ME 354

Fracture Test Formal Report

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Section AB

Abstract

This lab examines the fracture properties of three materials: PMMA (Acrylic), Polycarbonate and 3D printed Titanium alloy Ti_6Al_4V. Compact tension specimens were machined based on the dimensions specified in ASTM Standard E399 to measure the plane strain fracture toughness of the materials. The 3D printed titanium alloy samples exhibited the most plastic deformation prior to fracture and exhibited an average fracture toughness of 65 MPa $\sqrt{m}$. The polycarbonate samples exhibited the most brittle failure with the least plastic deformation prior to rapid crack propagation; the average fracture toughness of PC was calculated to be 3.829 MPa $\sqrt{m}$. The PMMA samples were a mixed bag, as some specimens exhibited more plastic deformation than others; the average fracture toughness of the PMMA was 0.955 MPa $\sqrt{m}$. These results show that 3D printed titanium exhibits a lower fracture toughness than solid titanium, and the implications of using titanium alloys in additive manufacturing must be investigated further.

1 Introduction

In this lab I conducted plane strain fracture tests on PMMA, polycarbonate, and 3D printed titanium in 0^{o} and 90^{o} orientations. The specimens were shaped to ASTM Standard E399 specifications and tested in an Instron 8511 Bench Top Dynamic Digital Control Material Testing System. These tests were performed to empirically obtain linear-elastic fracture toughness values for the materials in question, which are invaluable information for the design engineer such that they may create safe designs when using these materials.

Polymethyl methacrylate (PMMA), or more commonly known as acrylic, is a thermoplastic often used as a lighter and shatter-resistant alternative to soda-lime glass. It is frequently used in applications where it must endure pressure and impacts such as aquariums or ice hockey rinks, so it is imperative to understand it's fracture behavior as it may be used for safety critical components. Polycarbonates are a group of thermoplastic polymers containing carbonate groups and are heavily used in engineering applications. Common uses for polycarbonates include electronic components, construction materials, data storage, automotive, aircraft, and product packaging. This widespread use of polycarbonates lends to the need to understand their fracture mechanics better. Ti-6Al-4V is a titanium alloy that is used in implants/prostheses, additive manufacturing, aerospace/racing parts, gas turbine, and marine applications. As additive manufacturing is demonstrating to be a robust alternative to conventional manufacturing processes, it is important that we understand the implications of the additive manufacturing processes on the fracture behavior of materials. The titanium specimens analyzed in this report were 3D printed, so that we may contribute to the sparse wealth of knowledge on the fracture mechanics of 3D printed titanium.

Three specimens of each material were tested. The specimens were fabricated into a compact tension geometry and cracks were introduced at the roots of the machined notches. Tensile loading was introduced to each specimen such that the introduced cracks spread and eventually failed. Load and displacement data were collected from each specimen and used to determine force at initial cracking, peak load, and mode I critical stress intensity for the given material. From these results I draw conclusions on the validity of my calculations and provide recommendations on the applications each material is most suited for.

2 Theory

In this experiment I am interested in each material's fracture properties under mode I loading, specifically in the presence of surface flaws and defects. In my analyses I utilized linear elastic fracture mechanics, which is most suitable for analysis of materials which are linear elastic, brittle, and undergo small scale yielding. Using linear elastic fracture mechanics I found the fracture toughness K_{IC} of each material, or the critical stress intensity at which a crack will propagate unstably in the material. In the ASTM E399 method the loading and initial crack opening displacement are recorded throughout the duration of the test. The slope of the elastic loading-displacement region of each specimen was measured, and a line with a slope equal to 95% of the initial elastic loading slope was constructed on the load-displacement graph. The intersection of this line with the load-displacement data is taken to be the critical load P_Q at which each specimen's initial crack started to spread. A conditional fracture toughness K_Q was calculated for each specimen according to the equation

$$K_Q = \frac{P_Q F}{B\sqrt{W}} \ . \tag{1}$$

where B is the through-thickness of the specimen, W is the length from the flaw-free end of the specimen to the loading pins, and F is found from

$$F = \frac{(2+\alpha)[0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4]}{(1-\alpha)^{3/2}} \tag{2}$$

where α is the ratio of the crack size to the specimen width. To ensure the validity of each test and in order for the K_Q to be assumed to be equivalent to the fracture toughness K_{IC} of the specimen the following conditions must be satisfied:

$$W - a \geq 2.5\left(\frac{K_Q}{\sigma_y}\right)^2 \quad and \quad \frac{P_{Max}}{P_Q} < 1.10 \tag{3}$$

These conditions ensure that the plastic zone at the tip of a crack is sufficiently smaller than the specimen itself, such that linear elastic fracture mechanics are dominant.

3 Sample Preparation

The form factor of the compact tension specimen is illustrated in figure 1. The dimensions of each specimen were held to the ASTM E399 standard. The polycarbonate specimens were machined to these required specifications and the titanium samples were tested as fabricated. To introduce sharp cracks at the machined roots of the polycarbonate and PMMA samples razor blades were tapped at the root to create 1mm cracks. Fatigue pre-cracking was used to introduce such cracks in the titanium specimens. A time-varying tensile load was imposed on each specimen to cause a sharp crack to initiate and grow at the root of the machined notch. This loading was applied sinusoidally at 10 Hz with a mean load of 2.59 kN and an amplitude of 2.12 kN.This crack was propagated to be between 45% and 55% of the width of the sample. The width, thickness, and final crack lengths of all samples are displayed in table 1.

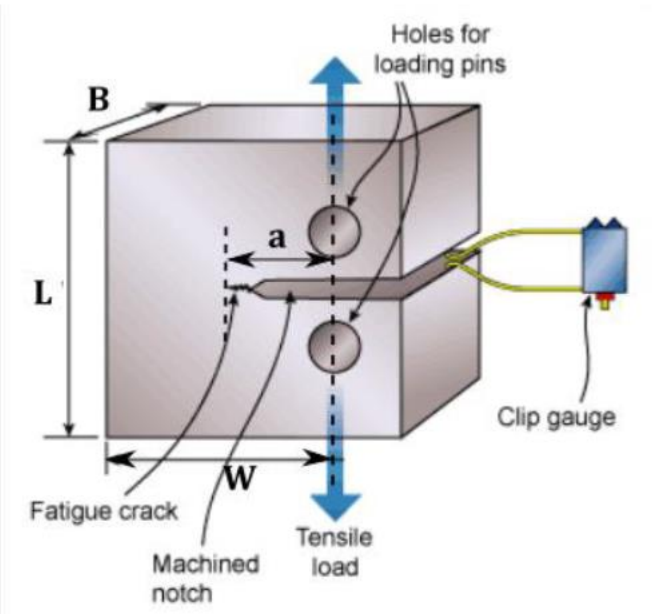


Figure 1: Schematic of the test specimen

Table 1: Width, thickness, and final crack lengths of all samples

Specimen	Width (mm)	Thickness (mm)	Final Crack Length (mm)
Ti-6Al-4V 0 Deg #1	24.0	6.0	9.34
Ti-6Al-4V 0 Deg #2	24.0	6.0	8.14
Ti-6Al-4V 0 Deg #3	24.0	6.0	8.24
Ti-6Al-4V 90 Deg #1	24.0	6.0	8.96
Ti-6Al-4V 90 Deg #2	24.0	6.0	7.078
Ti-6Al-4V 90 Deg #3	24.0	6.0	7.261
PMMA #1	25.4	6.14	8.50
PMMA #2	25.4	6.14	6.82
PMMA #3	25.4	6.14	6.94
PC #1	25.4	6.28	6.85
PC #2	25.4	6.28	5.48
PC #3	25.4	6.28	5.57

4 Experimental Setup and Procedure

Each specimen was aligned with the upper and lower fixtures on the loading stage of the Instron testing platform and fastened with pins. A clip gauge was placed at the crack opening of each specimen. A ramping loading waveform was then applied to each specimen; a ramp rate of 10 N/sec was used for the PC and PMMA, while a ramp rate of 80 N/sec was used for the titanium alloys. These loading rates were maintained until each sample fractured. Each fractured sample was then removed and imaged. Figure 2 shows a closeup of the testing setup.

