Mechanical Laboratory 2

Lab #6: Fracture Toughness

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MMAE-419-L01

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ABSTRACT:

Testing fracture toughness is used to measure resistance to cracking in notched specimens. Since nineteenth century brought increase of structural steel use and later in twentieth century structural aluminum also, testing of fracture toughness was developed to avoid catastrophic failures of such structures. In order to determine what type of material to use in their design, engineers have to conduct toughness testing. Testing is done to satisfy limitations and proper factor of safety. When testing fracture toughness, load displacement of pre-cracked specimen is recorded. Load rate and specimen dimensions are factors on which will shape of load vs. displacement curve depend. Charpy V-Notch impact testing is cheaper version of fracture toughness testing, but it is not as accurate since many approximations are used in notched impact testing. ASTM testing is standard procedure by which fracture toughness testing has been done for this lab.

INTRODUCTION:

For this lab students were conducting fracture toughness testing on various materials. Tests were done on 1018 steel and three aluminum (2024,6061,7075) specimens and two sets for each material were done. Instron 5500R was used for loading and measure of displacement and load were recorded. Multiple materials had different sizes and different loading rate was used, 0.08 or 0.1[in/min]. load was increased until fracture. Data was collected with Bluehill-2 software. When collected data is plotted, $\boldsymbol{P_{max}}$ can be demined so as $\boldsymbol{P_Q}$. $\boldsymbol{P_{max}}$ is simply largest load that happened during testing of specimen while $\boldsymbol{P_Q}$ corresponds to load at which early stage of cracking occur. $\boldsymbol{P_5}$ is load when 5% secant line meet experimental curve. First test of validity is being tested by using ***(1)*** and it states that ratio of maximum load vs. load when cracking starts to occur is less than 1.1. In other words, difference between P_{max} and P_Q must be less than 10% in order to have valid test.

$$1.1 > \frac{P_{max}}{P_Q} \qquad (1)$$

Second validity test equation is:

$$(W - a) > 2.5\left[\frac{K_Q}{\sigma_{ys}}\right]^2 \qquad (2)$$

It states that specimen ligament size ***(W – a)*** must be greater than value that can be found on the right side of equation ***(2)***, where $\boldsymbol{\sigma_{ys}}$ is the 0.2% offset yield strength, ***a (Figure 1)*** is the average crack length (in), ***W (Figure 1)*** is specimen width (in) and $\boldsymbol{K_Q}$ (stress intensity factor) can be found using by using equation (3).

$$K_Q = f\left(\frac{a}{W}\right)\frac{P_Q}{B\sqrt{W}} \qquad (3)$$

Where ***B (Figure 1)*** is the thickness of the Compact Tension (CT) specimen and $\boldsymbol{f\left(\frac{a}{W}\right)}$ is called the geometric factor and can be calculated by using equation ***(4)***

$$f\left(\frac{a}{W}\right) = \left(2 + \frac{a}{W}\right)\frac{\left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right]}{\left(1 - \frac{a}{W}\right)^{3/2}} \qquad (4)$$

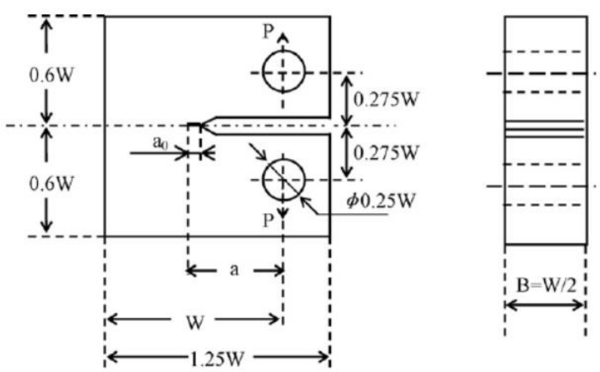

Figure 1. Compact Tension (CT) specimen standard according to ASTM E399-09

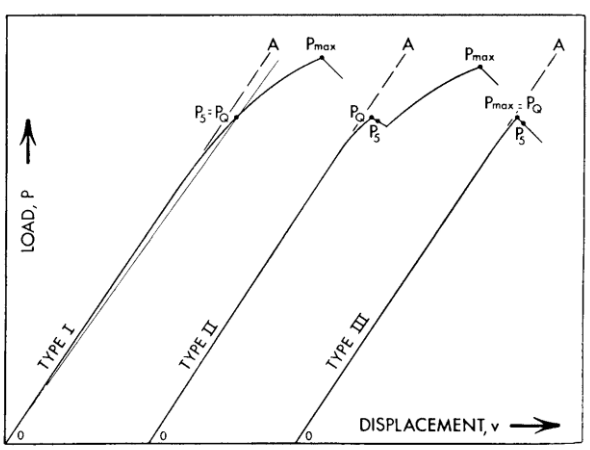

Figure 2. Three types of force vs. displacement behavior

PROCEDURE:

Measures of the thickness (***B***) and width (***W***) of the Compact Tension (CT) specimen were taken. Specimen that is pre-cracked to a particular crack location (given by the ratio of crack length to specimen width) is than placed and secured in Instron 5500R. When specimen is placed and secured extensimeter (**Figure 3**) is placed on it to measure displacement with respect to load. Both displacement and load are recorded by using software. Experiment started, load was applied until specimen fractured (**Figure 4**). Rate of load applied varied (0.08 or 0.1 [in/min]) in each experiment so as dimensions of specimens that were tested. When each specimen fractured it was removed and taken to optical comparator (**Figure 5**) in order to examine the fracture surface. Crack lengths are measured at mid-thickness and the two quarter-thickness points and average of these three measurements are later used as ***a***. This measures at optical comparator were repeated for each eight specimens.

