5.3 Discussions

As stated before, evaluating the compatibility of selected engine materials with kerosene is the main theme of this research. Hence evaluation criteria is based on the test results and the allowable variation from baseline which represents dry test results.

For Hysol EA 9394, as given above in Section 5.1, being exposed to kerosene for 28 days had a significant impact on its shear strength properties. The average strength decrased from 3144 to 1415 psi, which indicates 55 % reduction on products performance. Another tested adhesive is Loctite 609 and was subject to static shear test. At the end of the 28-day soak period it is

observed that exposure to kerosene improves its static shear strength; dry test results show the average of 3330 psi and post-soak tests result in 3723 psi. Although, the improvement of mechanical response after soaking apears unconventional, but this type of improvement has been reported before (see **William G. Fortener Susan S. Saliba,** 2005 *Fuel System Materials Compatibility Testing of Fuel Additives for Reducing the Amount of Small Particulate in Turbine Engine Exhaust.*).

Another series of test were performed on the effect of soaking on testspecimens coated with EC 776SR and 825x309. These coated specimens were tested for pensile hardness and peeling tests before and after soaking. As for tape adhesion (peeling test) both before and after soak they were rated 5A which indicates no removal on the surface. In pencil hardness they exhibit different performance; EC 776SR is rated 3H before soak and H after soak, 825x309 is rated higher than 6H both before and after soak.

In this research work, O-Ring specimens were subject to tensile, volume swell, and hardness tests. The soaking resulted in a significant decrease in tensile properties. Aaverage tensile strength and elongation rate dropped from 2218 psi and 405 % to 1573 psi and 192 %. In terms of volume swell performance materials were swollen by 35 %. Shore M hardness results showed significant difference between post and pre soak states and hardness value increased from 73 to 82 shore M reading scale.

Upilex-S was the only film to be tested. Only tensile and elongation characteristics were of interest. Average tensile strength of the material fell from 18107 to 15934 psi whereas elongation rate rose from 40.5 to 44.2 % after soaking.

Similarly, only CrestFoam foam was to be studied. And the only concern was on its tensile and elongation properties. As illustrated in the results section the drop in tensile strength was

insignificant, 11 psi before soak and 10.6 psi after soak. Such argument could also be made for elongation rate as the drop in elongation of 504 to 427 % was experienced.

There were 5 types of sealants to be tested in accordance with volume swell, tensile, and hardness tests. Among the sealants PS 890 showed the lowest volume change by 6 %. PR 1776 and PR 1828 had the highest rate of change by 18 %. The remaining two sealants, PR 1422 and Q4-2817 experienced a volume swell of 16 and 9 % respectively. As for hardness evaluation PR-1422 had 57 Shore A for both pre and post soak states. PS 890 had an increase of 7 points due to soaking from presoak of 51 on shore A scale to 58 respectively. Similarly, Q4-2817 experienced an increase of hardness by 9 points after soaked, from 45 to 54 on shore A scale. Comparing to PS 890 and Q4-2817, PR 1828 has a low increase in its hardness value, 44 pre-soak and 49 post-soak on same shore A scale. PR 1776 is the only sealant to get softer after incubation. However, the drop in its hardness was not significant, 49 pre soak and 48 post-soak. They also illustrated interesting results in terms of tensile and elongation characteristics. PR 1422 had a significant decrease in both tensile strength and elongation rate; tensile strength drops from 523 to 375 psi and elongation from 547 to 388 %. PS 890 showed similar results but the decrease in tensile strength was less significant; tensile strength decreased from 320 to 270 psi and elongation from 540 to 300 %. Q4-2817 was the most resilient sealant, showing very close characteristic between pre-soak and post-soak states; 573 psi tensile strength , 567 % elongation initially , and 545 psi, 450 % after being soaked. Another detrimentally affected sealant is PR 1776; both in tensile strength and elongation a notable drop was observed. Tensile strength and elongation decreased from 384 to 217 psi and 471 to 197 % respectively. PR 1828 also followed the same trend as its tensile strength and elongation dropped noticeably from 505 to 395 psi. The noteworthy decrease

was in elongation rate from 880 to 296 %. The primary reason for these results could be attributed to the hardening of the materials after soaking.

Metallic materials were intended to be inspected visually under low magnification both before and after soak in order to trace staining, corrosion or any other form of surface deformation. As the results indicate, there were no significant staining corrosion or surface pits.

Chapter 6 Conclusions and Recommendations

As stated before, the purpose of this research was to determine the compatibility of a list of non-metallic and metallic materials prescribed by ASTM with Jet fuels (Kerosene in this case), and after the results were obtained, each material was assessed through the eligibility criteria (TABLE 3.3).

There was a major problem encountered during the preparation of sealant specimens; the very first specimens contained bubbles and voids because of the viscous nature of sealants and that caused a noteworthy decrease in physical properties especially tensile strength. The issue was sorted out by applying vibration over the moulds. Sealants show a great deal of compatibility with kerosene; there has been no issue with tensile strength and elongation, volume swell, and hardness. PR 1828, comparing to rest of the sealants, shows really poor results specifically in tensile properties but still meets the requirements.

As for coatings, results provided that 825x309 perfectly conform to the requirements. The same judgment cannot be made for EC 776SR, even though it meets the tape adhesion requirement, since hardness value dropped by 2 levels from 3H to H. Hence EC 776SR failed in meeting the pencil hardness requirement which shall be above or equal to the dry test result.

Adhesive EA 9394 performed poorly after being fuel-wetted; lap shear strength was mandated to be over 1500 psi but 1415 psi was obtained. Since only 3 specimens were tested, and even though the results obtained from each were really close, there was not sufficient statistical data to make judgments whether the material is recommended or not. Another adhesive Loctite 609 presented a good characteristic which meets the requirements. Since the surface preparation and

clamp pressure were important on material's performance, specimens were prepared and tested before soak in order to get optimum results. Overall it is recommended to test numerous adhesive specimens to obtain more stable statistical data.

O-ring product VM 128 failed to meet the requirements, both volume-swell and hardness test. The O-ring showed 35% volume swell and an increase in hardness by 9 points which should be between 0 and 10 %, and ± 5 points from pre-soaked state respectively. According to the technical data sheet, the optimum operation condition is between 50 and 150 C. Since the material was soaked at 163 C, another material or lower temperatures may be suggested.

Upilex-S Kapton film and Crestfoam have no compatibility issues. Metallic materials were not affected at all by the fuel used in this work.

Overall, through many steps including material procurement, specimen preparation, generating plots for application of ASTM standards, and purchasing and calibration of test equipments in-house capability of F.R.A.M.E.S. reached a level that future alternative fuel studies can easily be conducted.