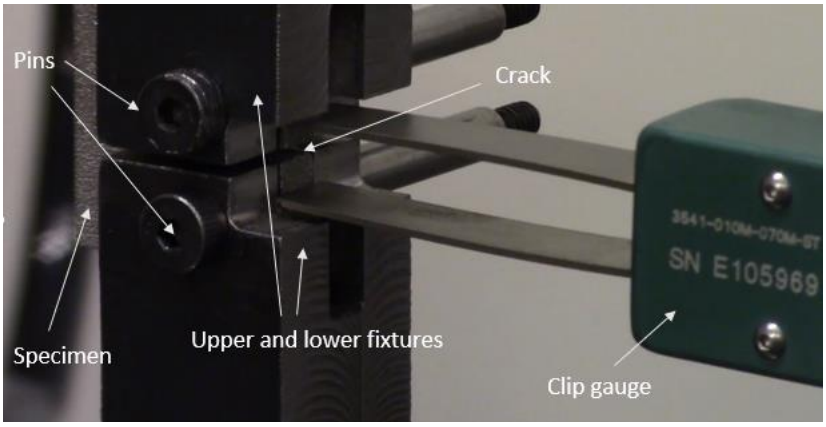


Figure 2: Image of the testing setup

5 Results

3.1 0-degree Ti_6Al_4V Analysis

The 0-degree Ti-6Al-4V specimens all exhibited generally linear elasticity up to the critical load, where plastic deformation started to dominate and the pre-cracks started to propagate. Each specimen reached peak loading before failure; the load magnitude at failure was universally lower than the peak load. Failure in each specimen was sudden as the cracks rapidly propagated through the full width and length of the specimens. Figure 3 displays the cross section of one of the specimens after failure.

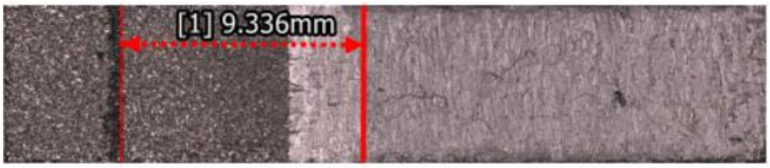


Figure 3: Titanium specimen after failure

Specimen	P_Q (N)	F	K$_{ic}$ (MPa $\sqrt{m}$)	Final Crack Length (mm)	$Pmax$ (N)
0-degree Ti-6Al-4V #1	8152	7.074	62.05	9.34	8786
0-degree Ti-6Al-4V #2	10956	6.217	73.27	8.14	11232
0-degree Ti-6Al-4V #3	9215	6.283	62.29	8.24	10834

Table 2: Calculated properties of Titanium samples.

Table 2 shows the obtained values for each specimen. Figure 4 shows the load-displacement graph of each specimen along with the linear-elastic slope fit, the corresponding 95% slope line, the intersection of the 95% line with the experimental data, and the peak loading experienced by each specimen. Table 3 shows the average values along with their standard deviations. Table 4 shows the results of the validity tests for each specimen.

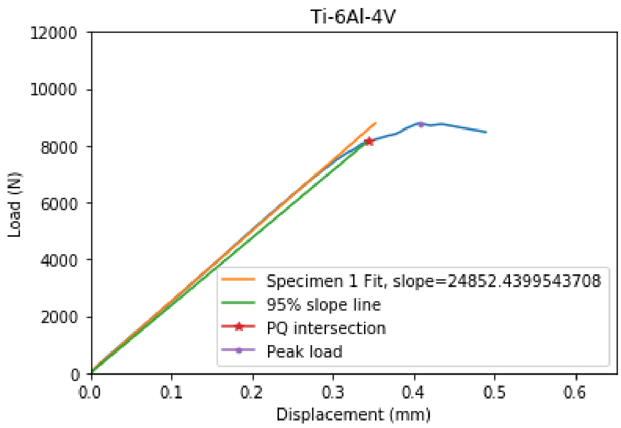
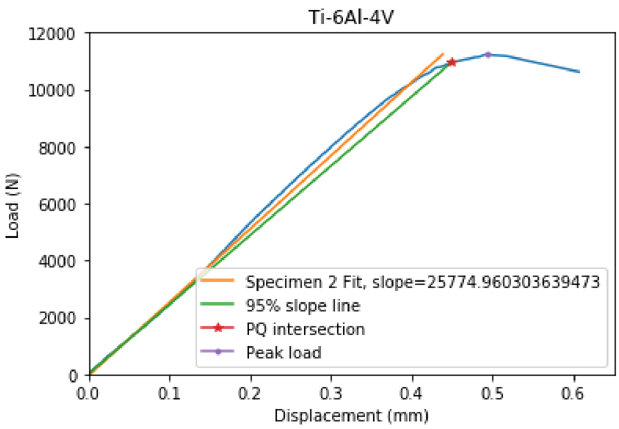
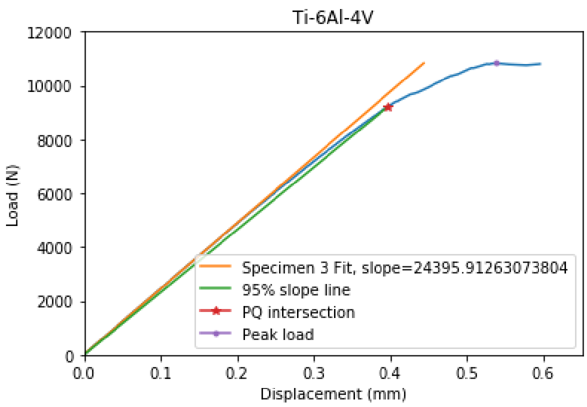


Figure 4: Load displacement plots for Titanium specimens

Material	$P_{Q,ave}$ (N)	F_{ave}	K$_{ic,ave}$ (MPa $\sqrt{m}$)	$Pmax$,ave (N)





0-degree Ti-6Al-4V	9441 ± 1156	6.52 ± 0.389	65.87 ± 5.23	10284 ± 1071

Table 3: Averaged values with standard deviations

Specimen	W – a (mm)	$2.5(\frac{K_Q}{\sigma_y})^2$	$\frac{P_{max}}{P_Q}$
0-degree Ti-6Al-4V #1	0.0146	0.0116	1.078
0-degree Ti-6Al-4V #2	0.0159	0.0162	1.026
0-degree Ti-6Al-4V #3	0.0158	0.0117	1.176

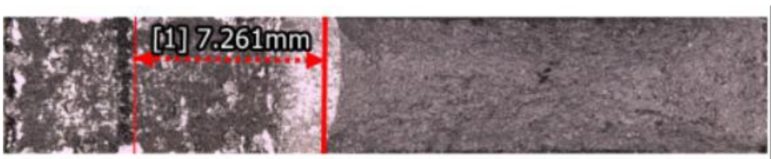
Table 4: Validity tests

The results in table 4 suggest that the calculated fracture toughness for the first specimen is valid based on both criteria, the toughness for the second specimen is invalid based on the first criterion, and the toughness for the third specimen is invalid based on the second criterion.

