Detailed Design Decision: Material Selection of a Wheel

Grounds:
In the advancement of our design from Beta Release to the One-Pager, team T18 has converged to FRONT: Force Redirection Object Negotiator Tool, a retrofit extension designed to be attached to the actuator bar of the handle of a can opener to allow opening of cans with less directed work and make it easier for people of differing abilities to use in daily life. FRONT is a retrofit module that aims to convert a simpler pulling force in any direction to the traditional rotary force needed to cut a can. The nature of the design is intuitive; to cut the can one simply attaches the module and pulls on a string attached to a rotary guide wheel, guaranteeing that there is some component of force in the direction of undisturbed motion(useful work). See figures 1 and 2 below for conceptual design and attachment

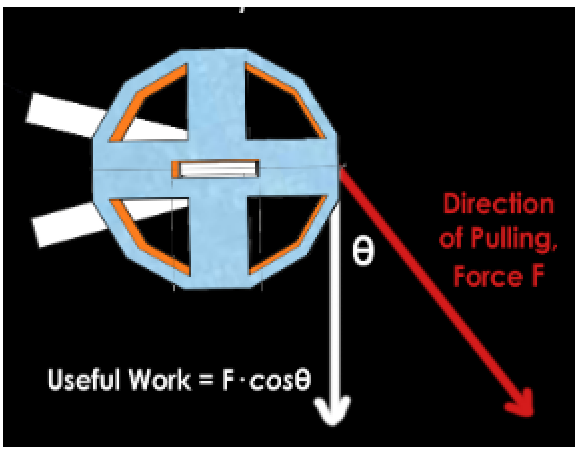


Figure 1: Conceptual Design, string attached to wheel allows user to pull in any direction as some force is always resolved in useful direction

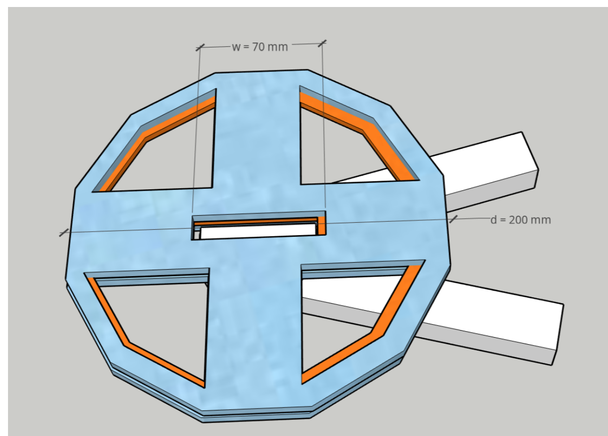


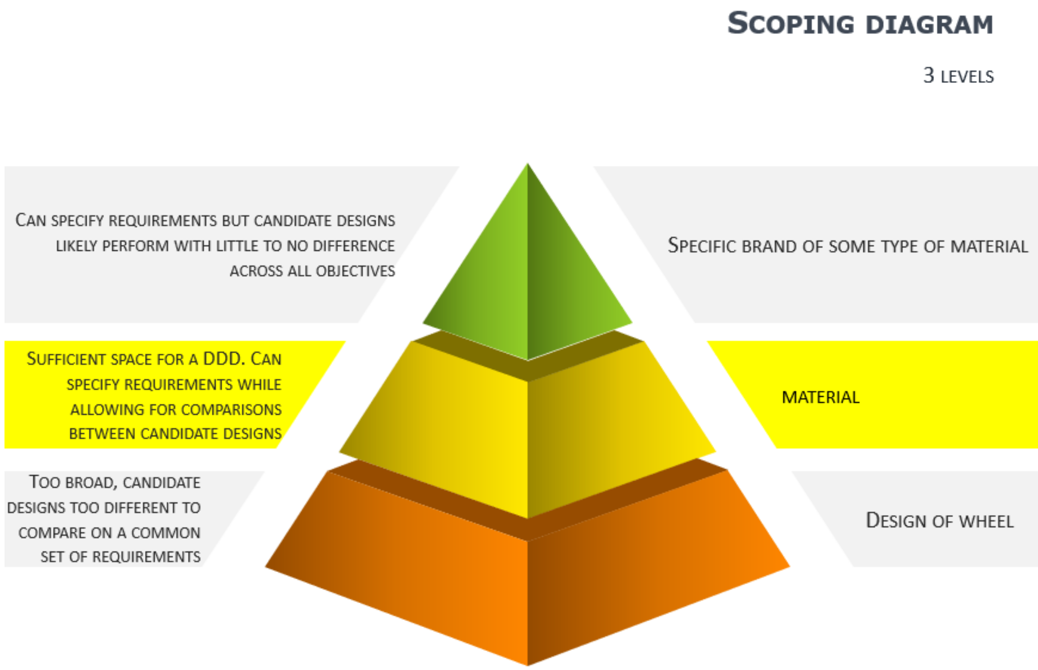
Figure 2: Attachment of retrofit kit (blue and orange) to existing can opener