Figure 3. Specimen with extensimeter

Figure 4. Specimen after fracture

Figure 5. Optical Comparator

Figure 6. Specimen surface after fracture

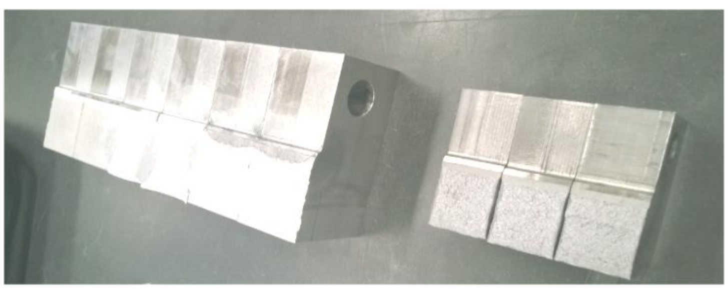

Figure 7. Specimen surfaces

Figure 8. Specimen surface

RESULTS:

First experimental data was plotted and then curve was fitted through straight part of plot. 5% secant line than could be fitted so we could see to which one of three types of force vs. displacement behavior does it belong to. Where 5% secant line meats experimental data plot is $\boldsymbol{P_5}$. Pre-cracked specimen under load have three way it behaves (**Figure 2**), and only if behavior is type II, there will be different $\boldsymbol{P_Q}$, $\boldsymbol{P_{max}}$ and $\boldsymbol{P_5}$. When behavior can be described as type I than $\boldsymbol{P_Q}$ is equal to $\boldsymbol{P_5}$, and if behavior is type III, $\boldsymbol{P_{max}}$ is equal to $\boldsymbol{P_Q}$. Experimental data is plotted for each material (***plots 9-16)*** together with regression equation that describe offset line and from there $\boldsymbol{P_Q}$, $\boldsymbol{P_{max}}$ and $\boldsymbol{P_5}$ can be found. The thickness (***B***) and width (***W***) of the Compact Tension (CT) specimen are measured and ***a*** is the average crack length at mid-thickness and the two quarter-thickness points. ***R*** is rate of loading, and ***sy*** is yield strength and it is given for each material. When $\boldsymbol{P_Q}$ and $\boldsymbol{P_{max}}$ are known than 1st validity test can be done using **(1)**. In order to check for 2nd validity (2), $\boldsymbol{K_Q}$ (stress intensity factor) and $\boldsymbol{f\left(\frac{a}{W}\right)}$ (geometric factor) can be found using **(3)** and **(4)** respectfully. All data and validity tests are shown in **Table 1**.