5.2 90-degree Ti_6Al_4V Analysis

The 90-degree Ti-6Al-4V specimens all exhibited generally linear elasticity up to the critical load, where plastic deformation started to dominate and the pre-cracks started to propagate. Each specimen reached peak loading before failure; the load magnitude at failure was universally lower than the peak load. Failure in each specimen was sudden as the cracks rapidly propagated through the full width and length of the specimens. Figure 5 displays the cross section of one of the specimens after failure.

Figure 5: Titanium specimen after failure



Specimen	P_Q (N)	F	K_{ic} (MPa $\sqrt{m}$)	Final Crack Length (mm)	$Pmax$ (N)
90-degree Ti-6Al-4V #1	8858	6.788	64.68	8.96	10494
90-degree Ti-6Al-4V #2	11039	5.547	65.88	7.078	13820
90-degree Ti-6Al-4V #3	10421	5.658	63.43	7.261	16787

Table 5: Calculated properties of Titanium samples.

Table 5 shows the obtained values for each specimen. Figure 6 shows the load-displacement graph of each specimen along with the linear-elastic slope fit, the corresponding 95% slope line, the intersection of the 95% line with the experimental data, and the peak loading experienced by each specimen. Table 6 shows the average values along with their standard deviations. Table 7 shows the results of the validity tests for each specimen.

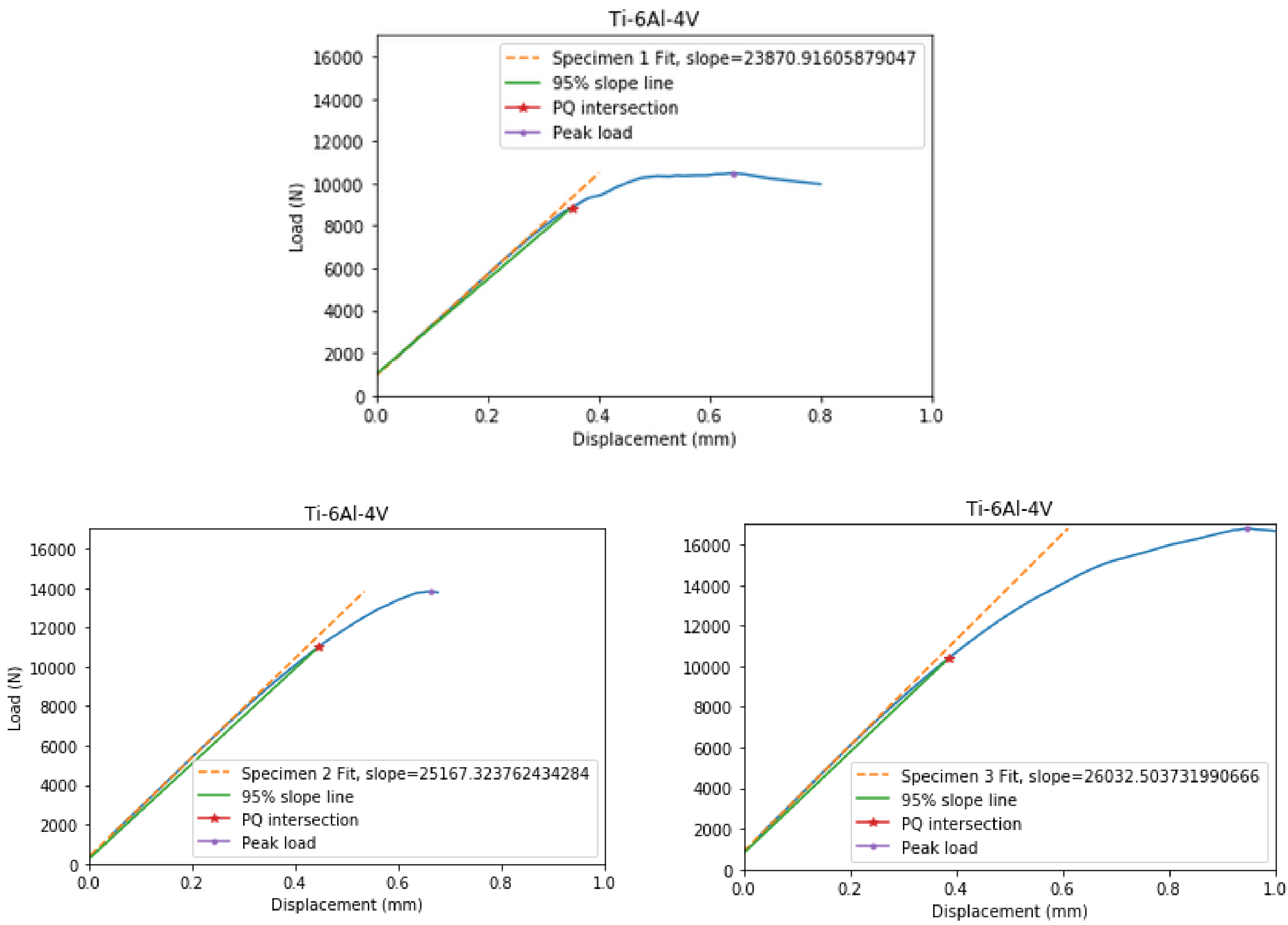


Figure 6: Load displacement plots for titanium specimens

Material	$P_{Q,ave}$ (N)	F_{ave}	$K_{ic,ave}$ (MPa $\sqrt{m}$)	$Pmax$,ave (N)
90-degree Ti-6Al-4V	10106 ± 918	6.00 ± 0.561	64.66 ± 1.00	13700 ± 2570

Table 6: Averaged values with standard deviations

Specimen	W – a (mm)	$2.5(\frac{K_Q}{\sigma_y})^2$	$\frac{P_{max}}{P_Q}$
90-degree Ti-6Al-4V #1	0.015	0.0126	1.185
90-degree Ti-6Al-4V #2	0.0169	0.0131	1.252
90-degree Ti-6Al-4V #3	0.0167	0.0121	1.611

Table 7: Validity tests

The results in table 7 suggest that the calculated fracture toughnesses for all of the specimens are not valid based on the second criterion.

5.3 PMMA (Acrylic) Analysis

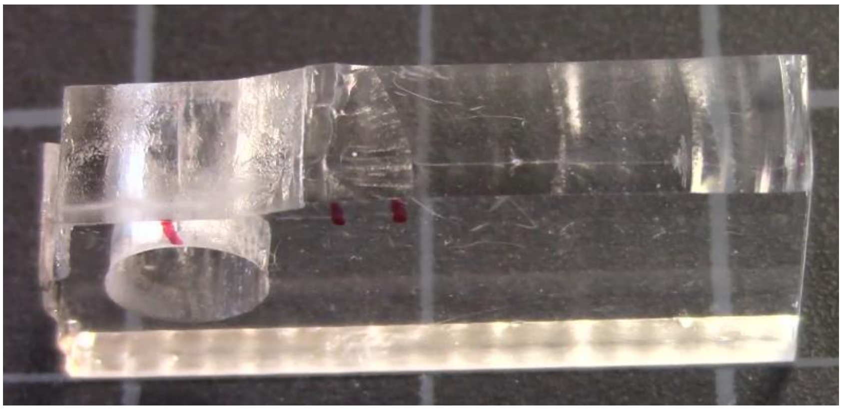


Figure 6: PMMA specimen after failure

The PMMA specimens all exhibited linear elasticity up to the critical load. The first and second specimen's load-displacement plots flattened out just before failure, indicating plastic deformation occurred prior to rapid crack propagation. Each specimen reached peak loading at failure. Failure in each specimen was sudden as the cracks rapidly propagated through the full width and length of the specimens. Figure 6 displays the cross section of one of the specimens after failure.