Refining Initial Concept Design:
Our initial conceptual design features a large hollow wheel attached to the actuation bar, with a string wound upon it. However, details are not given on the design of the wheel; specifically, material and geometric properties of the wheel are yet to be decided. As my other team members will be evaluating characteristics of the drawstring and edge guard; in this presentation I will narrow my scope to focus on the guide wheel, the only other aspect of our retrokit kit, and will frame this selection as an optimization problem.

The wheel is an essential part of the design; it is a result of applying SCAMPER to two competing designs- one that uses a longer actuation bar to decrease force by increasing distance of application of force, and another which is concerned with allowing input force applied by the user to do some; even if inefficient, work in useful direction. The latter concept works as described in Beta, the wheel can rotate in only one way, so the component of force applied by the user in the tangential direction to the wheel will cause rotation, and no other force.

Clearly the wheel is fundamental to our design, so an engineering recommendation opportunity exists for the design of this component. As estimates for the physical (geometric) dimensions of the wheel have been put to place(see T18:CORE), I will frame this discussion as a recommendation for the type of material to be used for it. This way, more productive decisions will be made that push our design towards its final stages.

Scoping Diagram:



High Level Objectives:

The high level objective of our overall design is to improve independence of participants at Kohai by presenting them with a tool they can use to help them in the cooking program. The high level objectives when selecting the best material follow those of our overall design, they are listed below:

1. [HLO1]Select a material for the wheel that results in the best performance when cutting cans
2. [HLO2]Ensure sustainability of the wheel (as part of the retrofit kit) during the lifespan of a typical can opener at Kohai
3. [HLO2]Outline a standard procedure for engineers to follow when tasked with material selection

Material Selection

The detailed level objectives here follow standard procedures for material selection.

Detailed Objectives:

Effectiveness of our Design in “doing the job”:

[DO1: Performance] Currently, the string-wheel part of our design functions as follows: as the user pulls the string, the string must grip the wheel and redirect force to it to make it rotate. To ensure efficiency, then, we desire a material that is strongly gripped by nylon string, and that can rotate easily after that.

<u>Considering possible mechanisms of failure:</u>
[DO2: Failure Conditions] We want to make sure our design is durable enough to last the lifetime of a typical can-opener. So we want it to resist

- Loads during handling at any time
    - i) Doesn't fail from regular, expected loads (twisting)
    - ii) Doesn't fail by dynamically varying loads (accidents)
- Long term damage by excessive use

<u>Environmental and Thermal Considerations:</u>
These are standard aspects to consider when doing material selection. The service environment of any material must be considered when selecting a material.
[DO3: Environmental Resistance] This relates to the effect of the environment on the tool. We want to consider:

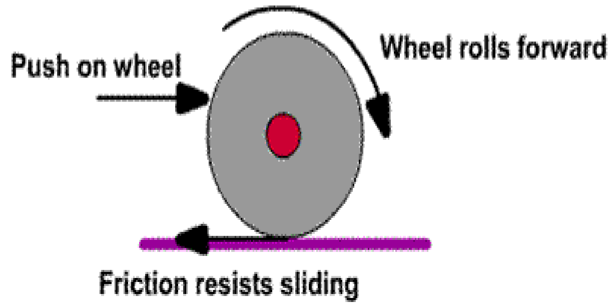
- Corrosion
- Rusting
- Gradual degradation

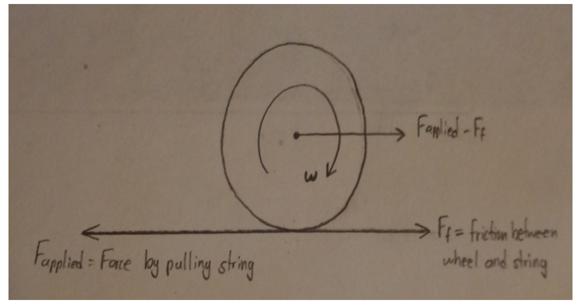
[DO4: Chemical Reactivity] This relates to the effect of the product on the environment, to ensure safety of the user. We want a final product that is stable to use in normal handling conditions.