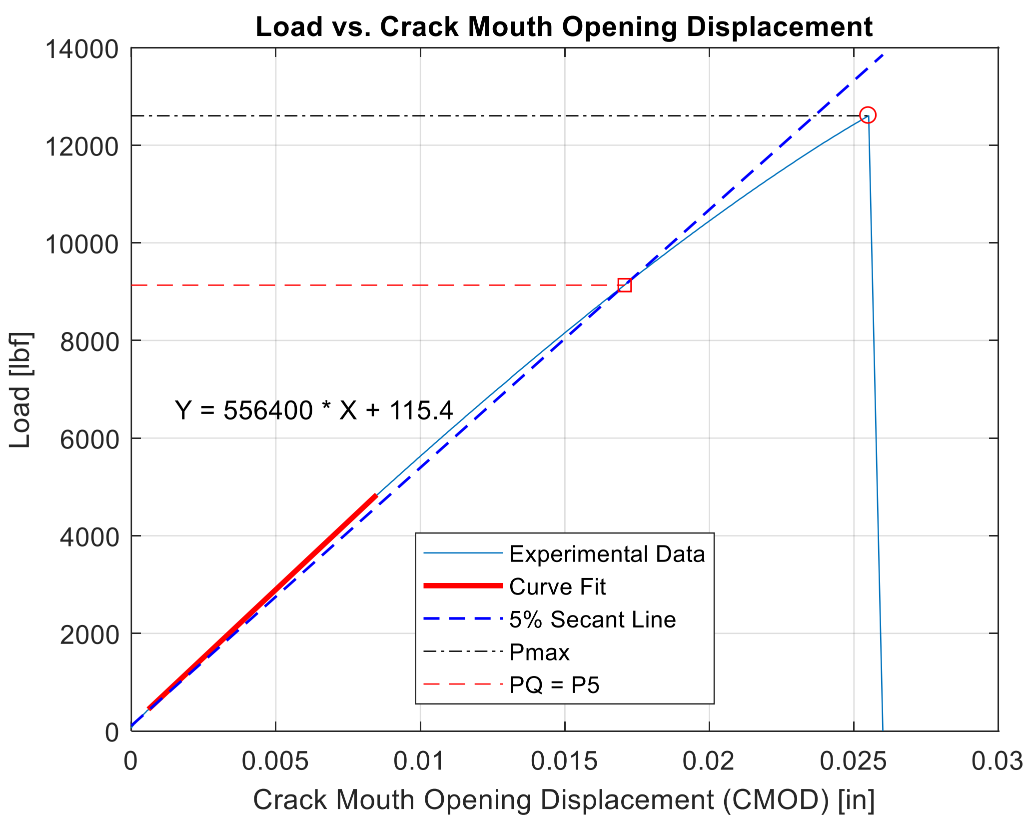

Figure 9. 1018 steel (1) plot

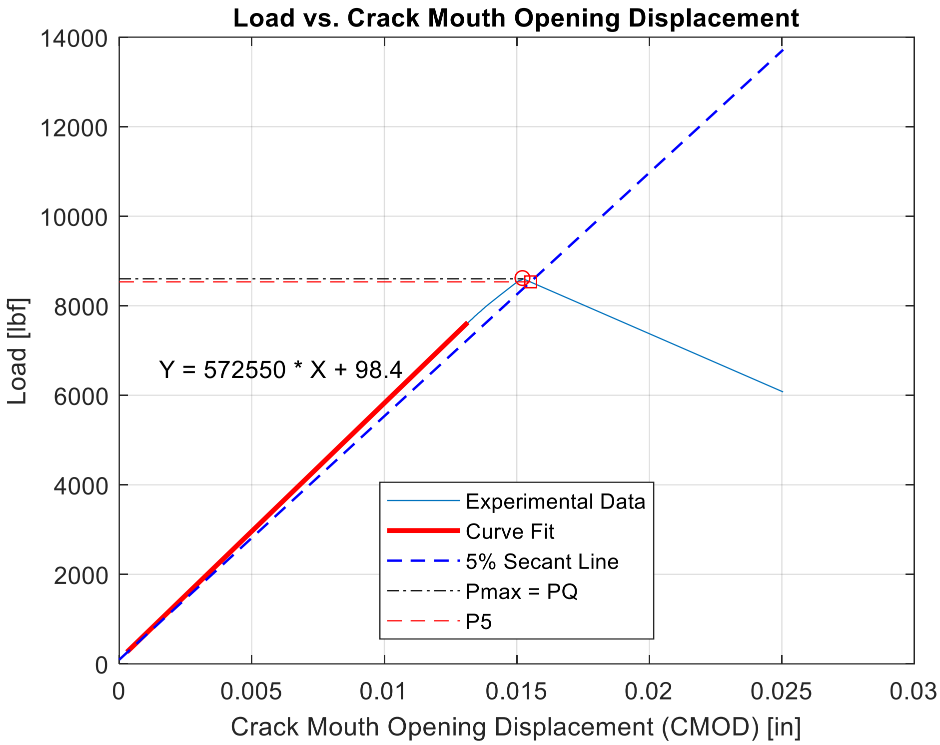

Figure 10 a). 1018 steel (2) plot

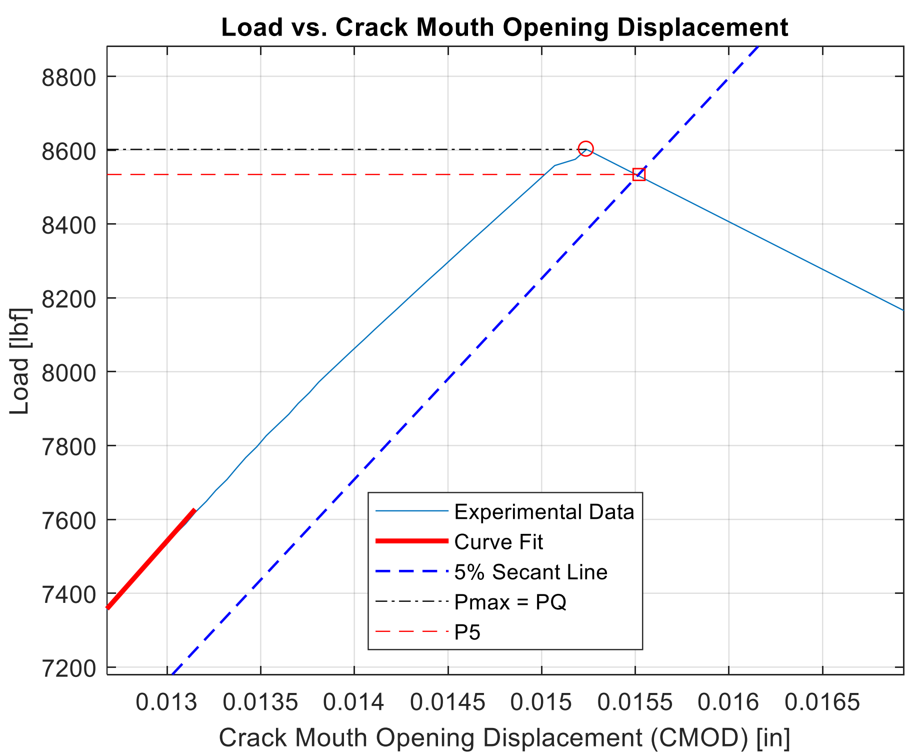

Figure 10 b). 1018 steel (2) zoom-in plot

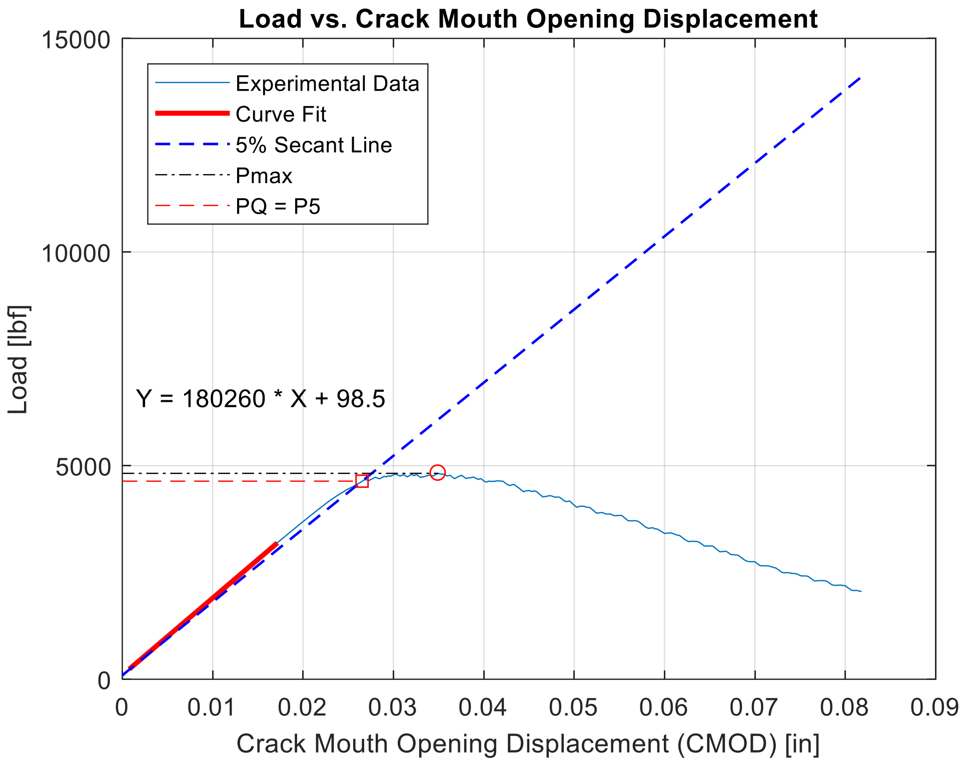

Figure 11 a). 2024 Aluminum (1) plot

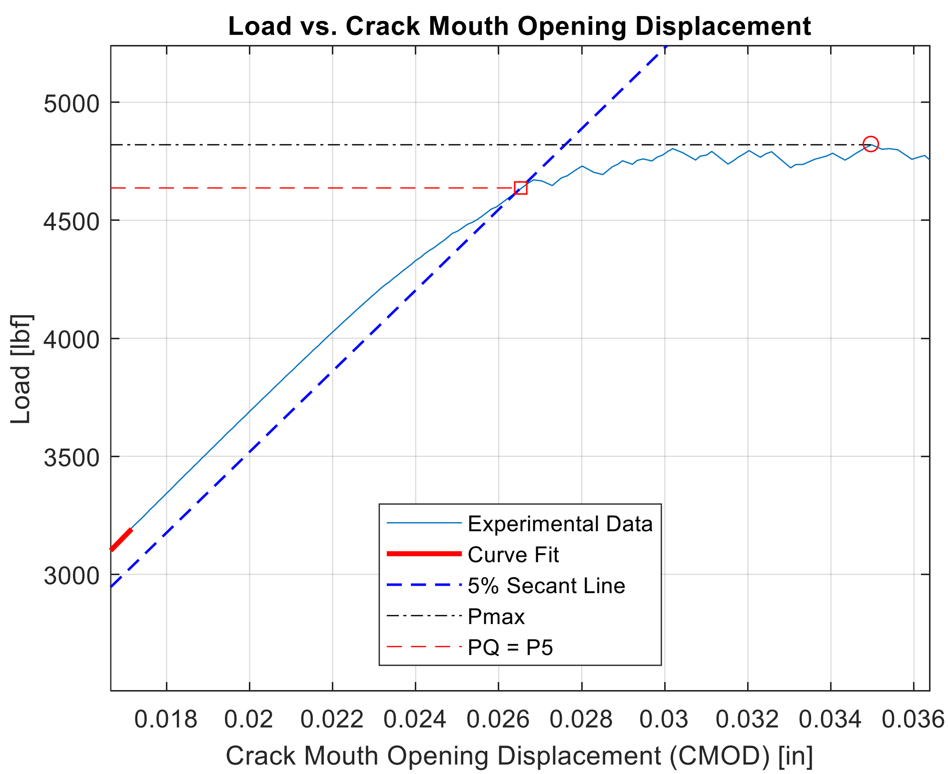

Figure 11 b). 2024 Aluminum (1) zoom-in plot

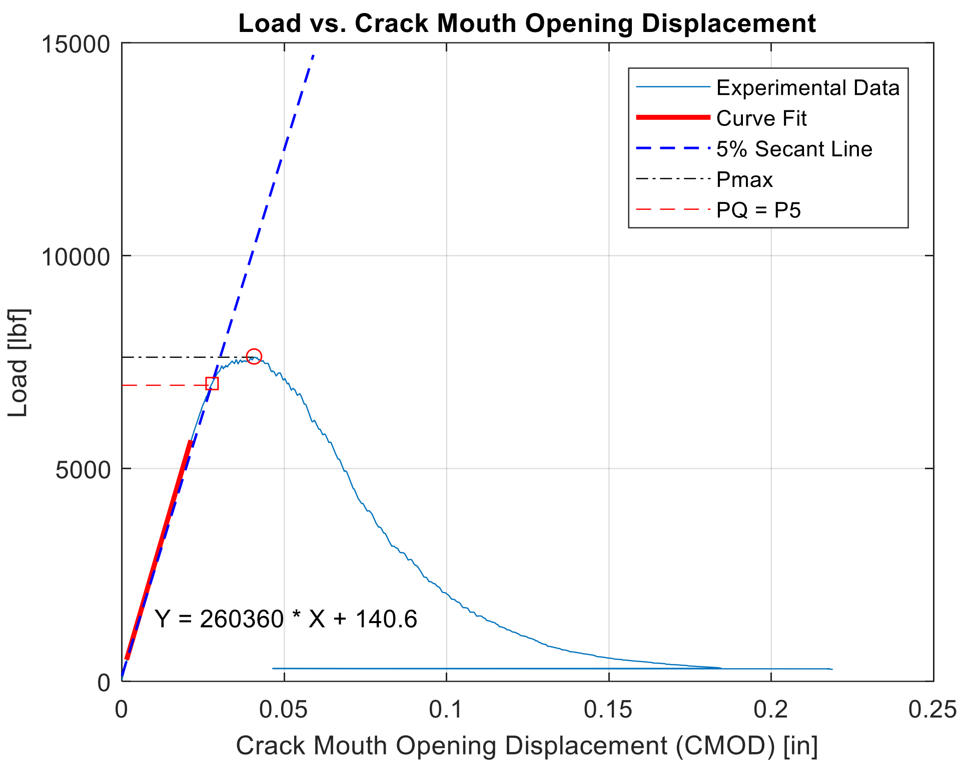

Figure 12 a). 2024 Aluminum (2) plot

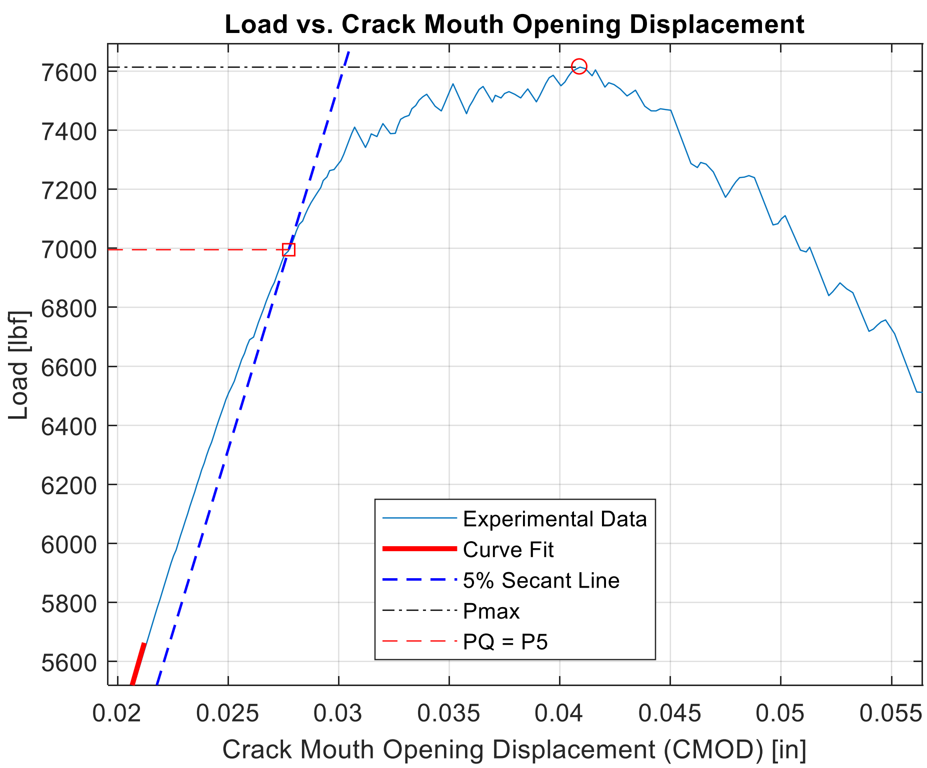

Figure 12 b). 2024 Aluminum (2) zoom-in plot

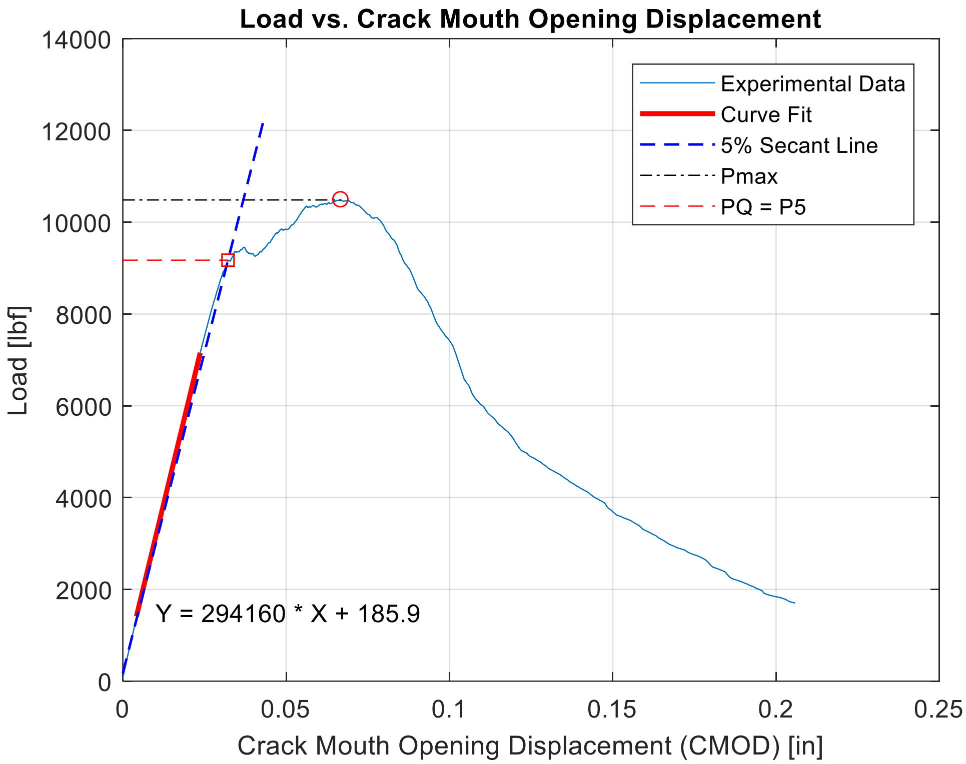

Figure 13 a). 6061 Aluminum (1) plot