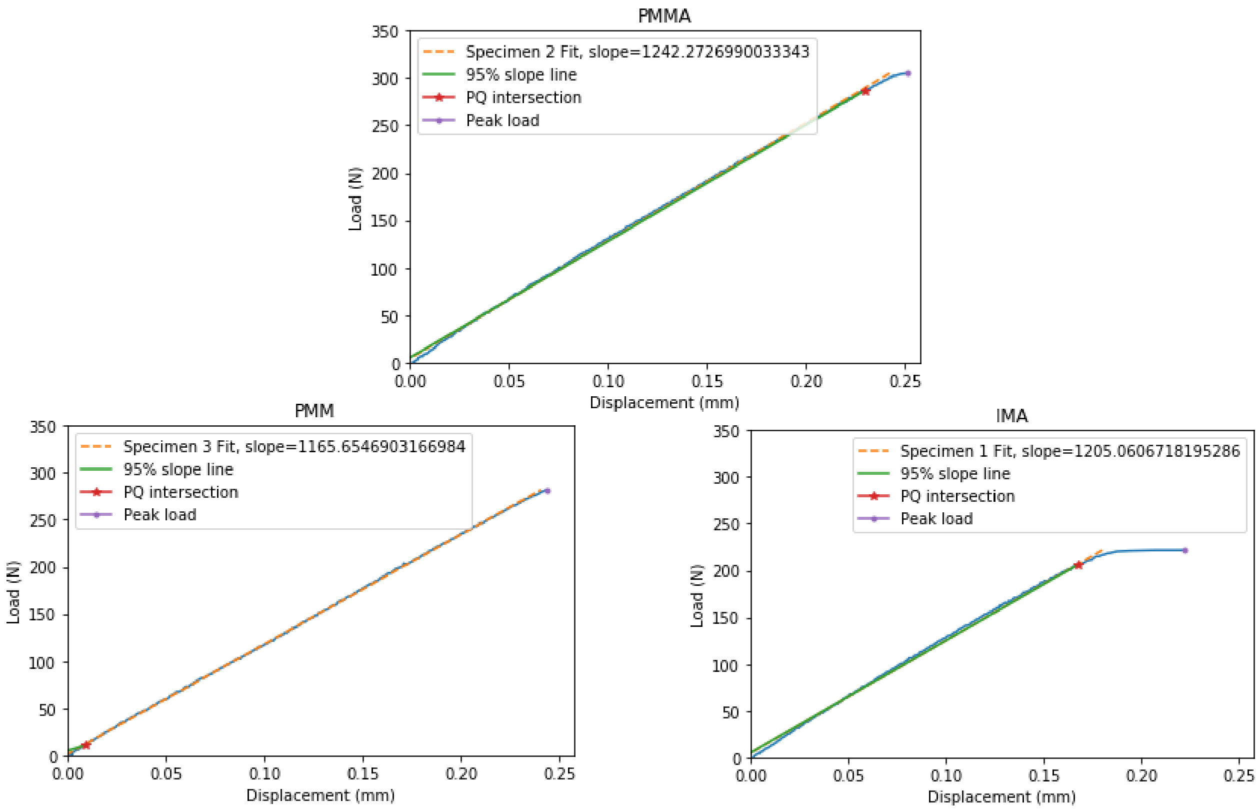


Figure 7: Load-displacement plots of PMMA specimens

Specimen	P_Q (N)	F	K_{ic} (MPa $\sqrt{m}$)	Final Crack Length (mm)	$Pmax$ (N)
PMMA #1	205.95	6.145	1.293	8.50	221.45
PMMA #2	286.84	5.176	1.517	6.82	304.92
PMMA #3	10.47	5.241	0.0561	6.94	281.72

Table 8: Calculated properties of PMMA

Material	$P_{Q,ave}$ (N)	F_{ave}	$K_{ic,ave}$ (MPa $\sqrt{m}$)	$Pmax$,ave (N)
PMMA	167.75 ± 116.02	5.52 ± 0.196	0.955 ± 0.642	269.36 ± 35.18

Table 9: Averaged values with standard deviations

Specimen	W – a (mm)	$2.5(\frac{K_Q}{\sigma_y})^2$	$\frac{P_{max}}{P_Q}$
PMMA #1	0.0169	0.00259	1.075
PMMA #2	0.01858	0.00356	1.063
PMMA #3	0.01846	4.87	26.90

Table 10: Validity tests

The results from table 10 suggest that the first and second specimens pass both of the validity tests while the third specimen fails both of them.

5.4 Polycarbonate Analysis

The PC specimens all exhibited linear elasticity up to the critical load. Each specimen reached peak loading at failure. Failure in each specimen was sudden as the cracks rapidly propagated through the full width and length of the specimens. The load-displacement plots of each specimen suggest that none of the samples underwent significant plastic deformation prior to failure. Figure 7 displays the cross section of one of the PC specimens after failure.