Appendix- Metallic Materials

17-4 pH

Sample 1

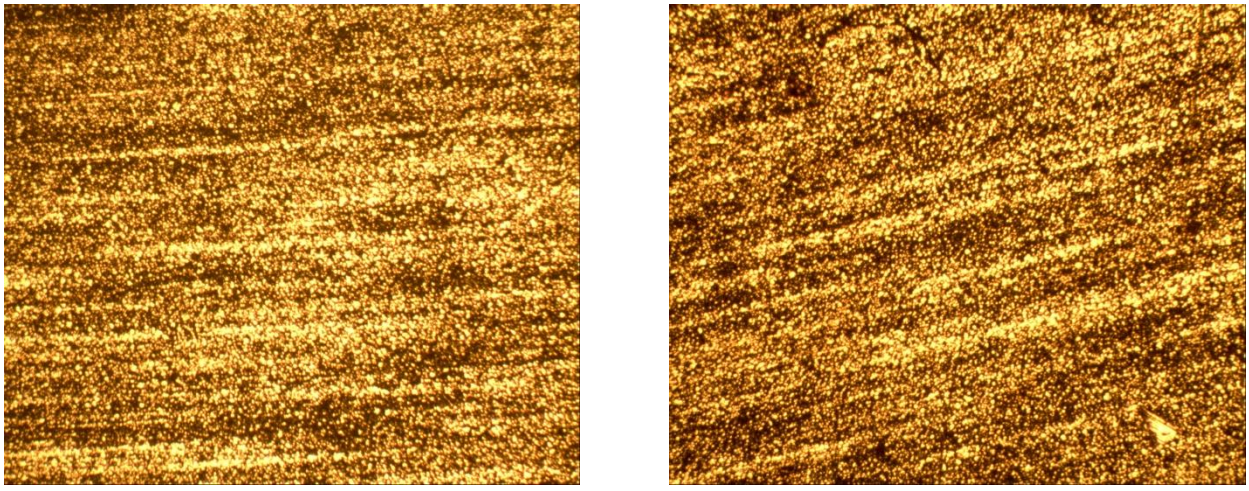


Figure 5.62 17-4 pH Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

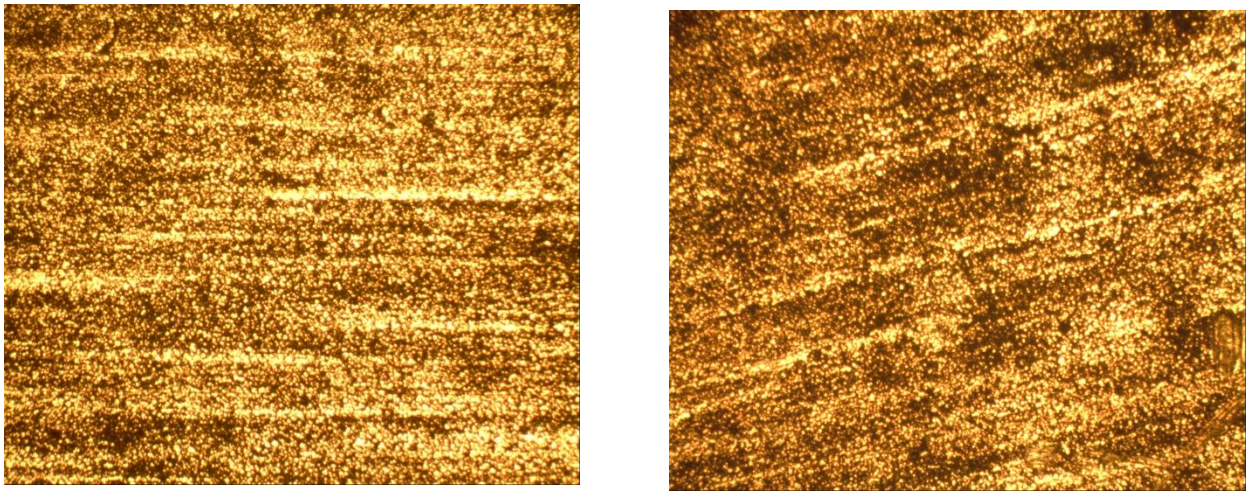


Figure 5.63 17-4 pH Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

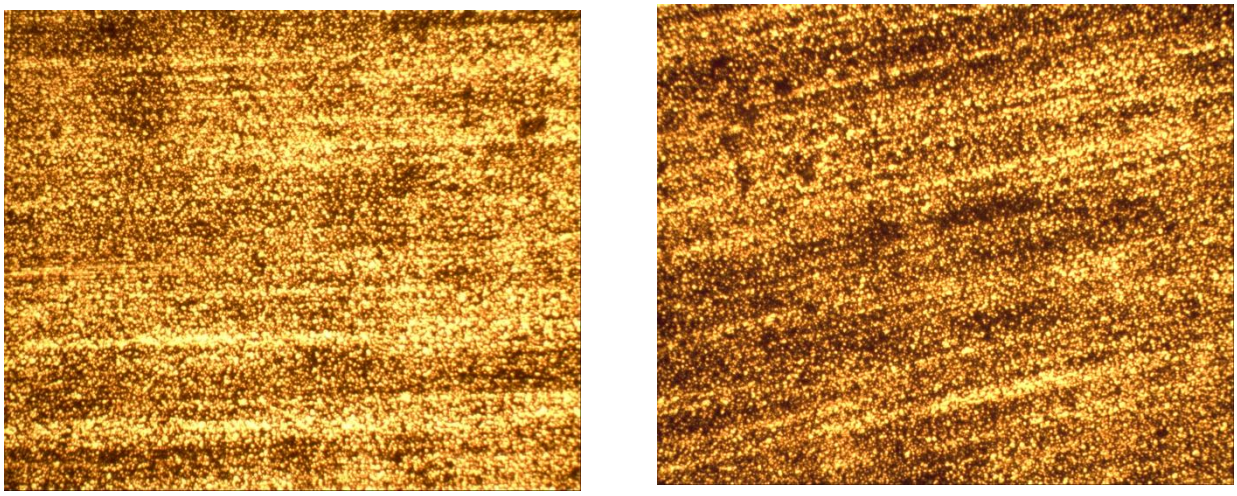


Figure 5.64 17-4 pH Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

304 SS

Sample 1

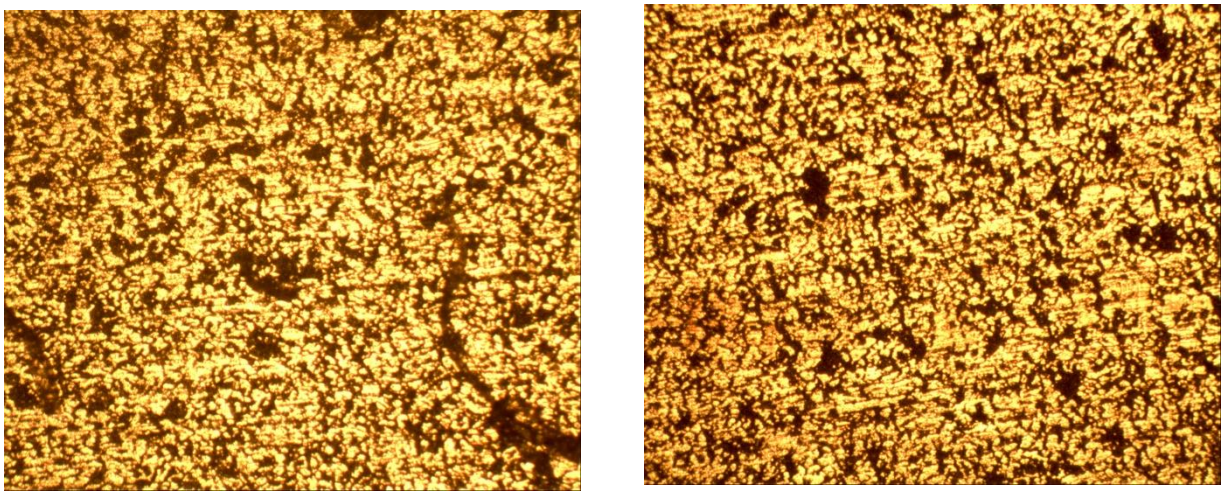


Figure 5.65 304 SS Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

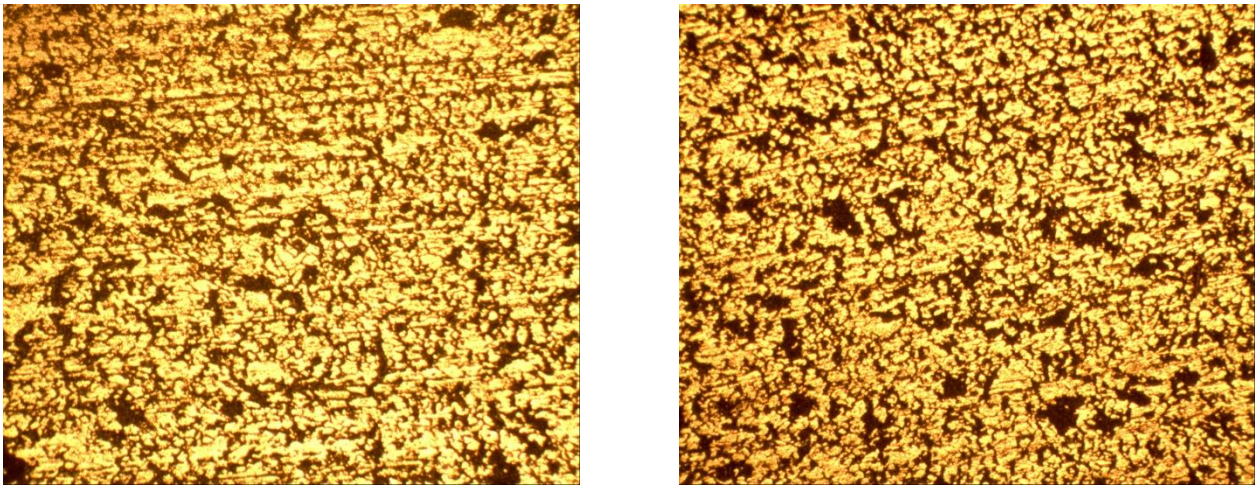


Figure 5.66 304 SS Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

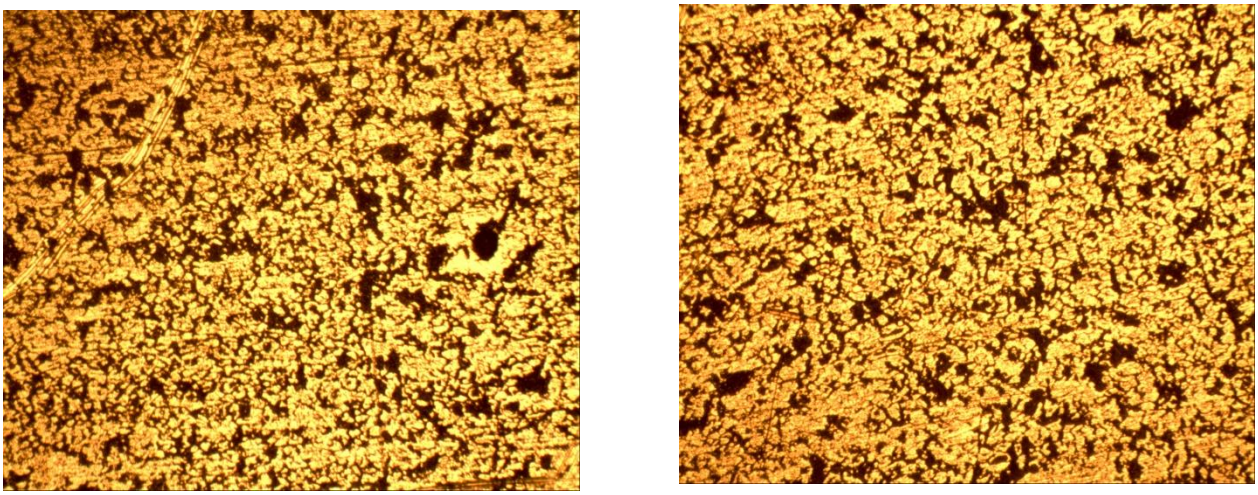


Figure 5.67 304 SS Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

2024-T3

Sample 1

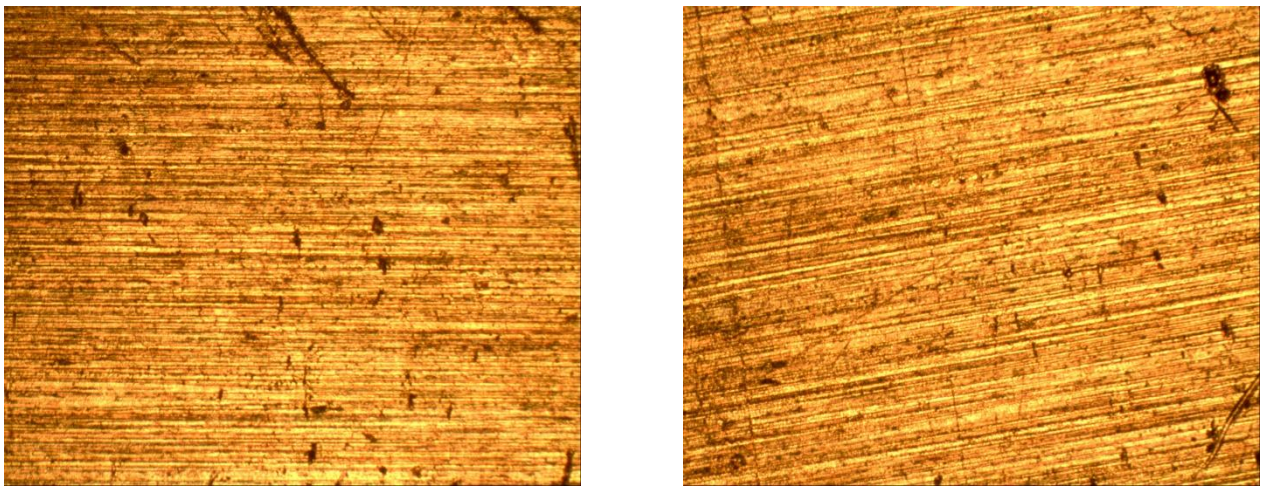


Figure 5.68 2024-T3 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

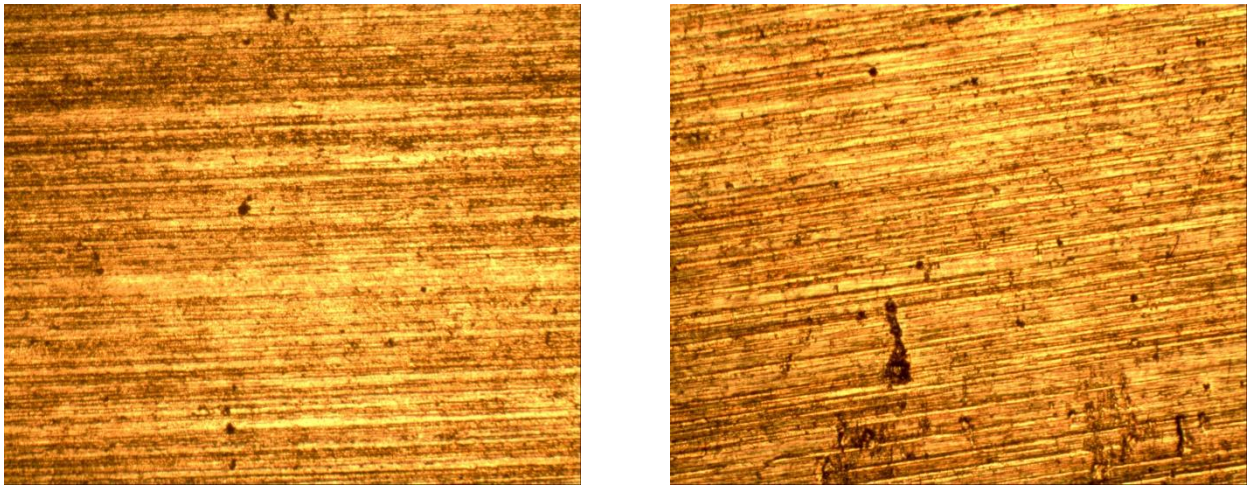


Figure 5.69 2024-T3 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