[DO5: Thermal Properties] The can opener may experience a wide range of thermal environments during its usage. I wish to minimize thermal stresses experienced by the can, as they can lead to failure[8]

<u>Monitoring Price:</u>
[DO6: Cost] This is a lower level objective. We are not mass-producing these retrofit kits, so material performance overrides cost considerations. Nevertheless, a cheaper design wil be selected when two designs compare against other objectives.

M1: Coefficient of Static Friction:
Associated Objective: DLO1
Pulling a string attached to a wheel is similar to a wheel rolling on the floor: the string is the floor in this case. Consider the diagram below[3], which gives a convenient model for the string wheel problem. The Free Body Diagram of our setup is slightly different, and is shown to the right.

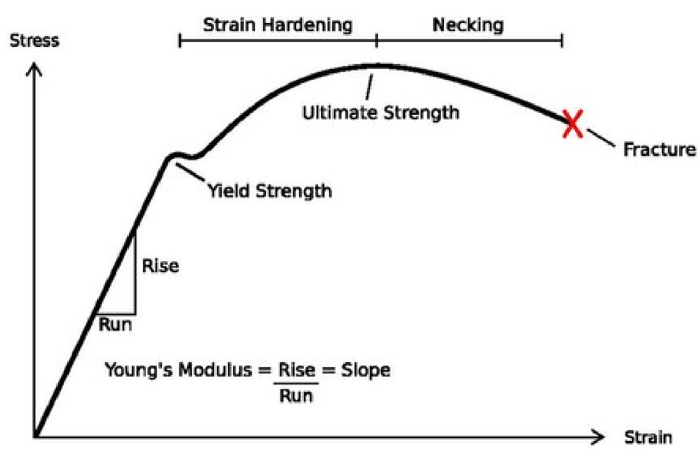




As the wheel rotates at the same angular velocity as the string is unwound, the wheel and string are at rest relative to each other; therefore, we investigate **coefficient of static friction** (and not kinetic friction). [Constraint] As coefficients of friction can really be any value, but do not make sense for values less than 0 and greater than 1, we restrict to $0 \leq \mu_s \leq 1$where μis coefficient of friction between the material of the wheel and nylon(material of string, as selected through another DDD by team member Ryan Ghosh).

[Criteria]: A higher coefficient of friction is preferred[4].

M2: Dent Resistance
Associated Objective: DLO2
The dent resistance of circular sheets with a particular thickness is directly related to the **yield strength of the material[1].** Experimentally, the yield strength of a material is the point at which we observe 2% plastic deformation, it is the end of the linear regime in the engineering stress-strain curve for that material.



[Criteria]: The conclusion of the work of Iran University of Science and Technology shows that higher yield strength corresponds to higher dent resistance in both static and dynamic conditions[1]. So, we prefer higher yield strengths. Mathematically[2], yield strength is the only material property below

:

$$D_r \propto \sigma_y\left(\frac{d\epsilon}{dt}\right)t^2$$

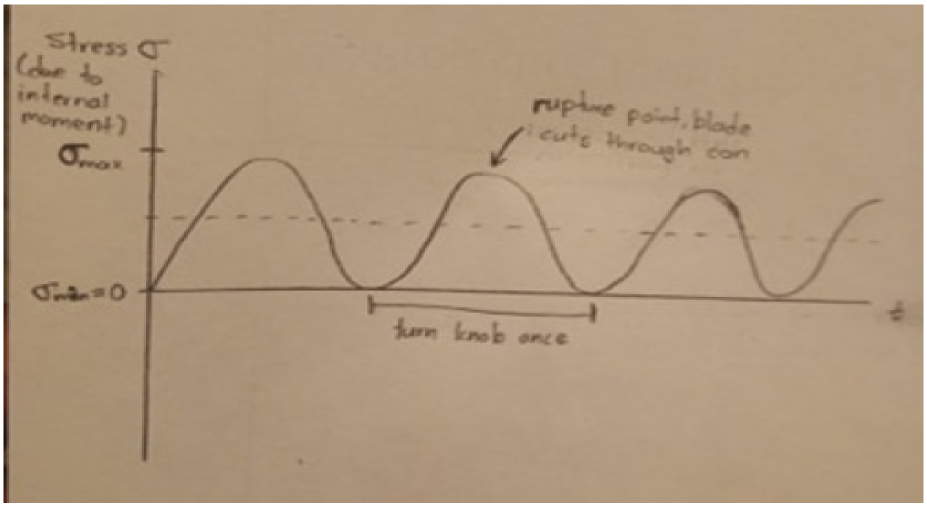
M3: Toughness
Associated Objective: DLO2
When opening a can lid, we must turn the actuation knob in order to increase the seam of the cut and rotate the can. When turning the knob, we apply a moment (internal torque) to the knob, which increases as we put more pressure on the lid. The internal moment is stored as potential energy until we fracture the lid, at which point the energy is released and gone into the cutting motion. Now, we must make sure that the wheel is able to resist the maximum moment it encounters.

Research from MIT shows that material toughness is related to a material property, fracture toughness, by the following equation:

$$\boxed{\sigma_f = \frac{K_{Ic}}{\alpha\sqrt{\pi a}}}$$

Observe that **critical stress intensity factor** is the only material property in the equation. So, it provides both a necessary and sufficient description of material toughness. At this stage, we have not made detailed design decisions on geometric properties described in the equation, so we cannot provide a constraint. The criterion, however, is immediate; since toughness is directly proportional to stress intensity factor, higher values are preferred.

M4: Fatigue Strength
Associated Objective: DLO2
The expected internal stresses due to the applied torque that the wheel experiences are shown in the diagram below, where one period represents turning the knob once to fracture the lid and the dashed line represents the mean stress.
Now, we recognize this stress as being cyclic, so fatigue quickly becomes an area of concern.



From [6], we know that fatigue life of a material experiencing cyclic stresses can be depicted through an S-N curve. The stress here is torsion stress caused by the moment (labelled T here), as in the following equation[7]:

$$T = \frac{J_{\mathrm{T}}}{r}\tau = \frac{J_{\mathrm{T}}}{\ell}G\varphi$$

So, we see T proportional to shear stress tau, so the usage of S-N curves is justified.

If a material has a **fatigue threshold**, then there is a maximum stress value such that for any stresses below that, failure due to fatigue will never happen(infinite cycles). If not, we are guaranteed that no matter the stress, failure to cyclic dynamic twisting will result in damage after time. Material performance relative to this can be tabulated according to the following rubrik.

Unacceptable	Satisfactory	Good	Outstanding
Fatigue threshold does not exist. For cycles below shear strength, failure after <= 10^4 cycles	Fatigue threshold does not exist For cycles below shear strength, failure after > 10^4 cycles	Fatigue threshold does exist. For cycles below shear strength, failure after <= 10^4 cycles	Fatigue Threshold Exists For cycles below shear strength, failure after > 10^4 cycles

[Constraint] Must NOT be unacceptable
[Criteria] Movement to the right of the rubrik is preferred
M5: Qualitative Assessment of Environmental Resistance

Associated Objective: DLO3
- Concern ourselves over lifespan of can
- Material will wear over time
- Look at susceptance to corrosion/rusting in metals, degradation in plastics

Unacceptable	Satisfactory	Good	Outstanding
Readily corrodes and/or rusts when exposed to air or common household materials	Some degree of corrosion and/or rusting, long term damage of material	Gradual degradation of material, does not significantly alter mechanical composition	No detectable degradation over lifespan of can

M6: Chemical stability
Associated Objective: DLO4
As can openers will be used with food products and handled potentially dangerous chemical materials, we must ensure they are chemically stable in room conditions. Look at Section 10 of MSDS for the material, “Stability and Chemical Reactivity”. Boolean metric:

= +1 if stable under normal storage and handling conditions

= -1 otherwise

[Constraint]: Must score 1

M7: Resistance to Thermal Expansion
Associated Objective: DLO5
We look at the coefficient of thermal expansion. This measurement describes how the size of an object changes with a change in temperature; it is the fractional increase in size per degree change in temperature at a constant pressure[]. As we want a firm, long lasting connection between the guide wheel and the actuation handle, a lower coefficient is preferred.