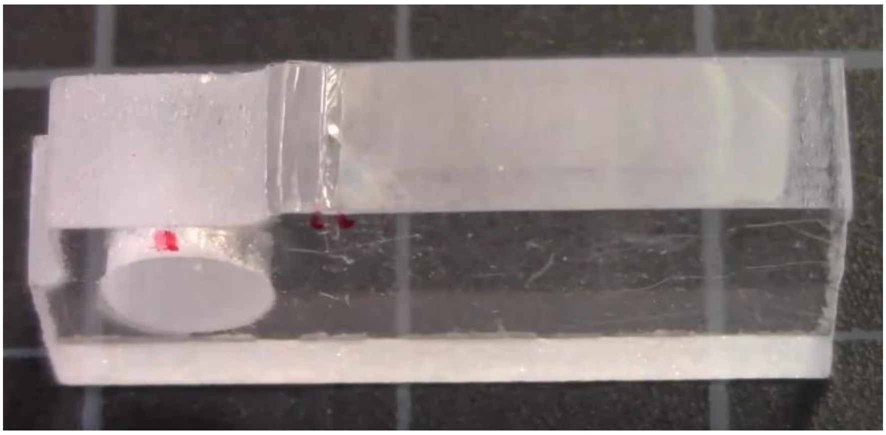


Figure 7: Polycarbonate specimen after failure

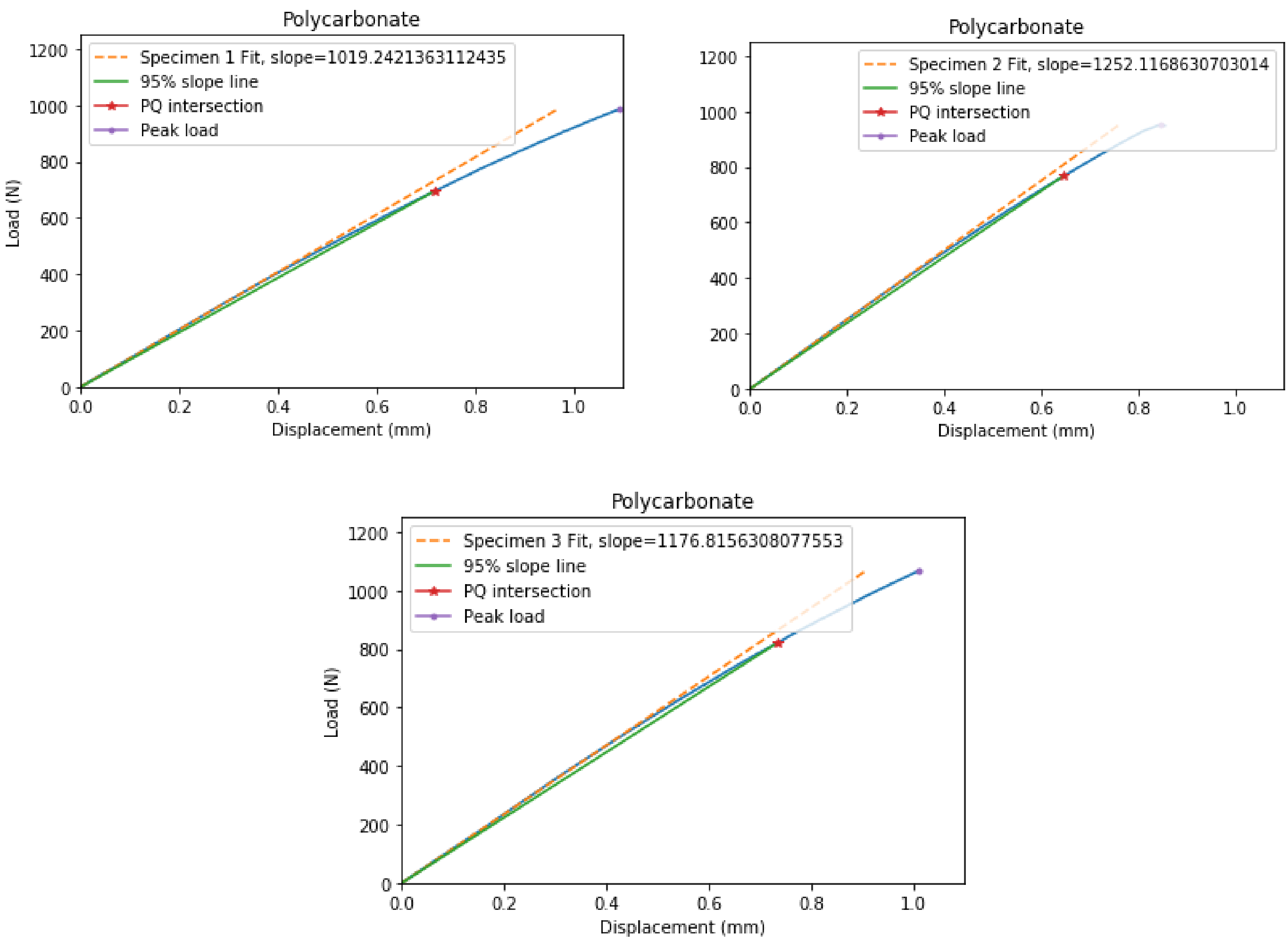


Figure 8: PC load-displacement plots

Specimen	P_Q (N)	F	K_{ic} (MPa $\sqrt{m}$)	Final Crack Length (mm)	$Pmax$ (N)
PC #1	696.6	5.411	3.874	6.85	985.3
PC #2	766.5	4.638	3.654	5.48	952.5
PC #3	821.6	4.687	3.958	5.57	1069.6

Table 11: Calculated properties of PC

Material	$P_{Q,ave}$ (N)	F_{ave}	$K_{ic,ave}$ (MPa $\sqrt{m}$)	$Pmax$,ave (N)
Polycarbonate	761.6 ± 51.2	4.912 ± 0.353	3.829 ± 0.128	1002.47± 49.32

Table 12: Averaged values with standard deviations

Specimen	W – a (mm)	$2.5(\frac{K_Q}{\sigma_y})^2$	$\frac{P_{max}}{P_Q}$
PC #1	0.01715	0.00937	1.414
PC #2	0.01852	0.00833	1.243
PC #3	0.01843	0.00978	1.302

Table 13: Validity tests

The test results in table 13 suggest that all of the PC specimens satisfy the first validity criterion but fail the second criterion.

6. Discussion

All materials tested in this report exhibited linear-elastic behavior up to the critical loading. After this critical loading is when differences in the materials' properties manifested in the test results. While the titanium specimens showed evidence of significant plastic deformation along with decreasing load magnitudes as the specimens approached failure, the PMMA specimens showed evidence of little plastic deformation prior to failure. The first PMMA exhibited the most plastic deformation with the plateauing of its load-displacement peak, while the second and third PMMA specimens did not exhibit as much of this. All of the PMMA specimens failed at their peak loading while the titanium specimens did not. The polycarbonate samples exhibited miniscule plastic deformation and failed at their peak loadings. These observations are also evident in the fracture surfaces of each material. The titanium specimens had rough surfaces around the initial crack area indicating ductile behavior. The fracture surfaces of the PMMA samples showed small rough regions in the vicinity of the initial crack areas and larger smooth regions through the rest of their widths. This indicates that the PMMA experienced some ductile behavior that led to plastic deformation before the rapid spread of the crack, upon which the PMMA experienced brittle behavior. The fracture surfaces of the PC showed very thin rough regions around the vicinities of the initial cracks, followed by much larger smooth regions through the rest of the specimens' fracture surfaces. These surfaces suggest that there was a very small amount of plastic deformation and ductile behavior in the polycarbonates before the specimens failed in brittle manner.

The fracture toughness of the titanium alloy did not change significantly as the direction of printing changed from 0 degrees to 90 degress. The average fracture toughness of the 0 degree printed specimens was 65.87 MPa $\sqrt{m}$, while the average for the 90 degree printed specimens was 64.66 MPa $\sqrt{m}$. These values are lower than the fracture toughness of solid titanium, which is tabulated at 87.93 MPa $\sqrt{m}$ [2]. This discrepancy can be explained by the process by which the solid and 3D printed titanium samples are manufactured. While solid titanium is generally microstructurally uniform after being forged in the Kroll process [3], the 3D printed titanium is susceptible to microstructural defects and weak bonding between the layers as they are laid down on the printing base. These flaws may bring the fracture toughness of the 3D printed samples lower than the solid samples.

The yield strength of polycarbonate is 63.3 MPa, the yield strength of PMMA is 40.2 MPa, and the yield strength of 3D printed titanium is 910 MPa. The presence of a crack in a sample of each of these materials introduces a geometric discontinuity that acts as a stress raiser, decreasing the loading required to make a sample fail. The yield strengths of materials are obtained from flawless specimens in tension tests, which is why the yield strength of a given material seems much higher than the fracture toughness.

The findings of this report warrant further investigation into the fracture behavior of 3D printed titanium alloys, PMMA, and polycarbonates. I would recommend that engineers use 3D printed titanium alloys in designs instead of conventionally machined alloys only when it is not possible to create the desired form factor through conventional machining. This report shows evidence that 3D printing titanium alloys reduce their fracture toughness, but further testing must be done to comprehensively catalogue the implications of using titanium alloys in additive manufacturing.

7 Conclusion

In this report I tested and analyzed the fracture properties of Ti-6Al-4V, PMMA, and polycarbonate. I found the average 3D printed Ti-6Al-4V fracture toughness to be approximately 65 MPa $\sqrt{m}$, the fracture toughness of PMMA to be an average of 0.955 MPa $\sqrt{m}$, and the fracture toughness of polycarbonate to be an average of 3.829 MPa $\sqrt{m}$. The titanium samples experienced the most ductile behavior and plastic deformation, while the polycarbonate samples experienced the most brittle behavior. Some PMMA samples exhibited more plastic deformation than others prior to rapid crack propagation. Based on the findings in this report and their shortcomings, I recommend that further investigation into the implications of using titanium alloys in additive manufacturing be conducted.