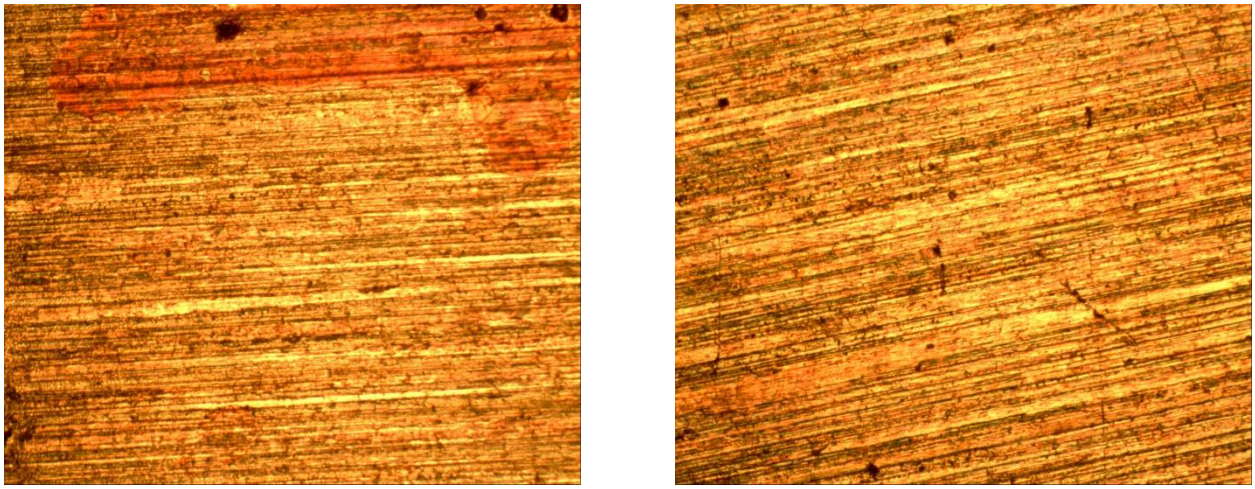


Figure 5.70 2024-T3 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

6061-T6

Sample 1

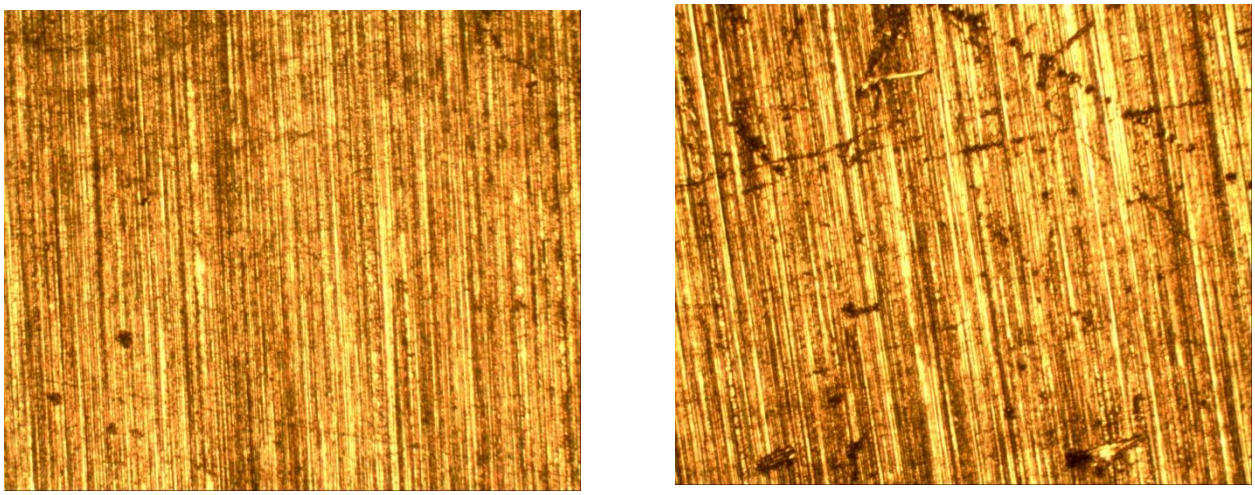


Figure 5.71 6061-T6 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

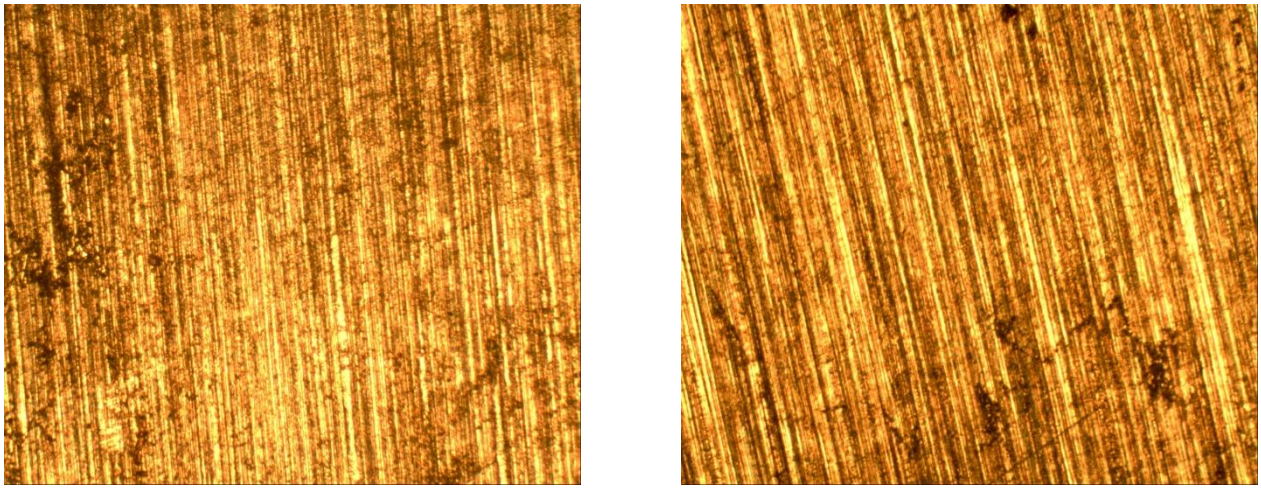


Figure 5.72 6061-T6 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

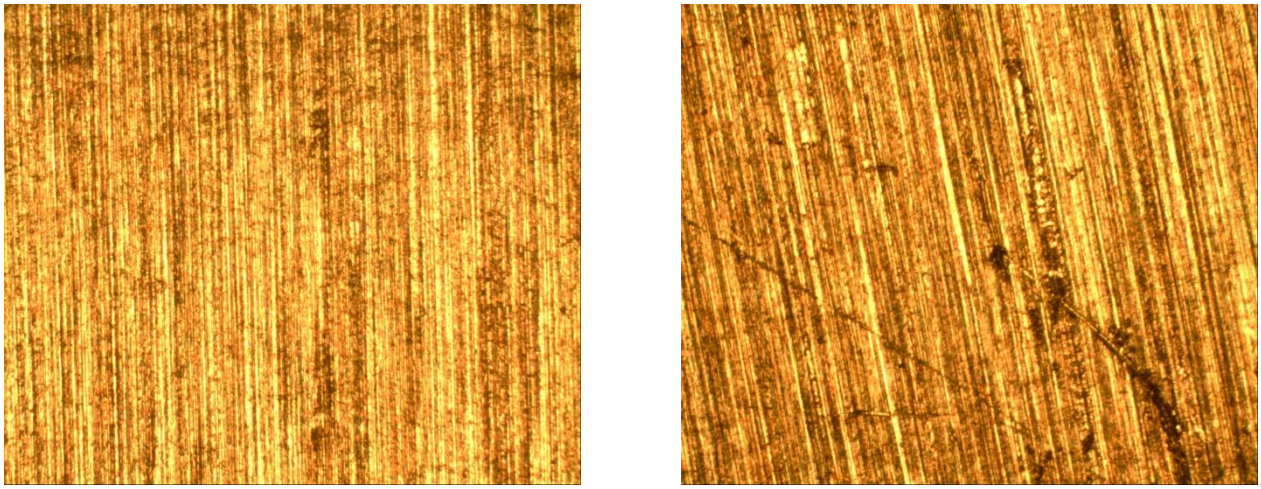


Figure 5.73 6061-T6 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

7076 Chromate Coated

Sample 1

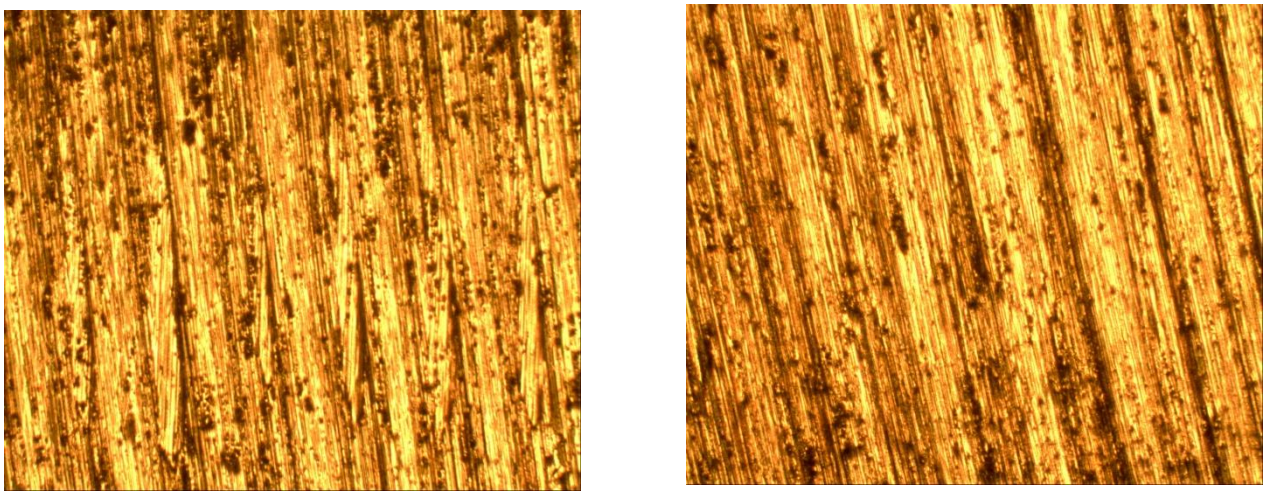


Figure 5.74 7076 Chromate Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

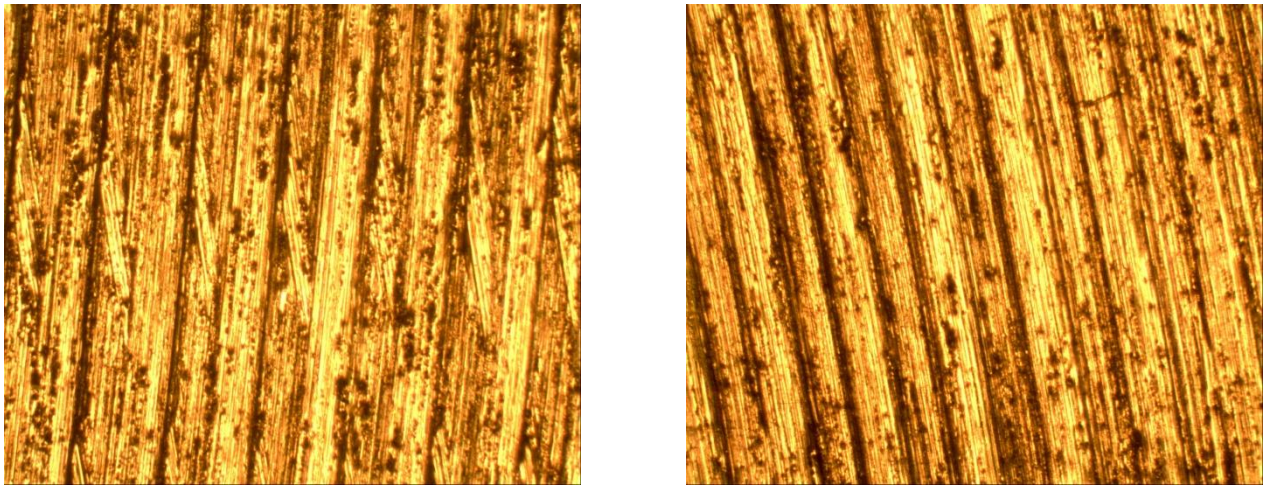


Figure 5.75 7076 Chromate Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

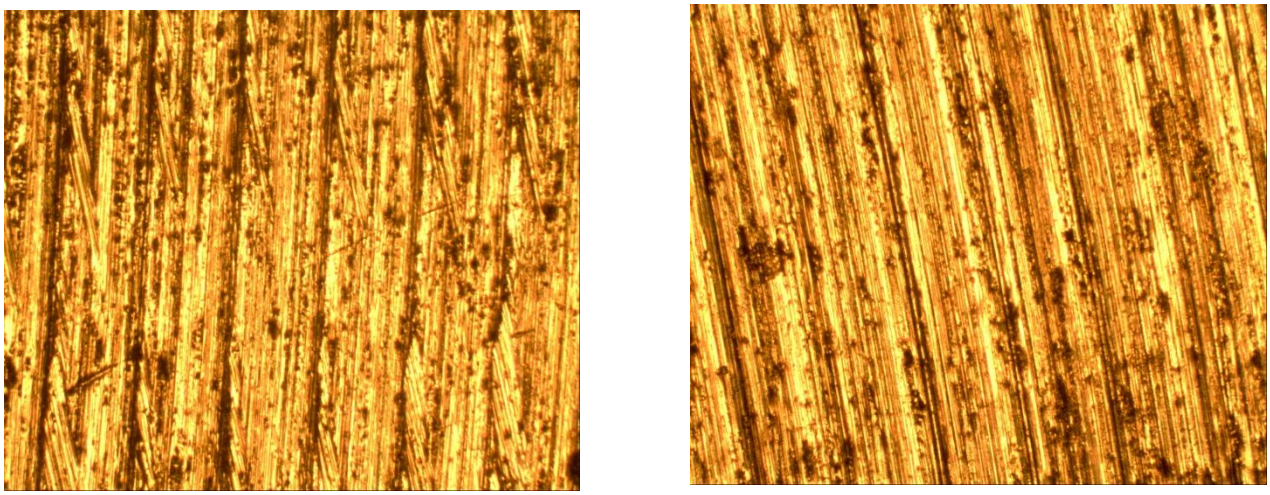


Figure 5.76 7076 Chromate Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

7076 Chromic Acid Anodized

Sample 1

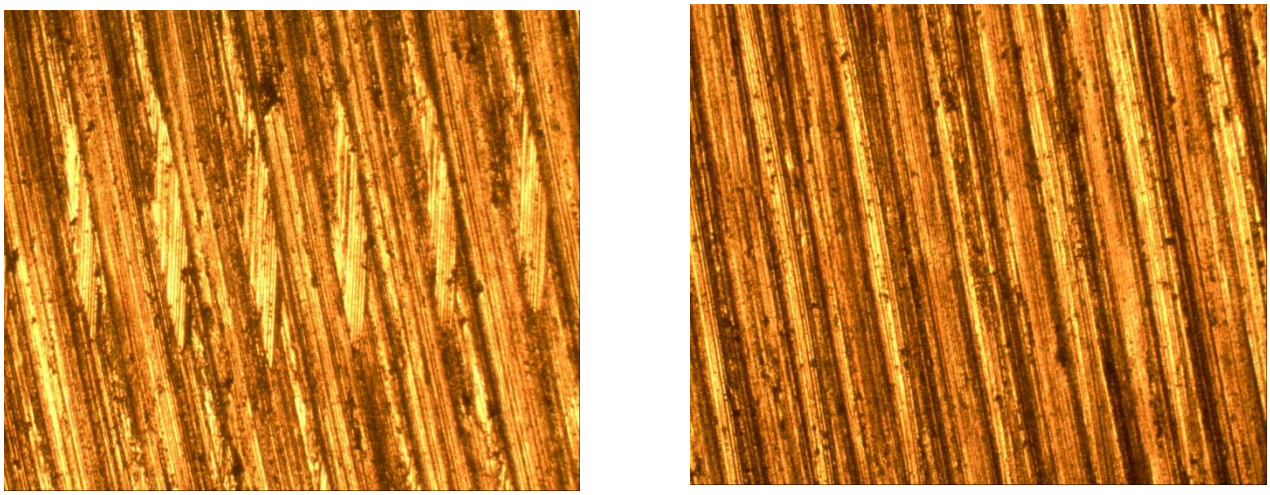


Figure 5.77 7076 Chromic Acid Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