M8: Cost per unit mass
As mentioned, this is a lower level objective, I don’t want to spend too much resources on material, so long as performance is good, anything cheaper will be selected.
[Constraint] Within Praxis II budget limit
[Criterion]: Cheaper is better

Objective Summary Table

Objective	Metric	Criteria	Constraint
Effectiveness	Coefficient of Static Friction	Closer to 0.1 is preferred	Between 0 and 1
Failure Conditions	Stress Intensity Factor [$MN/m^{3/2}$]	Higher is better	

	Yield Strength [MPa] Fatigue Threshold Existence	Higher is better See Rubrik	
Environmental Resistance	Qualitative Rubric Assessment	Higher level on rubric	Not be unacceptable
Chemical Reactivity	Boolean success variable		Must score +1
Thermal Properties	Coefficient of Thermal Expansion $[(\mu m/m)/°C]$	Lower is better	
Cost	Cost per unit mass [CAD $/kg]	Cheaper is better	Praxis II Budget Limit

Scoped Out Objectives

Ideally, one would consider material availability as a part of material selection. However, availability(e.g in stock or not) itself depends on a lot of time-dependent factors(ie supply and demand). While generic availability of common vs uncommon materials may be discussed, I have scoped this out to minimize risk during the uncertain conditions.

Selection of Candidate Designs:

The wheel in our design can be modelled as two circular disks with a string wound between them. This is strikingly familiar to the conceptual design of a yoyo. Both designs rely on pulling a string to induce rotational motion of the disk. Candidate designs were selected by a generic search of different materials used in yoyos.

Alternative	Generic Assessment in Yoyos	
Wood(spruce)	- Easy to turn - Feels nice	- Slightly wobbly - Uneven density
Polycarbonate	- Easy to turn	- Can degrade over time - May crack when thin
ABS	- Strong - Lightweight	- Easily scratched - Not rigid

Aluminum	- Looks good (aesthetics) - Smoother and less friction(qualitative)	- Susceptible to corrosion - Scratch easily
Titanium	- Strong - Light - Doesn't scratch easily	- expensive
Steel	- Strong - Attractive - Smooth	- Heavy - Rust easily
Magnesium	- Strong - Light	- expensive

Red- Metal
Orange- Composite
Blue- Polymer

Measurement matrix:

	M1	M2	M3	M4	M5	M6	M7	M8	M9
Wood(Spruce)	0.2-0.6	0.39-0.41	55	S	G[13]	1	7	0.12-0.13	$2/kg
Polycarbonate	0.26-0.37	4.2-6.7[10]	63	S	O	1	20-33	0.5-0.75	$3.5-4.1/kg
ABS	0.1-0.4	1.42[11]	43.6	S	O	1	120	0.1	$3/kg
Aluminum Alloy 7049	0.61	21-38[12]	470	S	G	1	24	154	$2.5/kg
Titanium Ti-6Al-4V (Grade 5), Annealed	0.4-0.6	75	880	O	G[14]	1	6.7	8.6	$20/kg
High Tensile Steel	0.27	50	1650	O	G	1	12	50.2	$1.5/kg
Magnesium AZ63	0.42	16-18	97	S	U	1	26.1 µm/m-°C	77	$2.10/kg

A comparison matrix to identify the importance of the metrics was conducted. I proceed with a design philosophy that metrics that relate directly to performance are most important, and assume that users use the retrofit module as intended. Cost is given a score of 0 in all categories because it is not part of our high level objectives. M1 and M2 relate directly to whether we can actually use the device as intended; they are critical in our design.

	M1	M2	M3	M4	M5	M7	M8	**Total**
M1	-	0	1	1	1	1	1	**5**
M2	1	-	1	1	1	1	1	**6**
M3	0	0	-	1	0	1	1	**3**
M4	0	0	0	-	0	1	1	**2**
M5	0	0	1	1	-	1	1	**4**
M7	0	0	0	0	0	-	1	**1**
M8	0	0	0	0	0	0	-	**0**

Comparison Matrix:
High tensile steel is a very commonly used material for its strength and other properties. I will choose it as the reference design in order to justify selecting another material or sticking with steel. Note that magnesium alloy does not meet constraints and is omitted.