8 Appendix

(code is after references)

9 References

[1] ASTM International Committee E08 on Fatigue and Fracture. Subcommittee E08. 07 on Fracture Mechanics. *Standard Test Method for Linear-elastic Plane-strain Fracture Toughness K [Ic] of Metallic Materials*. ASTM International, 2013.

[2] Fuwen Chen, Yulei Gu, Guanglong Xu, Yuwen Cui, Hui Chang, Lian Zhou, *Improved fracture toughness by microalloying of Fe in Ti-6Al-4V*, Materials & Design,Volume 185, 2020 , ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2019.108251.

[3] W. J. Kroll, “The Production of Ductile Titanium” Transactions of the Electrochemical Society volume 78 (1940) 35–47.

Ti0deg

December 7, 2020

1 Fracture Data Analysis Code ~ (* o *) ~

For this lab, your output data will consist of load vs displacement for all the samples tested. To calculate the fracture toughness of a given material, you will:

- Plot the load displacement data
- Calculate the slope of the initial elastic region as you did in the tension lab
- Construct another line with a slope equal to 95% of the initial elastic region
- Find the intersection of the constructed line with the original load displacement curve and record that value
- You will insert this value into equation (1) in the manual and obtain the fracture toughness of that sample
- Since 3 tests were conducted on the same material, please calculate average values and standard deviation for every material type.

All the Best!

1.0.1 All Imports

[1]:
```
# Import all libraries here
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from scipy.stats import linregress #Linear regression function built into the␣
↪Scipy library
```

1.0.2 Specimen Size

[2]:
```
## insert the width (W), thickness (B) and crack length (a) here for each␣
↪sample in meters
W = 0.024    #m
B = 0.006    #m
a_1 = 0.00934
a_2 = 0.00814
a_3 = 0.00824 #m
s_y = 910e6
```

1.0.3 Getting Data from Excel to Python

[3]:
```
# File with all the data
dataFile = 'Fracture data_Final_Aut 2020.xlsx'

# Create a list of strings corresponding to the tab names in the excel file,␣
↪then use that
#    to import data
Setnames = ['Ti 0deg 1', 'Ti 0deg 2', 'Ti 0deg 3' ]
Data = {x:{} for x in Setnames}

# Import Data
for File in Setnames:
    Data[File] = pd.read_excel(dataFile, sheet_name = File, skiprows = 4,␣
↪usecols = "B:C", header = None)
    # Naming the columns
    Data[File].columns = ['Displacement (mm)', 'Load (N)']

#Data[Setnames[1]].head() #To check the file is being correctly accessed
```

1.0.4 Linear Fitting

[4]:
```
# Write a function here to fit the slope of the elastic region-It is pretty␣
↪similar to what
#    you did to calculate the young's modulus in the tension lab analysis
# Inputs of the function can be the load and displacement data along with the␣
↪points between
#    which you want to fit the slope
# You can use linear regression to fit the slope
# Function should return the slope and the data like intercept (C), regression␣
↪(R) value and
#     X,Y points to visualize the fit on the stress strain curve

def slopeFit(Displacement,Load,a,b):
    slope,C,R,P,Err = linregress(Displacement[a:b],Load[a:b])
    Y = [0, max(Load)]
    X = [(y-C)/slope for y in Y]
    return slope,C,R,X,Y
```

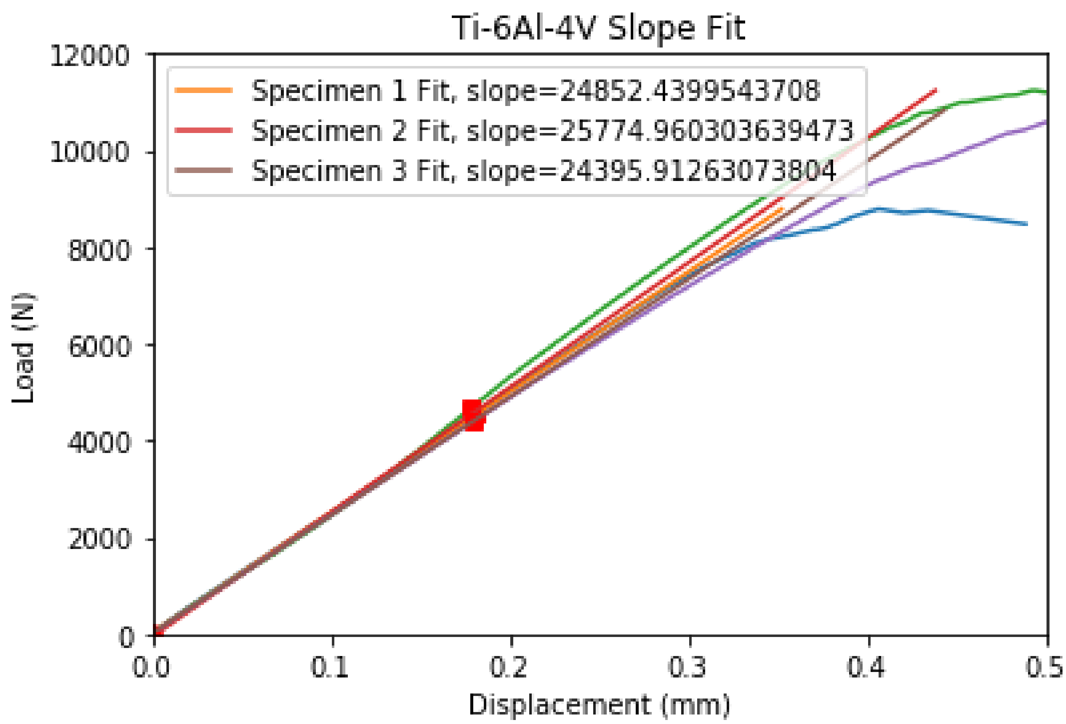
1.0.5 Plotting

[5]:
```
fig = plt.figure()
ax = fig.gca()



a = 0; b = 300
```

```
slopes = []
ER2Values = []
for File in Setnames:
    #Save dummy variables to make the code cleaner below
    Displacement = Data[File]['Displacement (mm)'].values
    Load = Data[File]['Load (N)'].values

    #Use the two fits
    slope,C,R,X,Y = slopeFit(Displacement,Load,a,b)


    #Plot the data
    ax.plot(Displacement,Load)
    ax.plot(Displacement[a],Load[a],'rd') #This is the first point we're␣
 ↪fitting from
    ax.plot(Displacement[b],Load[b],'rs') #this is the last point we're fitting␣
 ↪to


    #Plot the fits/
    ax.plot(X,Y,label='Specimen '+str(Setnames.index(File)+1)+' Fit,␣
 ↪slope='+str(slope))


    slopes.append(slope)

    ER2Values.append(R)
    print(X)
    print(Y)


ax.set_xlim(left = 0, right=0.5)
ax.set_ylim(bottom = 0, top=12000)
plt.title("Ti-6Al-4V Slope Fit")
plt.ylabel('Load (N)')
plt.xlabel('Displacement (mm)')
plt.legend()
plt.show()
print(slopes)
print(ER2Values)
```

```
[-0.0011953859455311384, 0.3523598350360885]
[0, 8786.7099]
[0.0023099935596522774, 0.438477256964228]
[0, 11242.1939]
[-0.0006445976195334465, 0.4434766272756805]
```

```
[0, 10834.7426]
```




```
[24852.4399543708, 25774.960303639473, 24395.91263073804]
[0.9999471564289474, 0.9990544637729714, 0.9999890505049154]
```