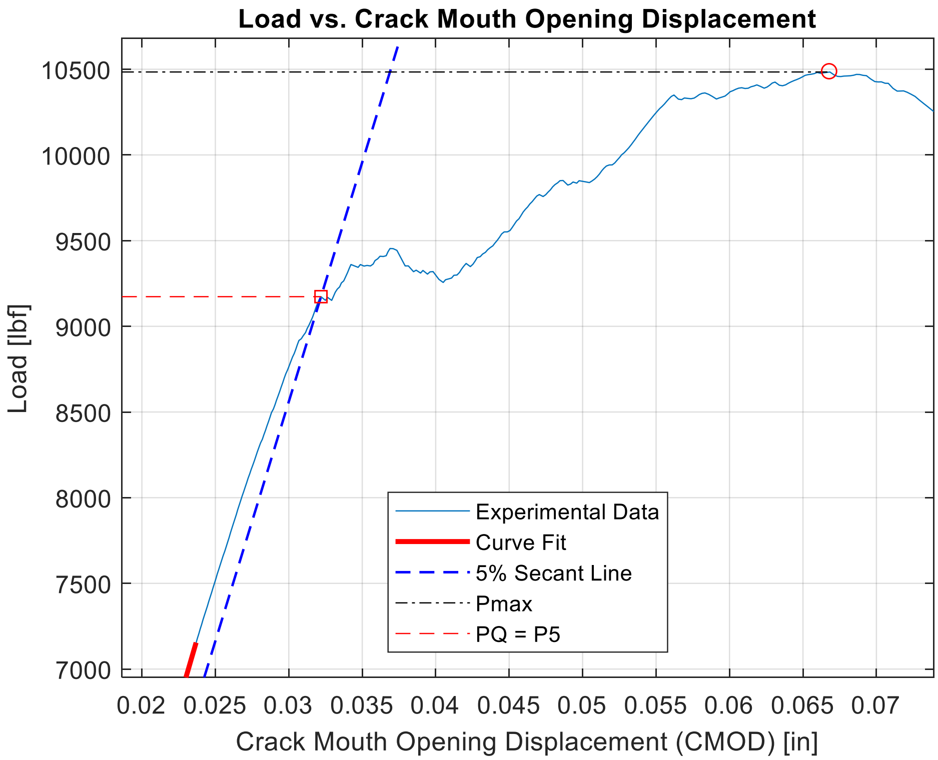

Figure 13 b). 6061 Aluminum (1) zoom-in plot

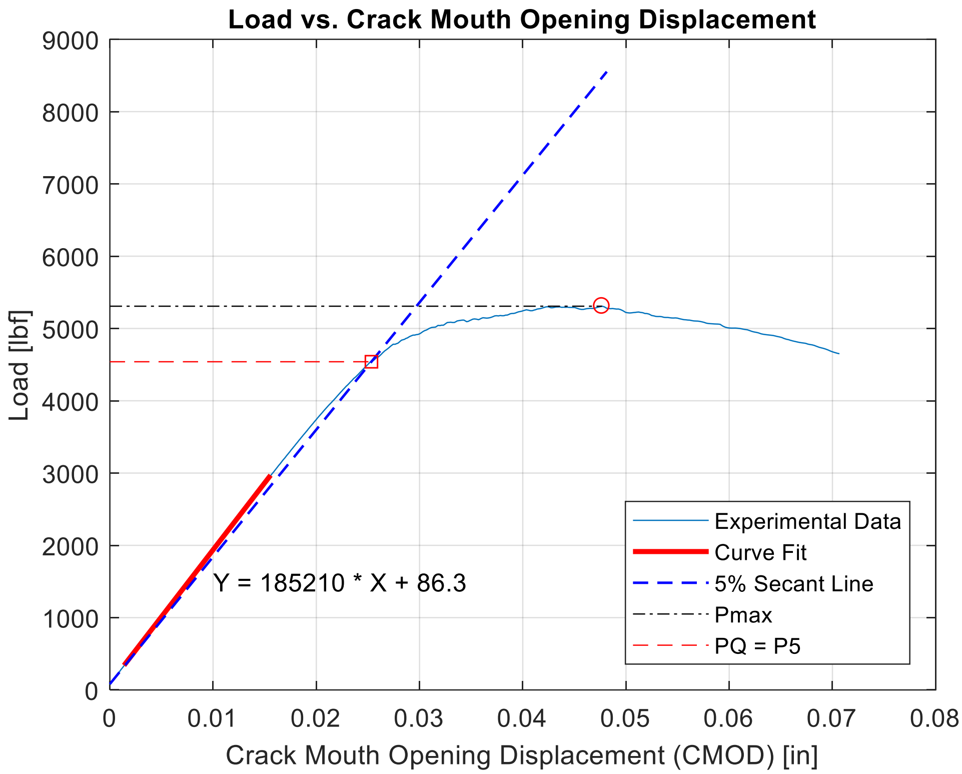

Figure 14 a). 6061 Aluminum (2) plot

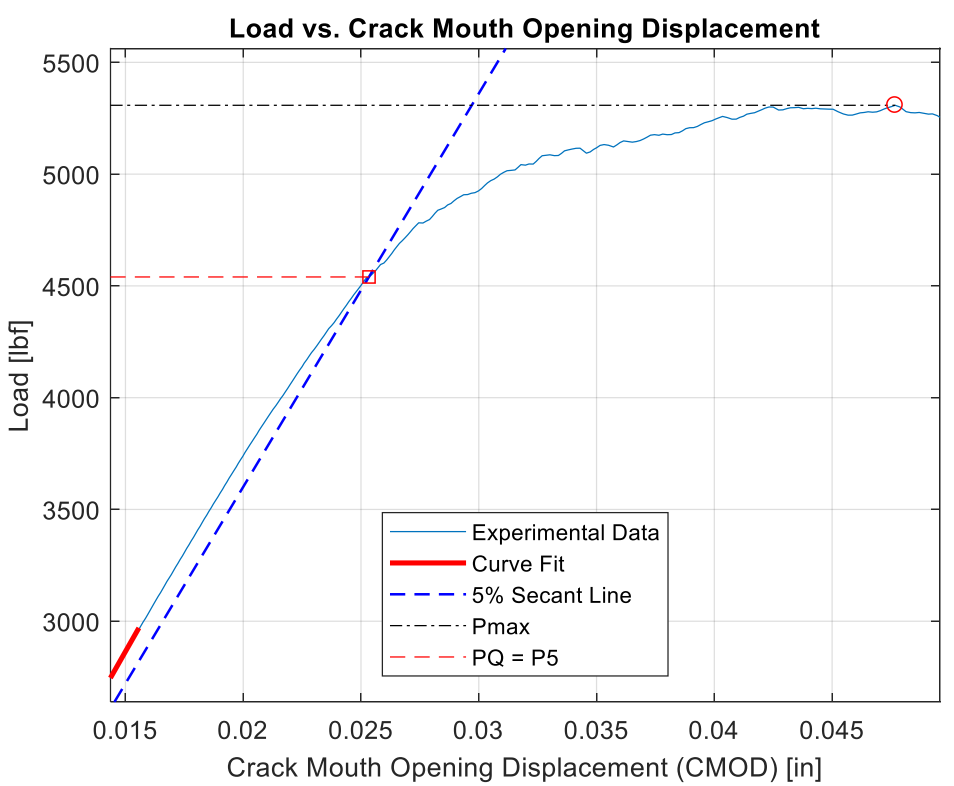

Figure 14 b). 6061 Aluminum (2) zoom-in plot

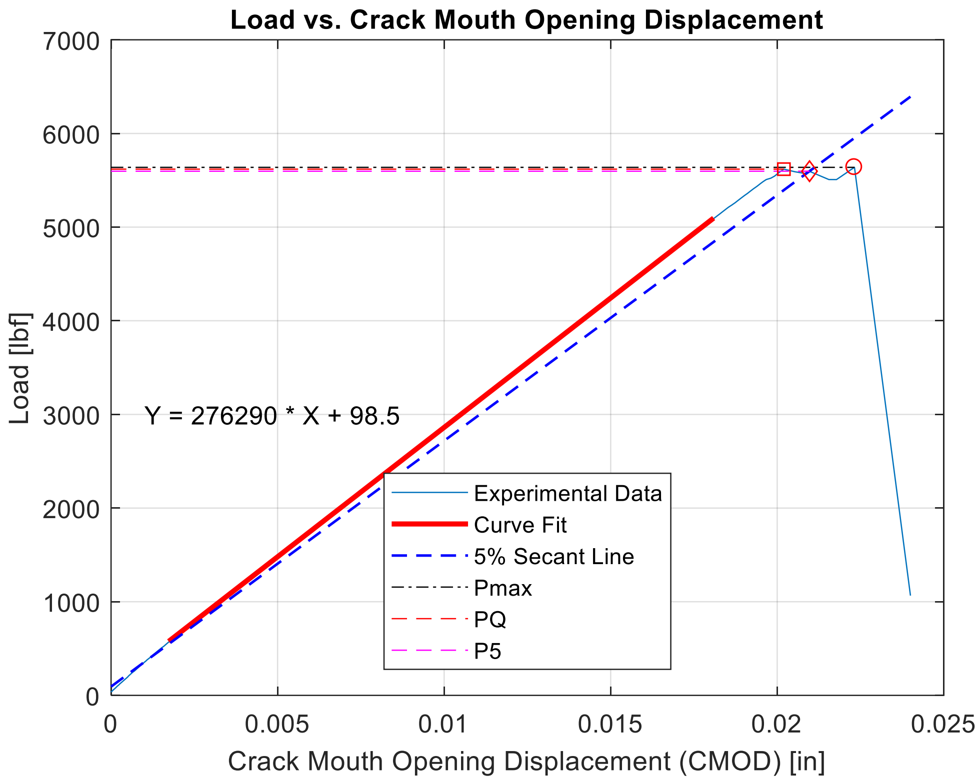

Figure 15 b). 7075 Aluminum (1) plot

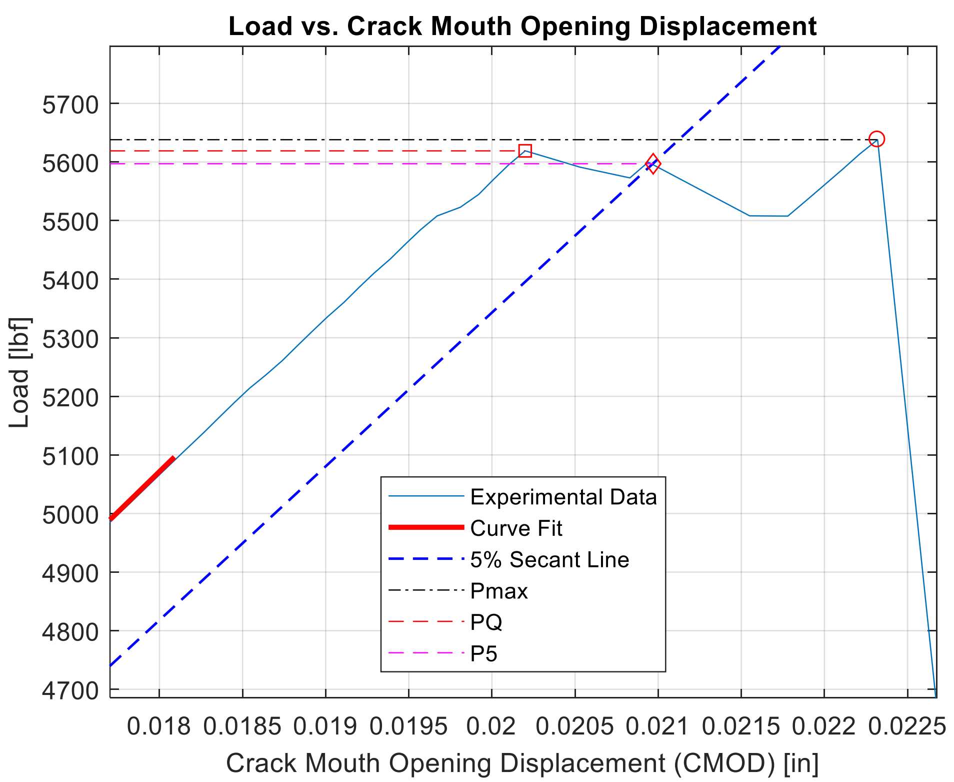

Figure 15 b). 7075 Aluminum (1) zoom-in plot

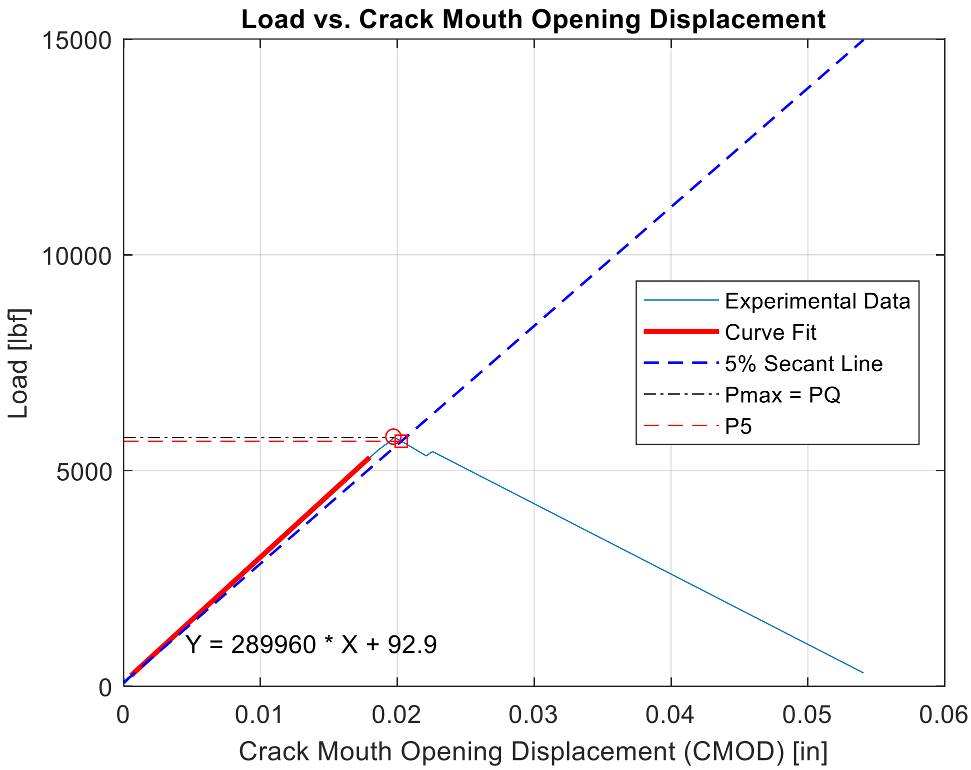

Figure 16 a). 7075 Aluminum (2) plot

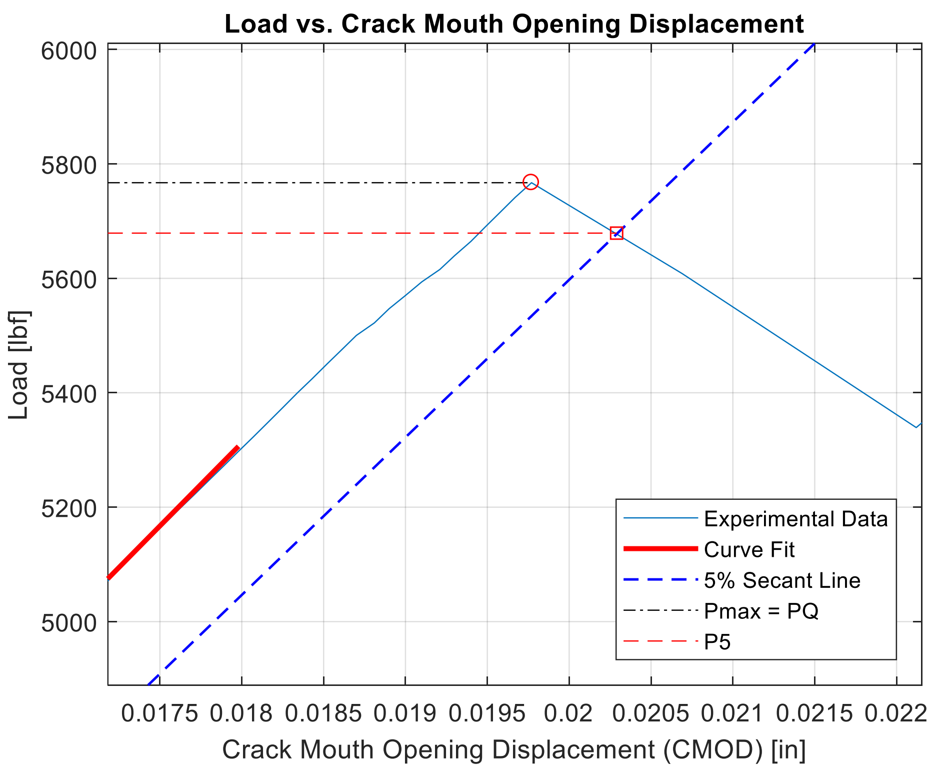

Figure 16 b). 7075 Aluminum (2) zoom-in plot

Table 1. Collected Data and Calculated Values

	STEEL		ALUMINUM					