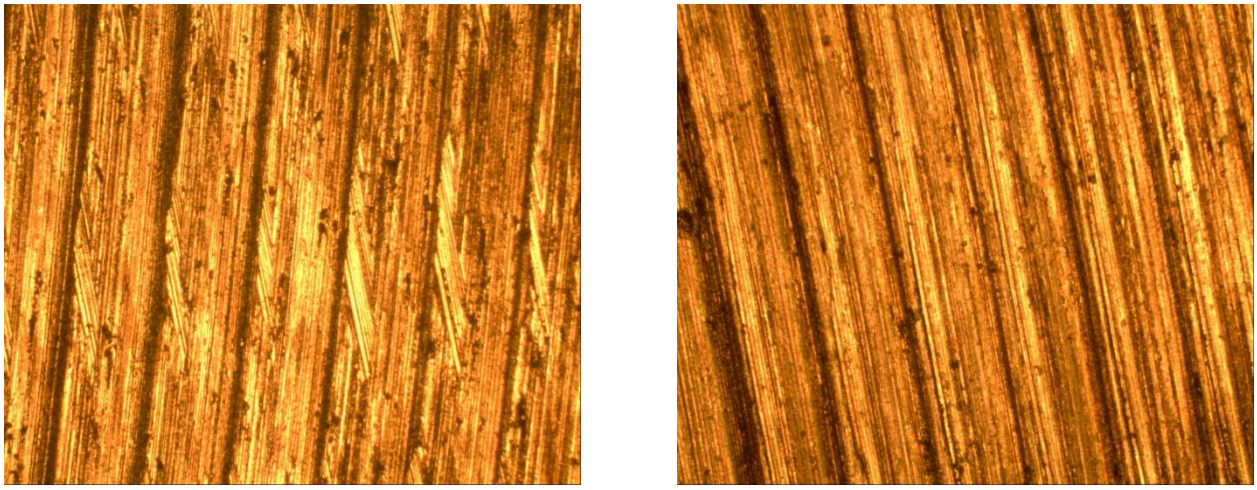


Figure 5.78 7076 Chromic Acid Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

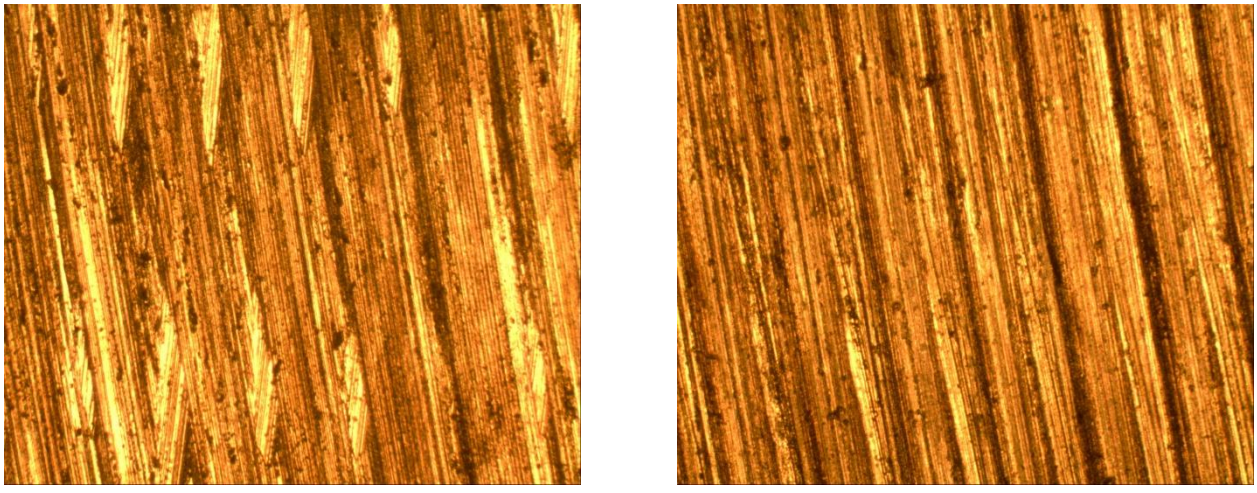


Figure 5.79 7076 Chromic Acid Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

7076 Sulphuric Acid Anodized

Sample 1

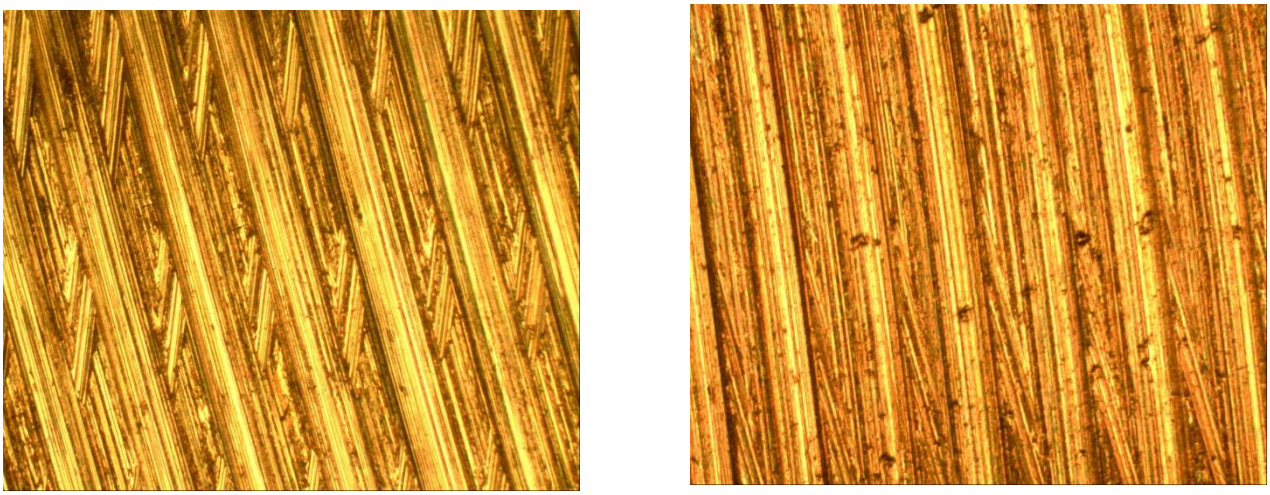


Figure 5.80 7076 Sulphuric Acid Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

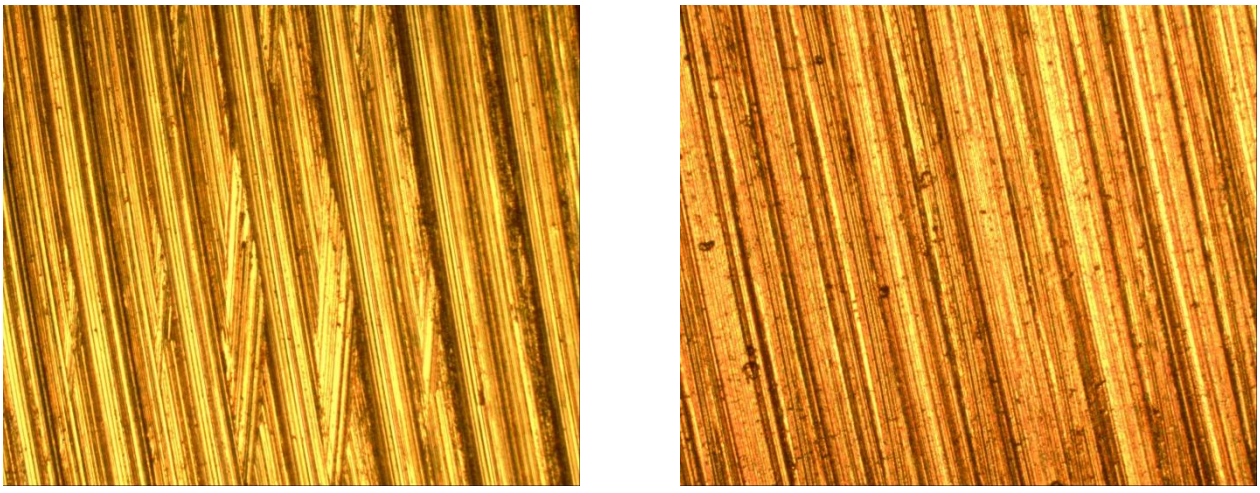


Figure 5.81 7076 Sulphuric Acid Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

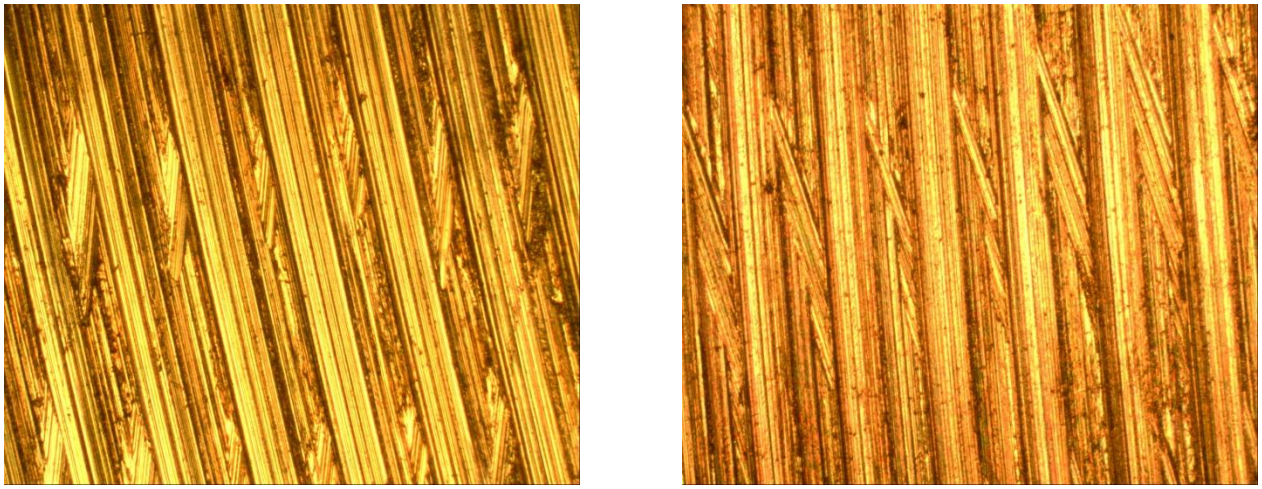


Figure 5.82 7076 Sulphuric Acid Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Inconel 625