1.0.6 Plotting main curve with 95% slope curve and finding Pq

[6]:
```
# Here we use the outputs (X,Y, slope) of the slope fit function. You first run
 ↪the function and
#    store these values as lists (X_values, Y_values, slope_values).
# Now use these values to calculate the 95% slope line. We do this by using the
 ↪simple line equation
#    y = m*x + c. To do this we use the X_values and Y_values as the initial
 ↪point (x1, y1) and then use
#    the list of displacement values (x2) to calculate the corresponding 95%
 ↪load values (y2)
# We store these values of (y2) as Load_95.
# All data entities above (X_values, Y_values, slope_values, Load_95) will be
 ↪list of lists
# Now we calculate the index of intersection, idx.
# Since PQ is the load where the 95% slope line intersects the load
 ↪displacement curve,
# one method to calculate PQ is to calculate the the y values of the 95% slope
 ↪line
```

```
#    for all displacement values and then use the numpy functions to calculate␣
↪where
#    the two curves intersect.
# We will store the value of those intersections, the last intersection will be
#    the point of maximum load = PQ

# Initialize empty lists to store values
X_values =[]
Y_values = []
Load_95 = []
Pq_values = []
slope_values = []
ER2Values = []
a = 0; b = 300
idxs = []




for File in Setnames:
    #Save dummy variables to make the code cleaner below
    Displacement = Data[File]['Displacement (mm)'].values
    Load = Data[File]['Load (N)'].values

    #Use the two fits
    slope,C,R,X,Y = slopeFit(Displacement,Load,a,b)
    X_values.append(X)
    Y_values.append(Y)
    slope_values.append(slope)



# Compute values of (x1.y1) and (x2,y2) for 95% slope line
for File in range (0, len(Setnames)):
    Load_95_tot =[]
    for i in range (0, len(Data[Setnames[File]]['Displacement (mm)'])):
        # This is the step to calculate (y2) by doing (y1 -m*(x2-x1))
        Load_values_95 = Y_values[File][0] + 0.
↪95*slope_values[File]*(Data[Setnames[File]]['Displacement (mm)'][i] -␣
↪X_values[File][0])
        # Appending the above calculated values
        Load_95_tot.append(Load_values_95)
    Load_95.append(Load_95_tot)
    # Converting the load values from the test into an np array for plotting␣
↪convenience
    Load_0 = np.array(Data[Setnames[File]]['Load (N)'])
```

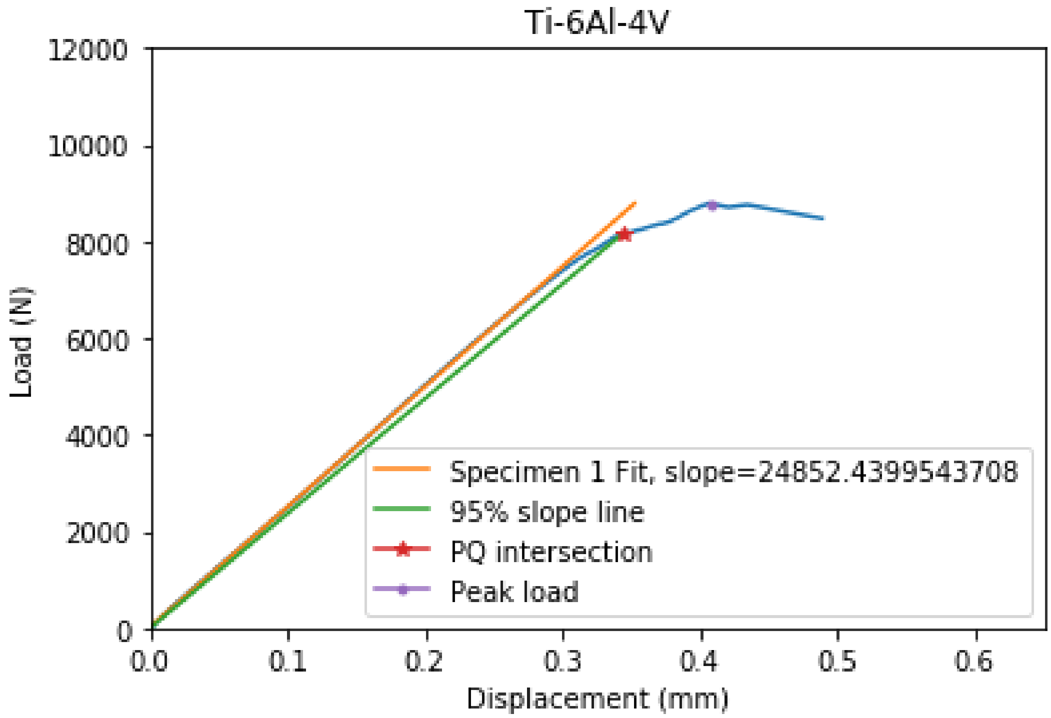
```python
    # Finding the point of intersection of the 95% slope line with the load␣
↪displacement curve
    idx = np.argwhere(np.diff(np.sign(Load_0 - Load_95[File]))).flatten()
    # Last intersection point is PQ
    P_Q = Load_0[max(idx)]
    # Appending PQ values
    Pq_values.append(P_Q)
    idxs.append(max(idx))

print(Pq_values)

print(slope_values)

print(len(Load_95))
print(idxs)
```

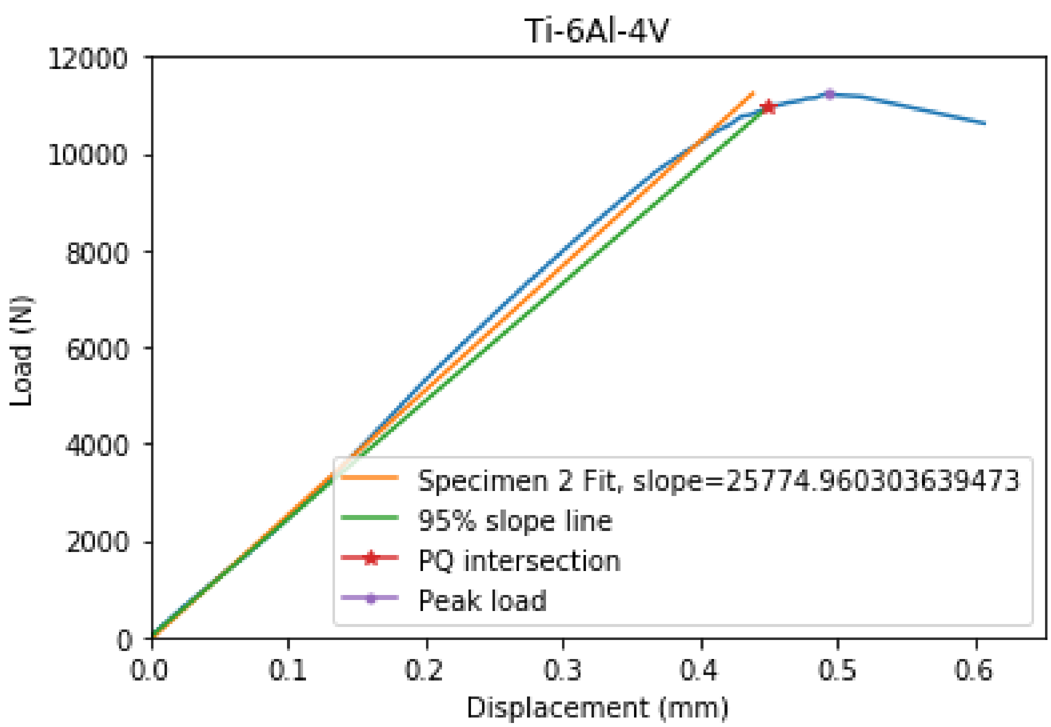
```
[8152.4842, 10956.0805, 9214.9417]
[24852.4399543708, 25774.960303639473, 24395.91263073804]
3
[538, 718, 620]
```