Criteria	Weight	Design Candidates					
		Spruce	Polycarbonate	ABS	Aluminum Alloy	Ti-6Al-4V	High Tensile Steel
M2: Grip	6	--	--	--	-	+	DATUM
M1: Dent Resistance	5	-	-	-	+	+	
M5: Toughness	4	=	+	+	=	=	
M3: Fatigue Strength	3	--	--	--	-	-	
M4: Wear	2	-	-	-	-	=	
M7: Chemical	1	+	-	--	-	+	

Stability							
M8: Cost	0	-	-	-	-	-	

The results of our analysis are immediate. Titanium outperforms high tensile steel in both our two most important metrics, and is equal to it for the third. Meanwhile, all other materials are worse. Titanium is worse than steel with regard to M3, yield strength, however, it is unlikely that a yield strength as high as steel's would even be needed when considering accidents such as dropping, bumping, etc.

The plastics seem to be a bad choice, as well as wood. Naturally, they would have some precedence as metals could corrode or rust, affecting service time. However, here we are considering alloys- particularly aluminum alloys and titanium alloys that have undergone chemical processes to ensure they are highly corrosion resistant.

Conclusion: Select titanium. Wood and plastics have double negatives in the most important category, a worrying sign. Steel is better than titanium when looking at yield strength, thermal conductivity and cost, but none of these are related to the actual task of opening cans. From everyday life, I know that plastics do not perform well when rigidity, strength, and durability are needed. This confirms the findings in the alternatives tables above, metals perform better than plastics. As titanium has the highest fracture toughness, the second highest yield strength, and highest resistance to thermal stresses, we conclude that titanium is better than stell while no other are; so, we justify selecting titanium instead.

[1] https://pdfs.semanticscholar.org/9344/18fc2cf0573e5e1d6636b26bb0fce34bfb7c.pdf

- A complete stress-strain curve achieved from the tension test should be used in the denting simulation for good accuracy.
- Dent resistance decreases if panel thickness is reduced.
- Material strength has approximately direct effect on the dent resistance for circular flat sheet panel.
- Dent resistance decreases if the material strength reduces.

[2] https://pdfs.semanticscholar.org/f18b/0fb126b424b575432ce0130c04d87c46f3e2.pdf

1.2.2.2 Dynamic Dent Resistance

There have been several studies published on dynamic denting; one of the first was by Johnson and Schaffnit [10]. Their experiments consisted of dropping an indentor onto rigidly constrained, flat, low-carbon steel plates of different thicknesses and yield strengths. For their work, they defined dynamic dent resistance as the following ratio:

$$Dent\ Resistance\ (D_r) = \frac{impact\ energy}{dent\ depth} \tag{1.8}$$

which they used to compare They were able to establish that the dent resistance of their samples followed the following relationship:

$$D_r \propto \sigma_y(\dot{\epsilon})t^2 \tag{1.9}$$

[3] https://www.school-for-champions.com/science/friction_rolling.htm#.XpJnjshKg2w

[4]https://www.sciencedirect.com/topics/chemistry/friction-coefficient

2.1.1 Coefficient of friction measurement

Coefficient of friction (COF) is a dimensionless number that is defined as the ratio between friction force and normal force (Eqn (2.1)). Materials with COF smaller than 0.1 are considered lubricous materials. COF depends on the nature of the materials and surface roughness. Usually, ASTM D1894-14 is the most widely used method for COF measurement. This method involves a polymer sheet or film with a fixed weight on top. The polymer sample is

[5] https://web.mit.edu/course/3/3.11/www/modules/frac.pdf

length $2a$, in an infinite plate	$\sigma_\infty\sqrt{\pi a}$
Edge crack, length a, in a semi-infinite plate	$1.12\ \sigma_\infty\sqrt{\pi a}$
Central penny-shaped crack, radius a, in in infinite body	$2\ \sigma_\infty\sqrt{\frac{a}{\pi}}$
Center crack, length $2a$ in plate of width W	$\sigma_\infty\sqrt{W\tan\left(\frac{\pi a}{W}\right)}$
2 symmetrical edge cracks, each length a, in plate of total width W	$\sigma_\infty\sqrt{W\left[\tan\left(\frac{\pi a}{W}\right)+0.1\sin\left(\frac{2\pi a}{W}\right)\right]}$

These stress intensity factors are used in design and analysis by arguing that the material can withstand crack tip stresses up to a critical value of stress intensity, termed K_{Ic}, beyond which the crack propagates rapidly. This *critical stress intensity factor* is then a measure of material toughness. The failure stress σ_f is then related to the crack length a and the fracture toughness by

$$\boxed{\sigma_f = \frac{K_{Ic}}{\alpha\sqrt{\pi a}}} \tag{5}$$

where α is a geometrical parameter equal to 1 for edge cracks and generally on the order of unity for other situations. Expressions for α are tabulated for a wide variety of specimen and crack geometries, and specialty finite element methods are available to compute it for new situations.