Material	1018 Steel (1)	1018 Steel (2)	2024 -AL (1)	2024 -AL (2)	6061 -AL (1)	6061 -AL (2)	7075 -AL (1)	7075 -AL (2)
a [in]	0.9812	0.9496	1.0173	1.5871	1.436	1.0153	1.5131	1.4784
B [in]	0.9978	1.019	0.9995	1.503	1.509	1.0092	1.499	1.5
W [in]	1.996	1.998	2	3.011	2.997	2.0135	3.001	3
R [in/min]	0.08	0.08	0.08	0.08	0.08	0.08	0.1	0.1
sy [ksi]	93	93	47	47	40	40	73	73
Pmax [kips]	12.603	8.602	4.82	7.61	10.484	5.308	5.638	5.767
PQ [kips]	9.18	8.602	4.637	6.99	9.173	4.54	5.597	5.767
P5 [kips]	9.18	8.534	4.637	6.99	9.173	4.54	5.619	5.679
Pmax/PQ	1.373	1	1.0395	1.0887	1.1429	1.1692	1.00732535	1
f(a/W)	9.415	8.9676	9.9221	10.5249	9.0701	9.7867	9.7853	9.449
KQ [ksi sqrt(in)]	61.342	53.555	32.549	28.2288	31.8485	31.027	21.0908	20.974
2.5(KQ/sy)^2	1.088	0.829	1.199	0.9018	1.5849	1.5042	0.2087	0.2064
W-a [in]	1.0148	1.0484	0.9827	1.4239	1.561	0.9982	1.4879	1.5216
TYPE	I	III	I	I	I	I	III	II
Validity #1	vot-valid	valid	valid	not-valid	not-valid	not valid	valid	valid
Validity #2	not-valid	valid	not- valid	valid	not-valid	not-valid	valid	valid
K_IC [ksi sqrt(in)]		53.555					21.0908	20.974

DISCUSSION:

Second steel 1018 tested and both tested 7075 aluminum passed both validity tests, and those were only three material that passed it. When both validity test are passed it can be concluded that K_{IC}(fracture toughness factor) is same as KQ, and that is presented in **Table 1**, together with all other results calculated and measured. All five specimens that have type I behavior were invalid tests, but on the other side both type III and one type II tests are valid.

CONCLUSION:

Fracture toughness experiment introduce students with not just experiments but also checking if test that they were conducting is valid or not. Factors such as loading rate, dimensions of specimen play major role for experiment while some other factors like humidity and environment temperature in room where experiment is being done does not play major role and can be neglected. Student did test on steel and aluminum for this experiment, because steel and aluminum alloys are used in industry more than ever.

Example of mass use of aluminum alloys is in car industry (aluminum wheels and engine blocks) and mass use of structural is steel buildings (structural steel frame of modern buildings). It would be interesting to conduct tests on more materials like copper or glass and to learn how would they behave while fracture toughness testing is conducted on them.

REFERENCES:

Mechanical Behavior of Materials 4th Ed. by Norman E. Dowling (Pearson, 2013 ISBN 0-13-139506-8)

Dr. Murat Vural, MMAE 419 Fracture Toughness Handout, IIT, Chicago