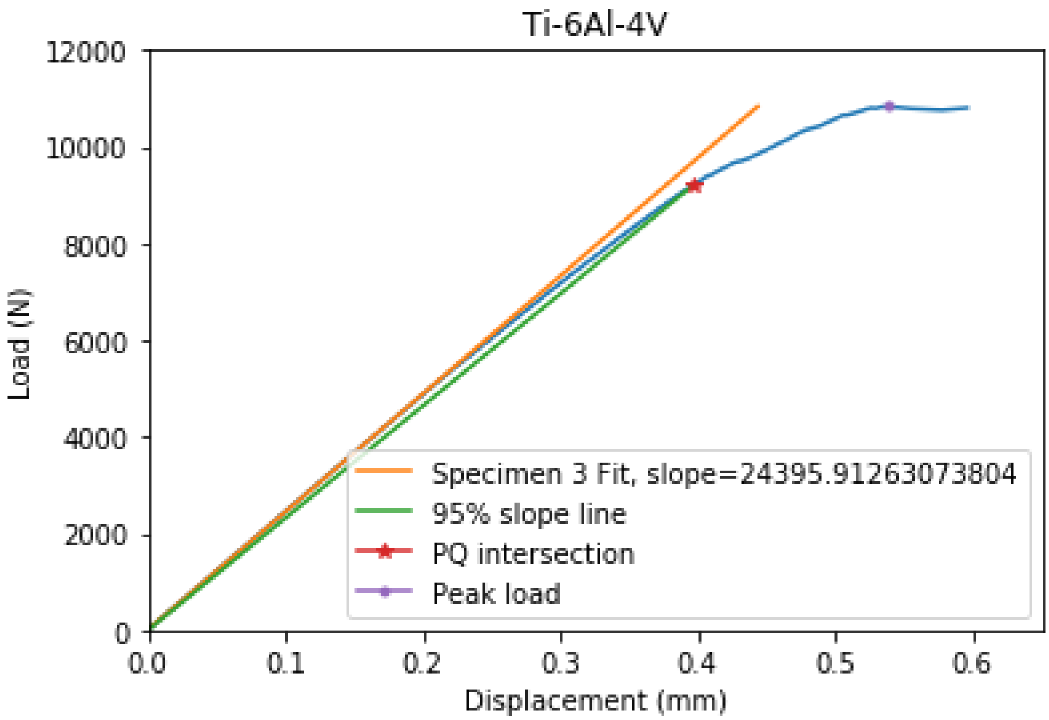
1.0.7 Plotting

[7]:
```python
# Plot the 95% slope line, stress strain curve and the linear fitting together␣
↪here



a = 0; b = 300



i=0
maxloads=[]

for File in Setnames:
    fig = plt.figure()
    ax = fig.gca()


    #Save dummy variables to make the code cleaner below
    Displacement = Data[File]['Displacement (mm)'].values
    Load = Data[File]['Load (N)'].values

    #Use the two fits
    slope,C,R,X,Y = slopeFit(Displacement,Load,a,b)
```

```
    maxload = max(Load)
    maxloads.append(maxload)




    #Plot the data
    ax.plot(Displacement,Load)


    #Plot the fits|
    ax.plot(X,Y,label='Specimen '+str(Setnames.index(File)+1)+' Fit,␣
↪slope='+str(slope))
    ax.plot([0,Data[File]['Displacement␣
↪(mm)'][idxs[i]]],[0,Pq_values[i]],label='95% slope line')
    ax.plot(Data[File]['Displacement (mm)'][idxs[i]],Pq_values[i],marker = '*',␣
↪label = 'PQ intersection')

    if i==0:
        ax.plot(0.4076,8786.71,marker='.', label='Peak load')
    elif i==1:
        ax.plot(0.4946,11232.19,marker='.', label='Peak load')
    elif i==2:
         ax.plot(0.5386,10834.74,marker='.', label='Peak load')

    slopes.append(slope)

    ER2Values.append(R)
    ax.set_xlim(left = 0, right=0.65)
    ax.set_ylim(bottom = 0, top=12000)
    plt.title("Ti-6Al-4V")
    plt.ylabel('Load (N)')
    plt.xlabel('Displacement (mm)')
    plt.legend()
    plt.show()
    i+=1
```


Ti-6Al-4V
12000
10000
8000
6000
4000
2000
0
Load (N)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Displacement (mm)
Specimen 1 Fit, slope=24852.4399543708
95% slope line
PQ intersection
Peak load


Ti-6Al-4V
12000
10000
8000
6000
4000
2000
0
Load (N)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Displacement (mm)
Specimen 2 Fit, slope=25774.960303639473
95% slope line
PQ intersection
Peak load



1.0.8 Calculate Fracture Toughness

[8]:

```
alpha1 = a_1/W
alpha2 = a_2/W
alpha3 = a_3/W
F1 = ((2+alpha1)*(0.886+4.64*alpha1-13.32*alpha1**2+14.72*alpha1**3-5.
 ↪6*alpha1**4))/((1-alpha1)**1.5)
print(F1)
F2 = ((2+alpha2)*(0.886+4.64*alpha2-13.32*alpha2**2+14.72*alpha2**3-5.
 ↪6*alpha2**4))/((1-alpha2)**1.5)
print(F2)
F3 = ((2+alpha3)*(0.886+4.64*alpha3-13.32*alpha3**2+14.72*alpha3**3-5.
 ↪6*alpha3**4))/((1-alpha3)**1.5)
print(F3)
```

```
7.074145442288701
6.216649781286395
6.28344854203534
```

[9]:

```
from numpy import std

Kq_1 = (Pq_values[0]*F1)/(B*(W**0.5))
Kq_2 = (Pq_values[1]*F2)/(B*(W**0.5))
```

```
Kq_3 = (Pq_values[2]*F3)/(B*(W**0.5))
print(Kq_1)
print(Kq_2)
print(Kq_3)
Kqs = [Kq_1,Kq_2,Kq_3]

average_Kq = (Kq_1 + Kq_2 + Kq_3)/3
print()
print(std(Kqs))
print(average_Kq)
```

```
62045041.45711867
73274817.45088634
62292216.376411386

5236479.846784122
65870691.76147213
```

1.1 Validity criteria 1

[10]:
```
diff_1 = W-a_1
print(diff_1)
diff1 = 2.5*(Kq_1/s_y)**2
print(diff1)

print()

diff_2 = W-a_2
print(diff_2)
diff2 = 2.5*(Kq_2/s_y)**2
print(diff2)

print()

diff_3 = W-a_3
print(diff_3)
diff3 = 2.5*(Kq_3/s_y)**2
print(diff3)
```

```
0.014660000000000001
0.011621746073588863

0.01586
0.016209391596608856

0.01576
0.011714527898459288
```

1.2 Validity criteria 2

[11]:
```
criteria2_1 = maxloads[0]/Pq_values[0]
criteria2_2 = maxloads[1]/Pq_values[1]
criteria2_3 = maxloads[2]/Pq_values[2]

print(criteria2_1)
print(criteria2_2)
print(criteria2_3)
```

```
1.077795391495515
1.0261145762848312
1.1757798315750603
```

[ ]:
```
```