Sample 1

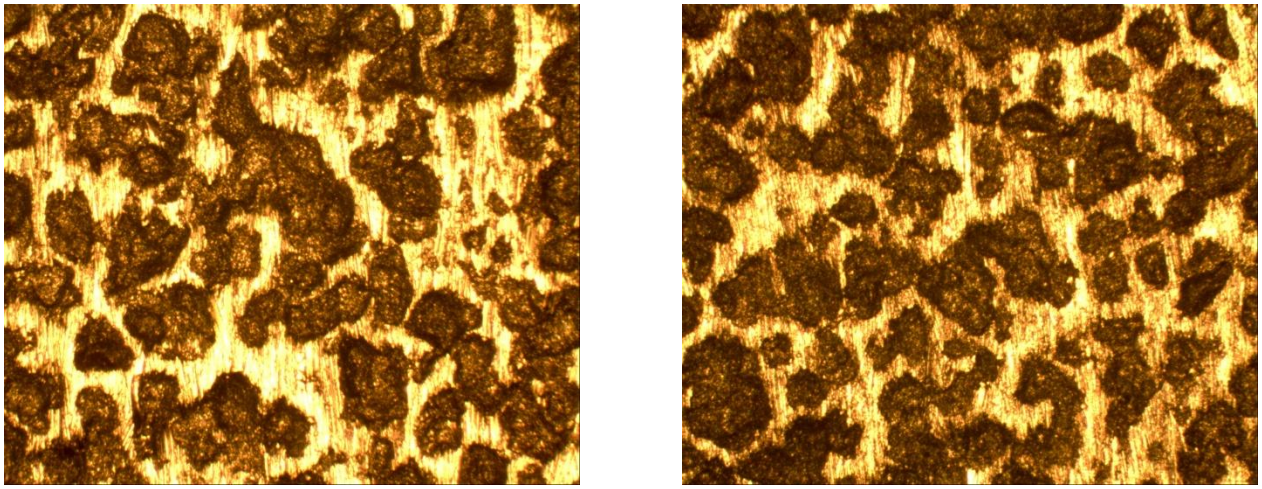


Figure 5.83 Inconel 625 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

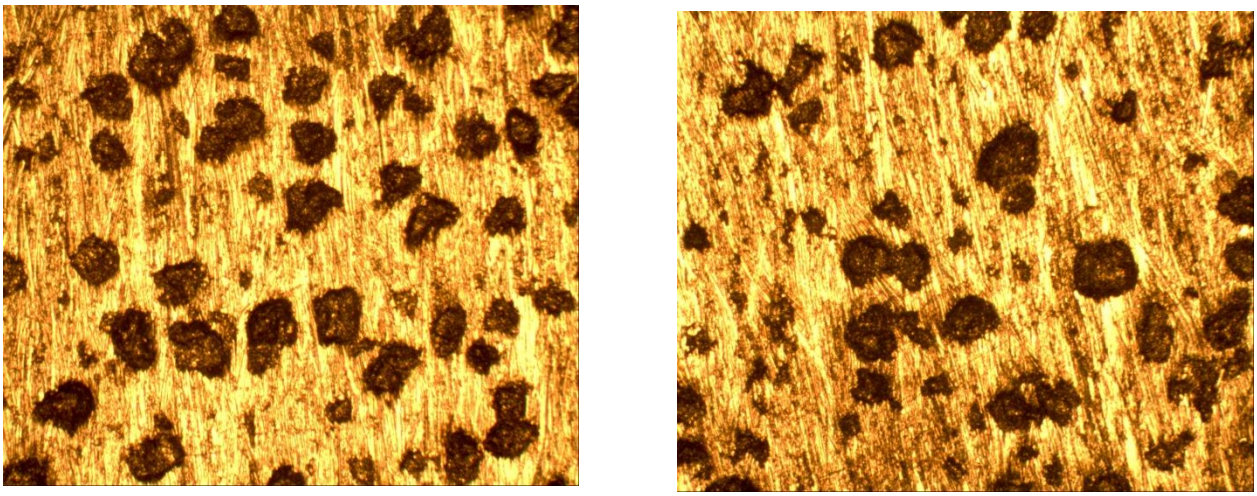


Figure 5.84 Inconel 625 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

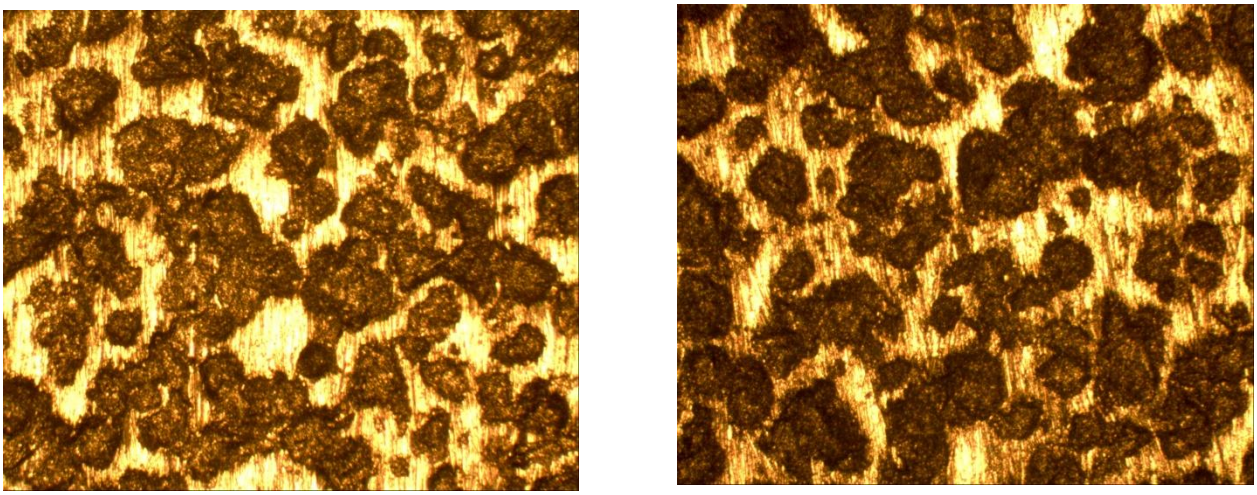


Figure 5.85 Inconel 625 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Inconel 718

Sample 1

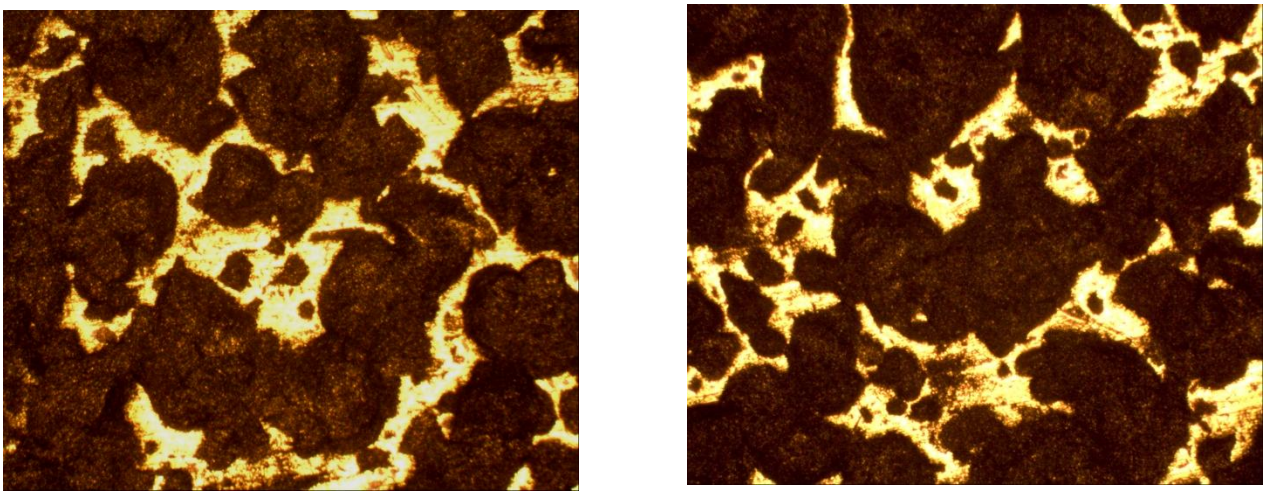


Figure 5.86 Inconel 718 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

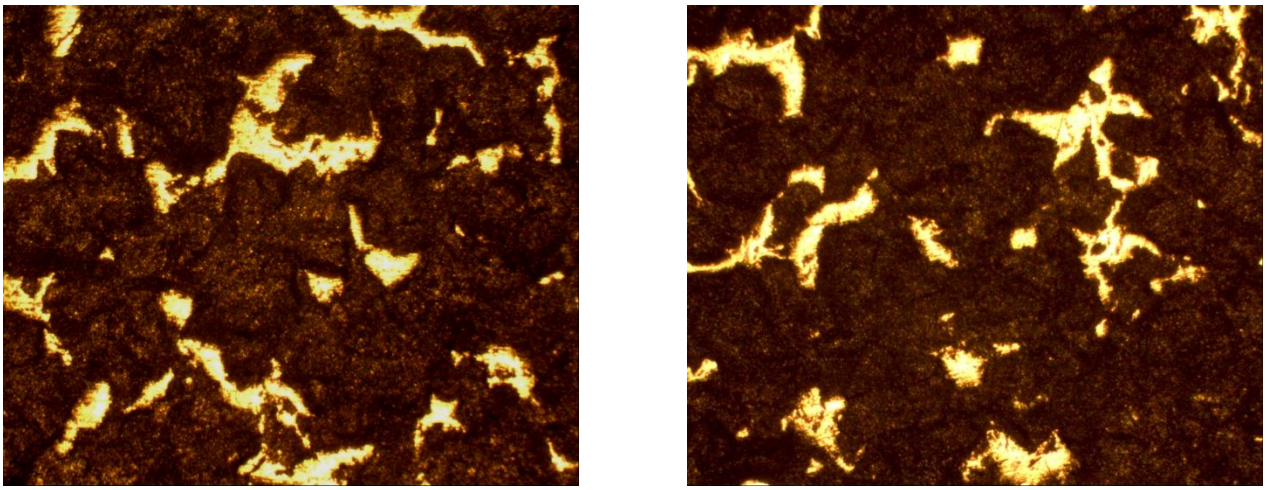


Figure 5.87 Inconel 718 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

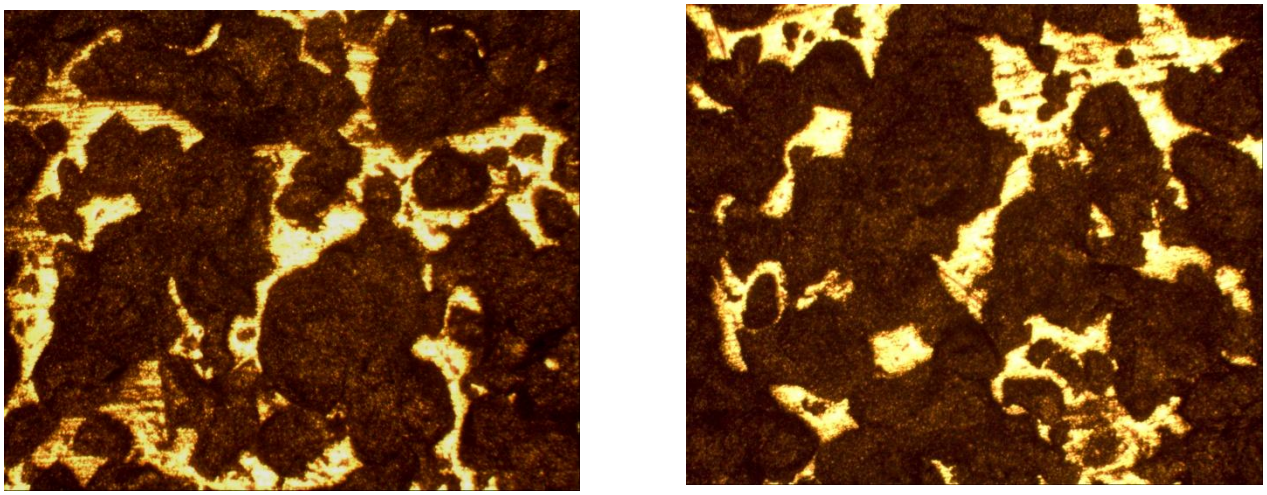


Figure 5.88 Inconel 718 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Monel 400

Sample 1

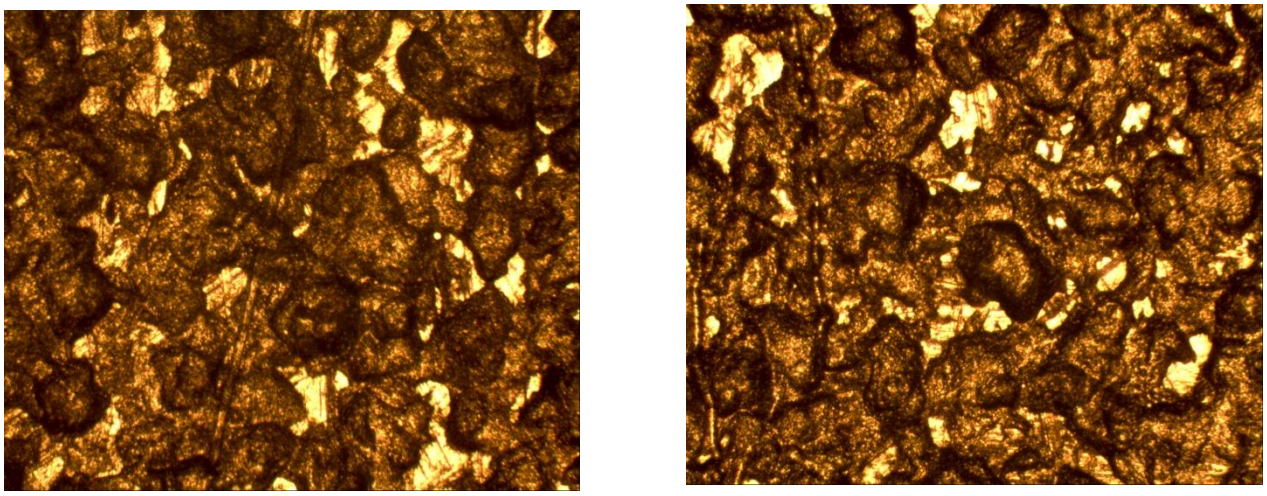


Figure 5.89 Monel 400 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

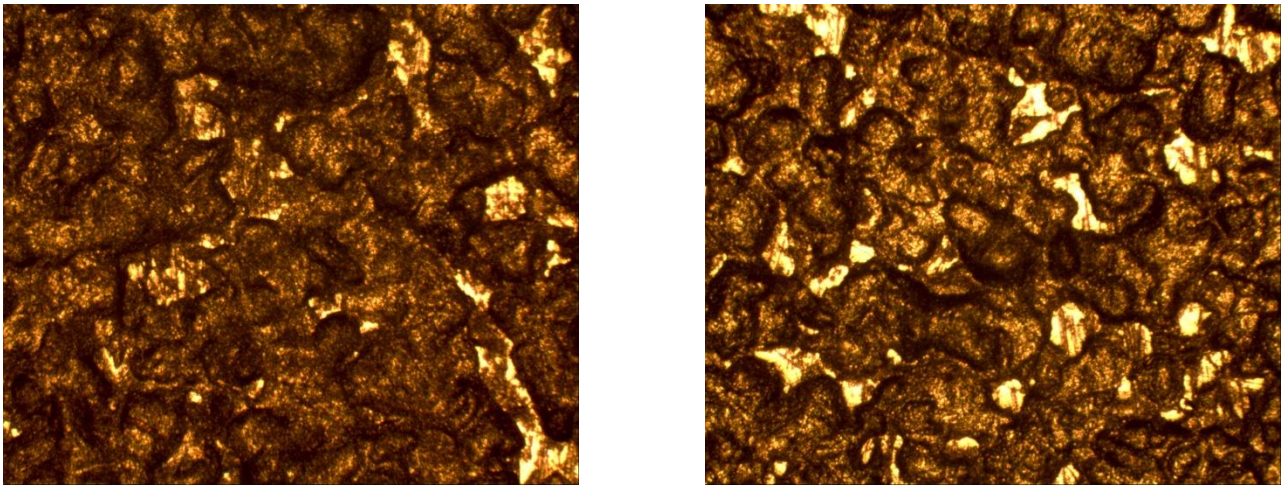


Figure 5.90 Monel 400 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

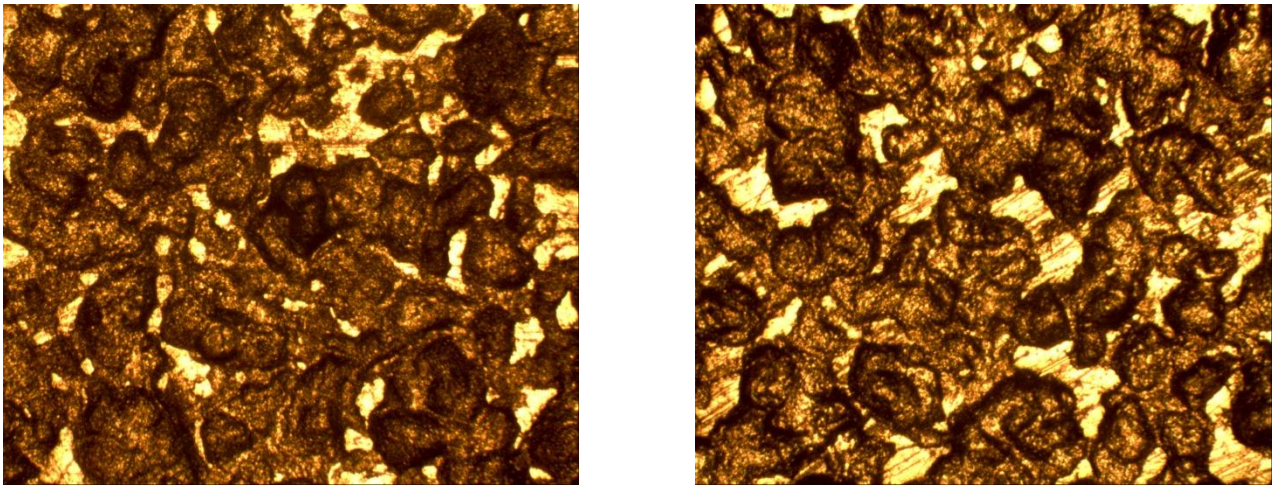


Figure 5.91 Monel 400 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Nickel 200

Sample 1

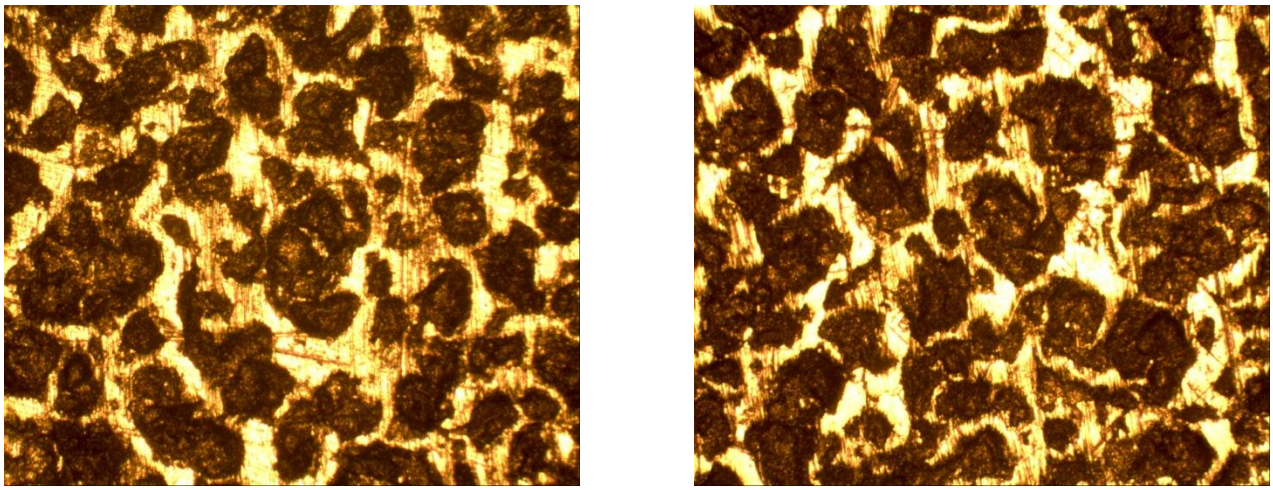


Figure 5.92 Nickel 200 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

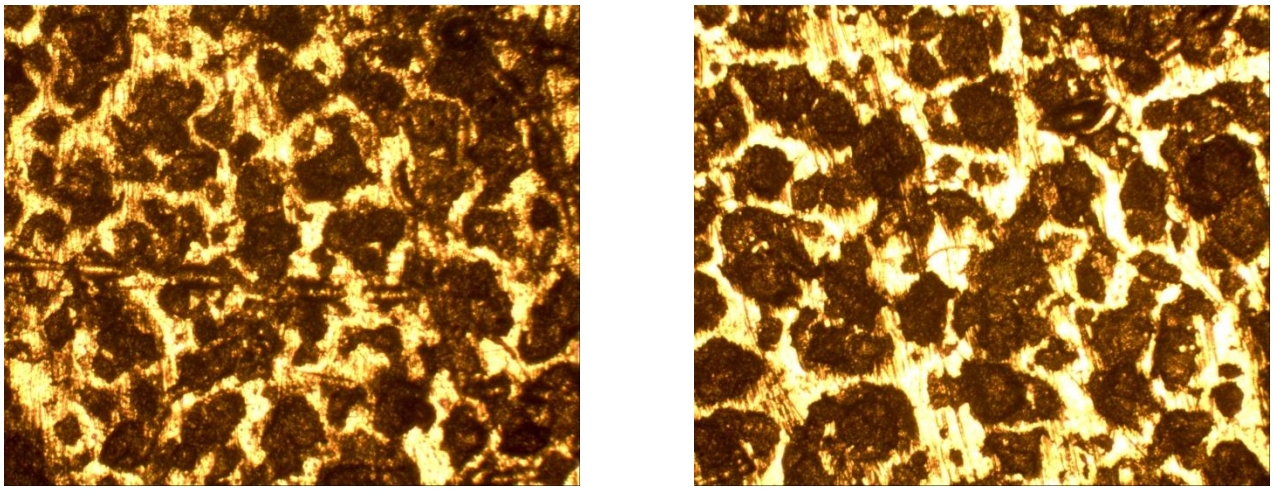


Figure 5.93 Nickel 200 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

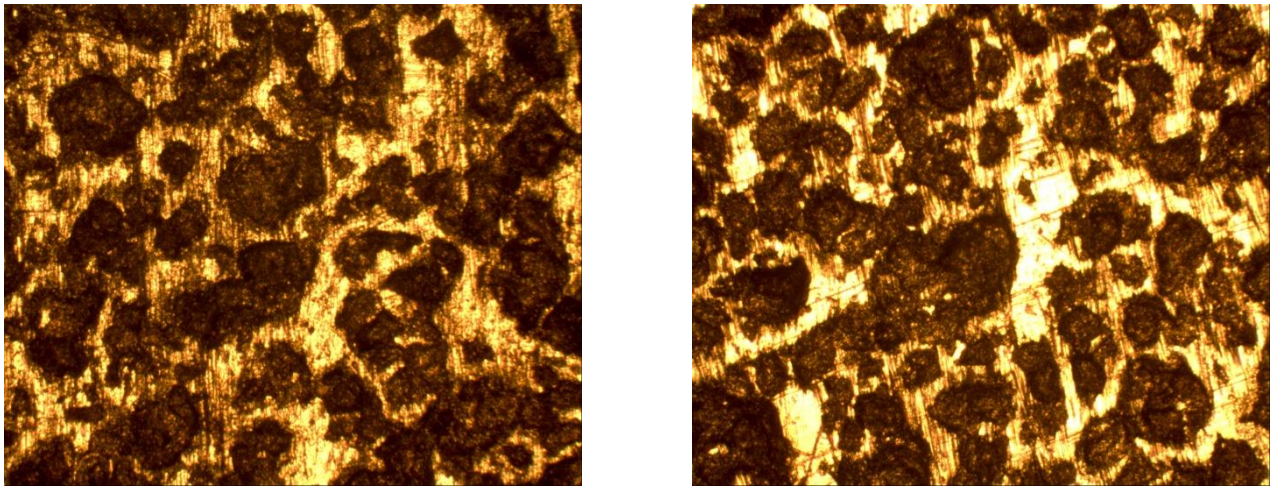


Figure 5.94 Nickel 200 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Titanium 3AL-2.5V

Sample 1

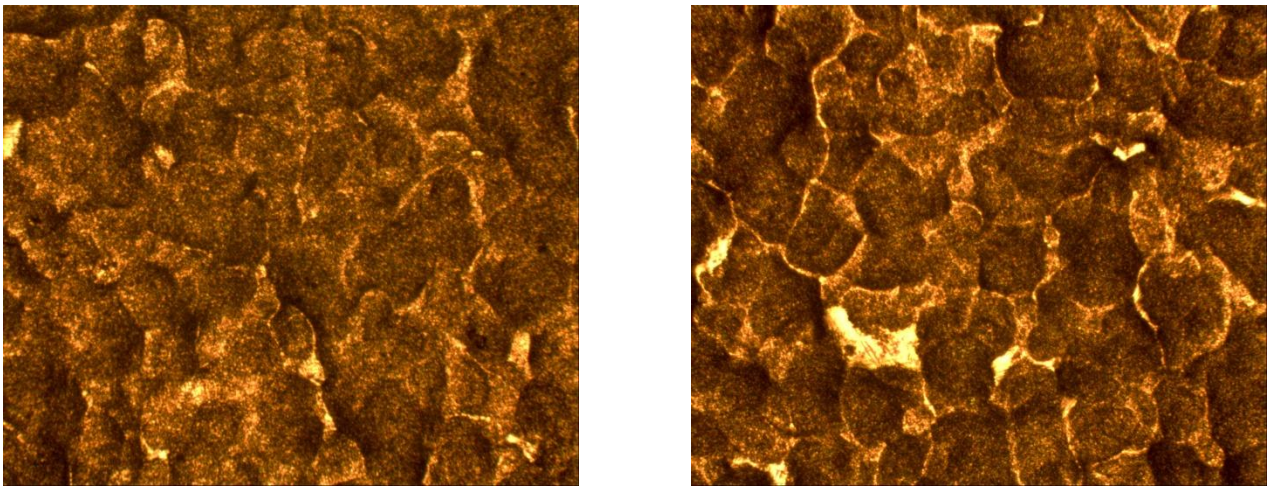


Figure 5.95 Ti 3Al-2.5V Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

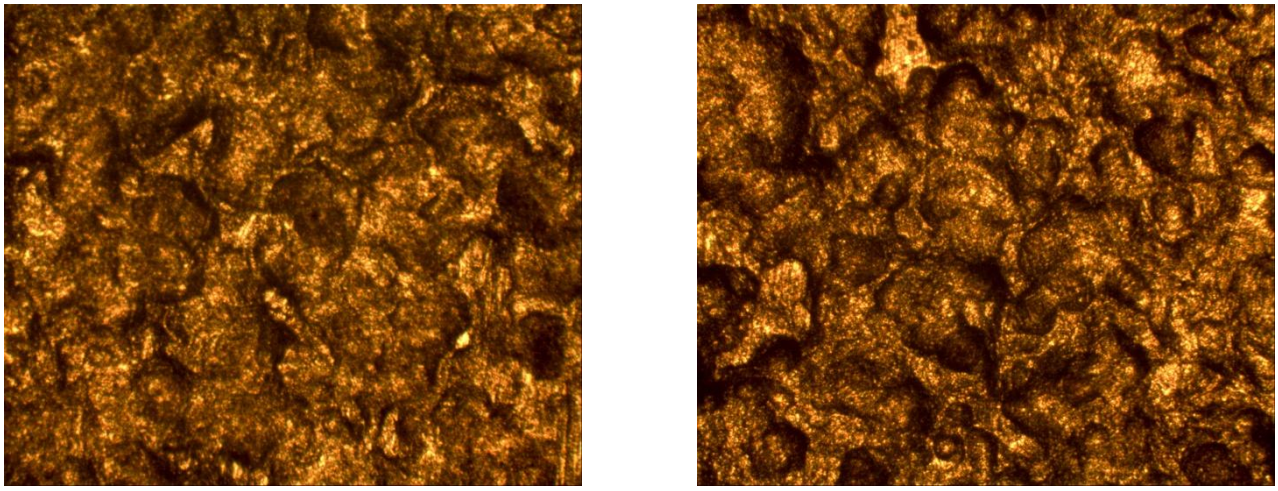


Figure 5.96 Ti 3Al-2.5V Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

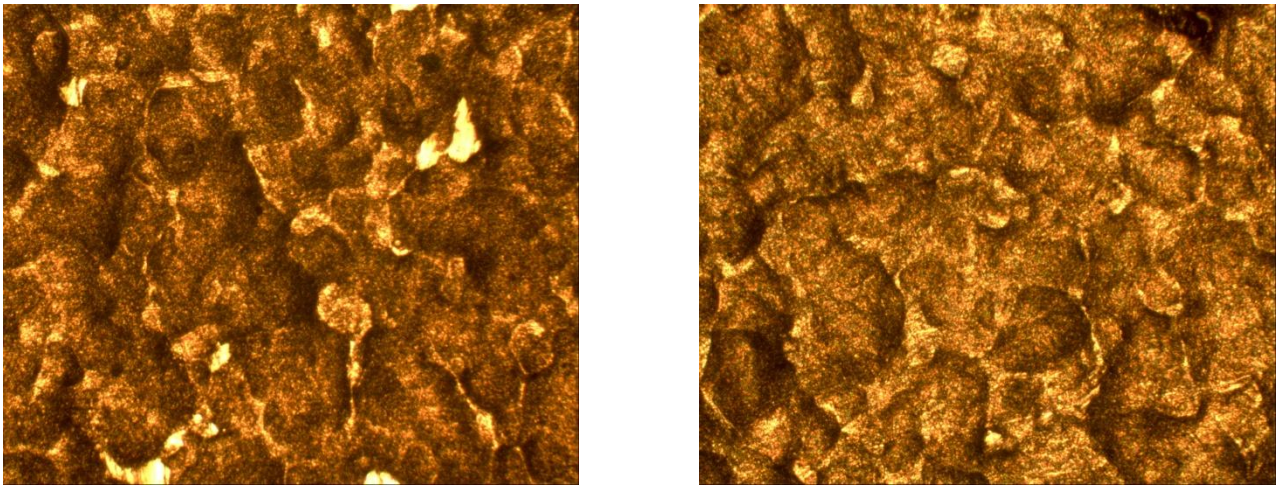


Figure 5.97 Ti 3Al-2.5V Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Titanium 8A1-1 Mo

Sample 1

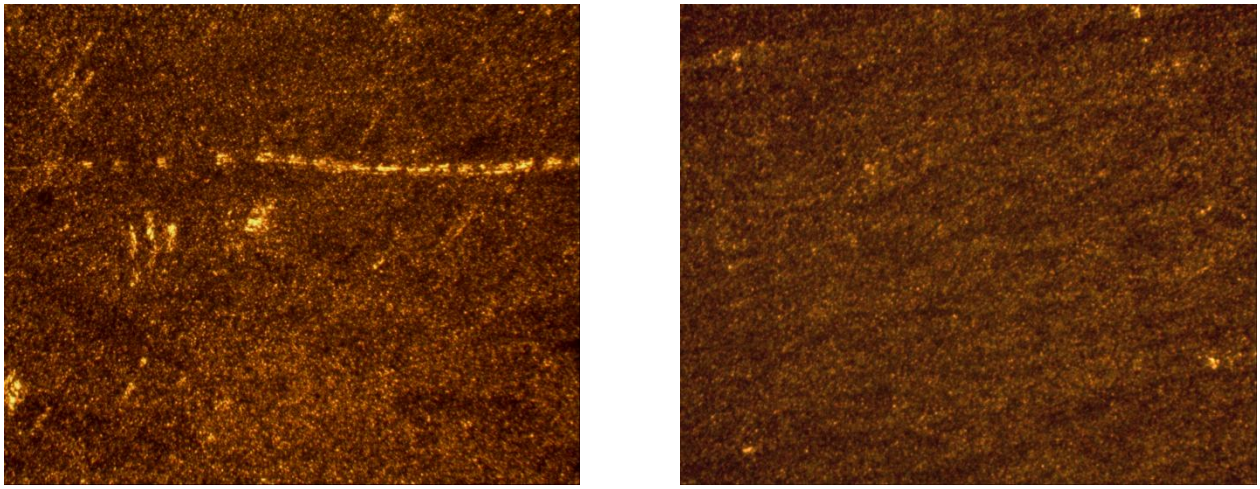


Figure 5.98Ti 8A1-1 Mo Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

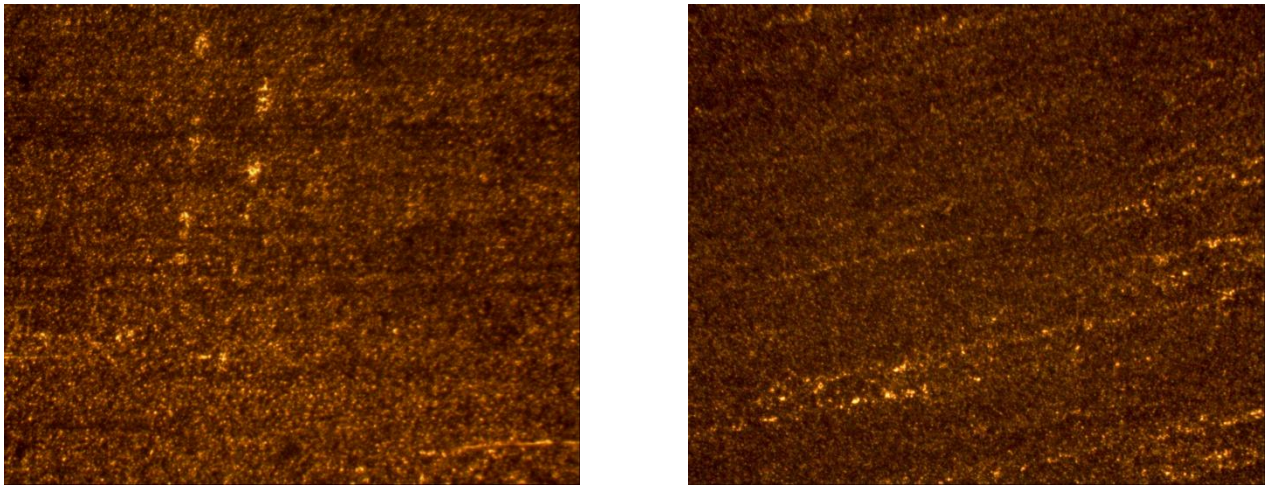


Figure 5.99 Ti 8A1-1 Mo Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

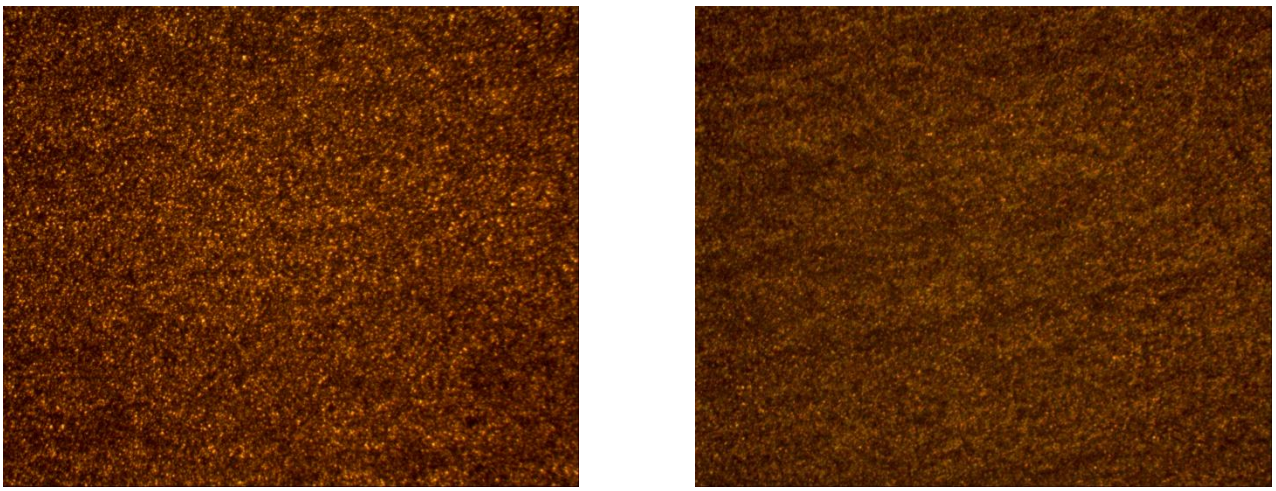


Figure 5.100 Ti 8A1-1 Mo Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Titanium CP 70

Sample 1

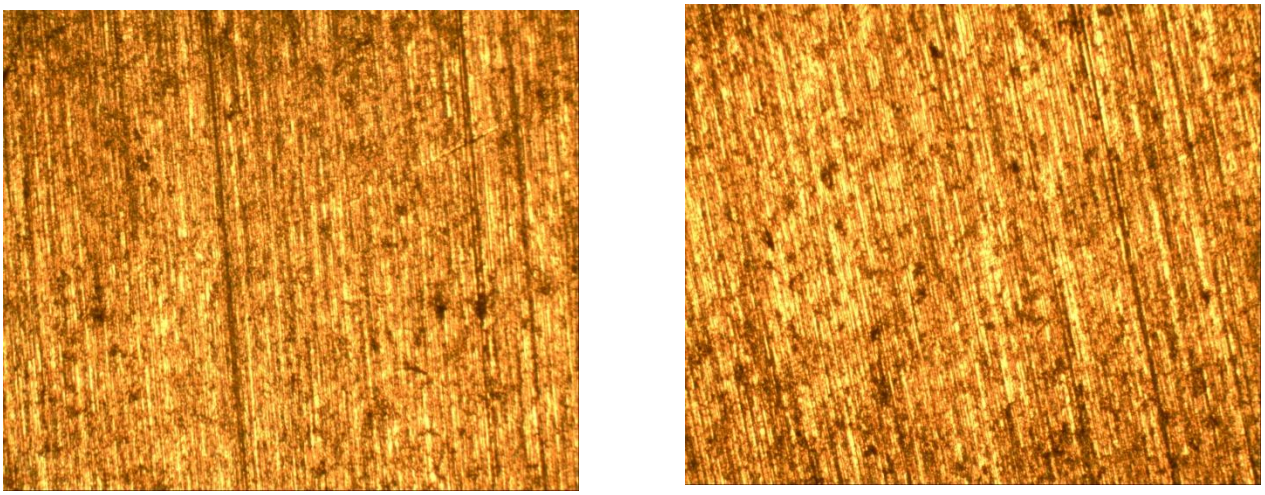


Figure 5.101 Ti CP 70 Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

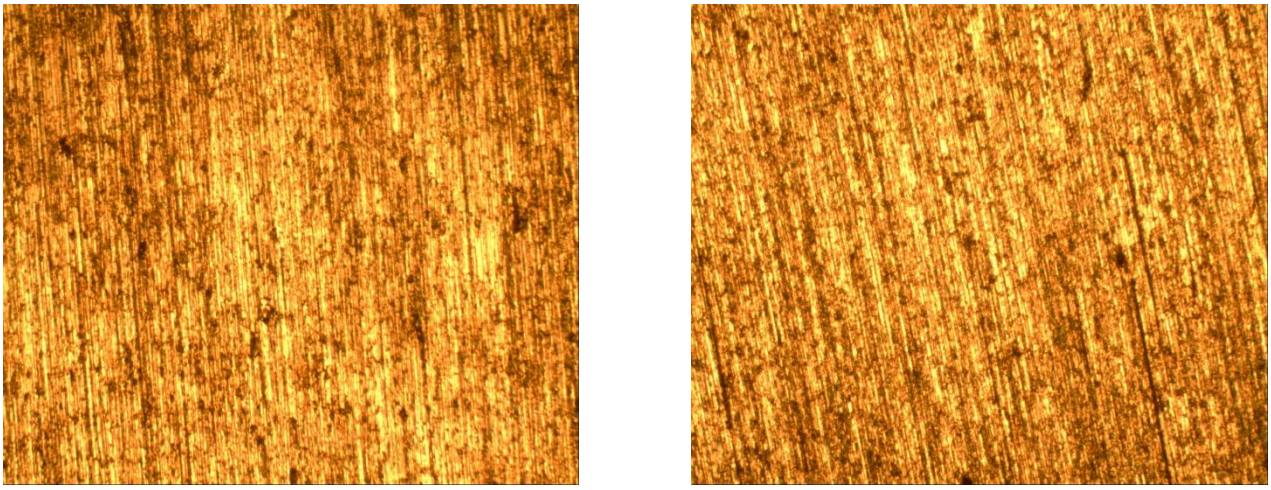


Figure 5.102 Ti CP 70 Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

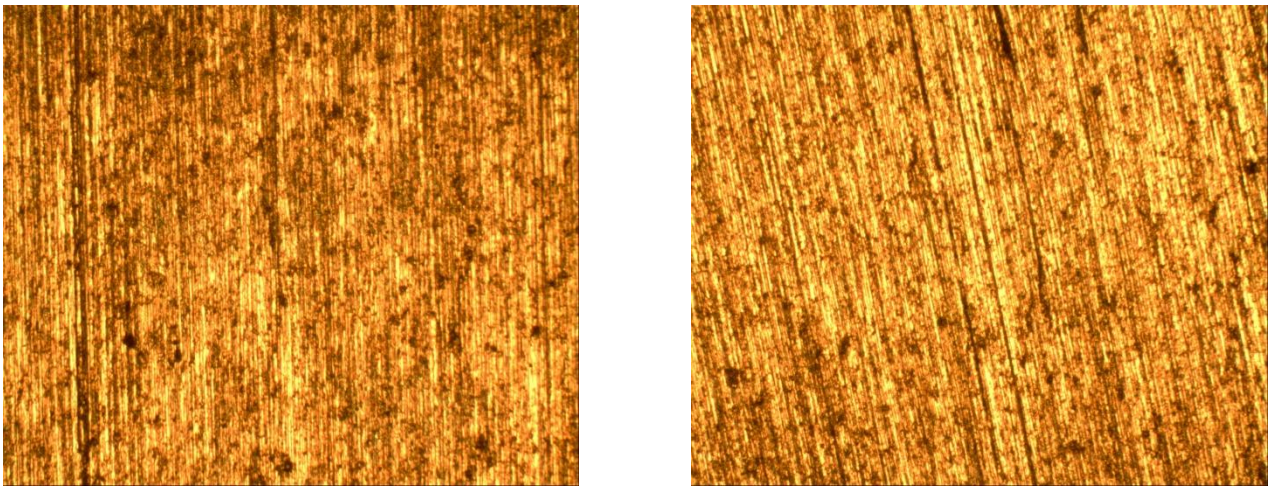


Figure 5.103 Ti CP 70 Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

Waspaloy

Sample 1

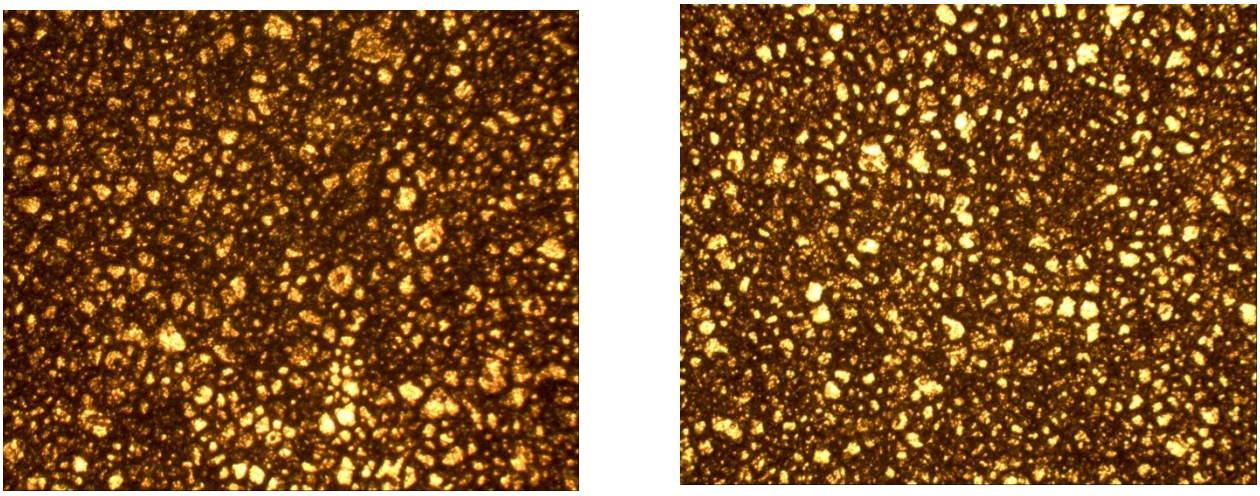


Figure 5.104 Waspaloy Sample 1 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 2

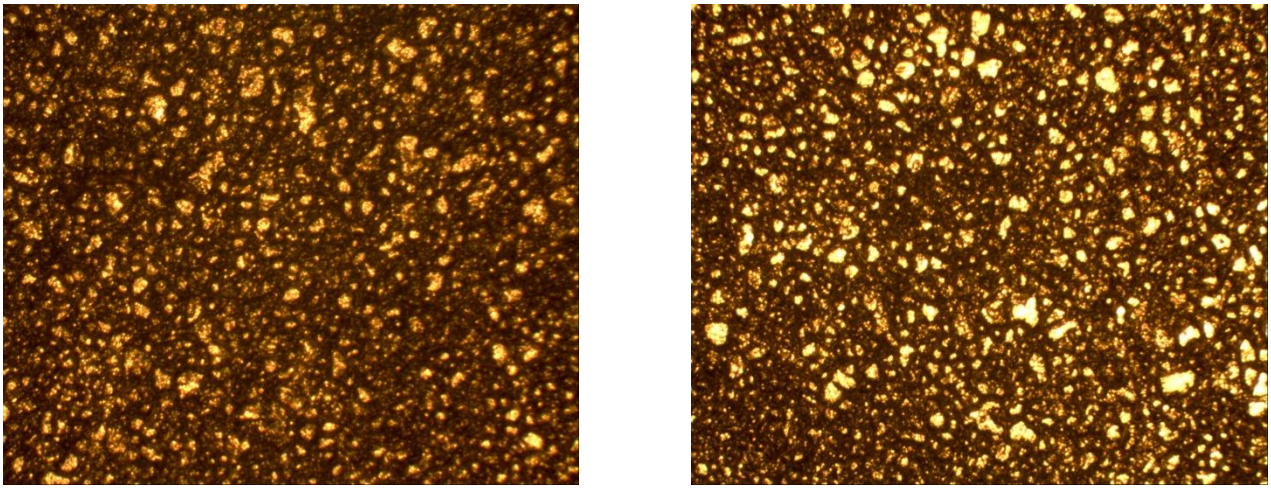


Figure 5.105 Waspaloy Sample 2 50X Visiual Inspection, Dry (left) and Soaked (right)

Sample 3

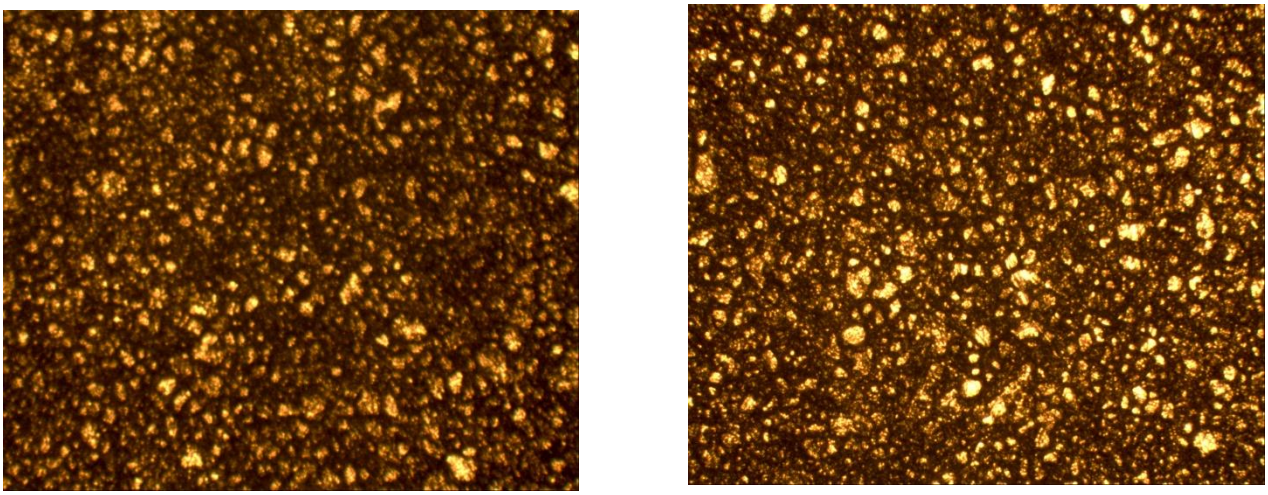


Figure 5.106 Waspaloy Sample 3 50X Visiual Inspection, Dry (left) and Soaked (right)

References

ASTM D412-98a, Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers-Tension.

ASTM D471-98e1, Standard Test Method for Rubber Property-Effect of Liquids.

ASTM D618-00, Standard Practice for Conditioning Plastics for Testing.

ASTM D1002-01, Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal).

ASTM D1414-94, Standard Test Methods for Rubber O-Rings.

ASTM D2240-03, Standard Test Method for Rubber Property—Durometer Hardness.

ASTM D3359-02, Standard Test Methods for Measuring Adhesion by Tape Test.

ASTM D3363-05, Standard Test Method for Film Hardness by Pencil Test.

ASTM D4054-09, Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives.

ASTM D4562-01, Standard Test Method for Shear Strength of Adhesives Using Pin-and-Collar Specimen.

ASTM D5363, Standard Specification for Anaerobic Single-Component Adhesives

Brian Reed, Stephen Harasim, 2001. Material Compatibility Testing with HAN-Based Monopropellants.

B Terry, 2005. Impact of Biodiesel on Fuel System Component Durability.

C. A. Moses, E. A. Frame, R.A. Alvarez, K. E. Stoecklein, T. L. Marbach, E. C. Owens, M. E. Lepera, C. J. Martin, 2000. Evaluation of Impacts of JP- 8+100 on Army Aviation and Ground Vehicles.

DeSoto® IFT integral fuel tank coatings, Technical Data Sheet.

DOW CORNING® Q42817Fluorosilicone Sealant, Technical Data Sheet.

G. B. Li, L-B Zhou, 2008. Experimental Research on the Resistance of Rubber Materials to Dimethyl Ether.

G.E. Fodor, 1989. Fuel elastomer compatibility studies.

Hysol® EA 9394, Technical Data Sheet.

Jeff Pyle, 1993. Low-cost coating stands up to alternative fuels.

Jiri Malac, 2005. Elastomers: Characterization of tensile behavior at lower deformations.

J. Harvey, P.G. Partridge, C. L. Snooke, 1985. Diffusion bonding and testing of Al-alloy lap shear test pieces.

J.R. Coleman and L.D. Gallop, 1982. Exposure of a nitrile rubber to fuels of varying aromatic levels.

K. J. Kallio, A. S. Nageye, M. S. Hedenqvist, 2009. Ageing Properties of car fuel-lines; Accelerated Testing in Close-to-Real Service Conditions.

Loctite® 609, Technical Data Sheet.

Mark E. Myers and Ismat A. Abu-Isa, 1985**.** Effects of Methanol Mixtures on Fluorocarbon Elastomers.

Matthew J. DeWitt, Edwin Corporan, John Graham, and Donald Minus, 2008. Effects of Aromatic Type and Concentration in Fischer-Tropsch Fuel on Emission Production and Material Compatibility.

Maxwell E. Shauck, Grazia Zanin, 2008. Biofuels in Aviation.

MIL-R-46082, Retaining Compounds, Single Component, Anaerobic.

Pat Muzzell, Leo Stavinoha, Rebecca Chapin, 2005. Synthetic FISCHER-TROPSCH (FT) JP-5/JP-8 Aviation Turbine Fuel Elastomer Compatibility.

PR-1422 Class B fuel tank sealant, Technical Data Sheet.

PR-1776 Class B low weight fuel tank sealant, Technical Data Sheet.

PR-1826 Class B rapid curing fuel tank sealant, Technical Data Sheet.

PS 890 Class B fuel tank sealant, Technical Data Sheet.

Robert W. Keller, 2009. Accurately Predicting O-Ring Swell.

SafeCrest® reticulated polyurethane foam, Technical Data Sheet.

Sylvain Chataigner, Jean-Francois Caron, Karim Benzarti, Marc Quiertant, Christophe Aubagnac, 2010. Use of a Single Lap Shear Test to Characterize Composite-to-Concrete or Composite-to-Steel Bonded Interfaces.

S. Bhowmik, R.Benedictus, J.A.Poulis, H.W.Bonin, V.T.Bui, 2008. High-performance nanoadhesive bonding of titanium for aerospace and space applications.

S. P. Heneghan, S. Zabarnick, D. R. Ballal, W. E. Harrison, III, 1996. JP-8+100 - The development of high thermal stability jet fuel.

UBE America Inc. UPILEX-S, Technical Data Sheet.

William G. Fortener, Susan S. Saliba, 2005. Fuel System Materials Compatibility Testing of Fuel Additives for Reducing the Amount of Small Particulate in Turbine Engine Exhaust.

Wimont Trakarnpruk, Suriya Porntangjitlikit, 2007. Palm Oil Biodiesel Synthesized with Potassium Loaded Calcined Hydrotalcite and Effect of Biodiesel Blend on Elastomer Properties.