The stress intensity and energy viewpoints are interrelated, as can be seen by comparing Eqns. 1 and 5 (with $\alpha = 1$):

[6] file:///C:/Users/hshma/Desktop/MSE160.pdf

[7]http://homepages.cae.wisc.edu/~me349/lecture_notes/material_selection.pdf

[8]https://iieiug.weebly.com/uploads/2/6/3/6/26362706/50588-ch22.pdf

[10] http://mate.tue.nl/mate/pdfs/12930.pdf
[11] https://onlinelibrary.wiley.com/doi/abs/10.1002/pen.23745
[12]
https://www.efunda.com/formulae/solid_mechanics/fracture_mechanics/fm_lefm_Kc_Matl.cfm
[13] https://www.fpl.fs.fed.us/documnts/pdf2008/fpl_2008_shupe001.pdf
[14] google search

Titanium is a very reactive metal that shows remarkable **corrosion resistance** in oxidizing acid environments by virtue of a passive oxide film. ... While **titanium** is **resistant** to these media, it is not immune and can be susceptible to pitting and crevice attack at elevated temperatures.

22.17 Which tool-material properties are suitable for interrupted cutting operations? Why?

In interrupted cutting operations, it is desirable to have tools with a high impact strength and toughness. From Tables 22.1 and 22.2 on pp. 649-650, the tool materials which have the best impact strength are high speed steels, and to a lesser extent, cast alloys and carbides. Therefore, one would prefer to use high-speed steels and carbides in interrupted cutting operations. In addition, in these operations, the tool is constantly being heated and reheated. It is therefore desirable to utilize materials with low coefficients of thermal expansion and

high thermal conductivity to minimize thermal stresses in the tool which could lead to tool failure.

As with other mechanical characteristics, the fatigue properties of materials can be determined from laboratory simulation tests.[7] A test apparatus should be designed to duplicate as nearly as possible the service stress conditions (stress level, time frequency, stress pattern, etc.). A schematic diagram of a rotating-bending test apparatus, commonly used for fatigue testing, is shown in Figure 8.18; the compression and tensile stresses are imposed on the specimen as it is simultaneously bent and rotated. Tests are also frequently conducted using an alternating uniaxial tension–compression stress cycle.

A series of tests are commenced by subjecting a specimen to the stress cycling at a relatively large maximum stress amplitude (σ_{max}), usually on the order of two-thirds of the static tensile strength; the number of cycles to failure is counted. This procedure is repeated on other specimens at progressively decreasing maximum stress amplitudes. Data are plotted as stress S versus the logarithm of the number N of cycles to failure for each of the specimens. The values of S are normally taken as stress amplitudes (σ_a, Equation 8.16); on occasion, σ_{max} or σ_{min} values may be used.

Two distinct types of S–N behavior are observed, which are represented schematically in Figure 8.19. As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure. For some ferrous (iron base) and titanium alloys, the S–N curve (Figure 8.19*a*) becomes horizontal at higher N values; or there is a limiting stress level, called the **fatigue limit** (also sometimes the *endurance limit*), below which fatigue failure will not occur. This fatigue limit represents the largest value of fluctuating stress that will *not* cause failure for essentially an infinite number of cycles. For many steels, fatigue limits range between 35% and 60% of the tensile strength.

Most nonferrous alloys (e.g., aluminum, copper, magnesium) do not have a fatigue limit, in that the S–N curve continues its downward trend at increasingly greater N values (Figure 8.19*b*). Thus, fatigue will ultimately occur regardless of the magnitude of the stress. For these materials, the fatigue response is specified as **fatigue strength,** which is defined as the stress level at which failure will occur for some specified number of cycles (e.g., 10^7 cycles). The determination of fatigue strength is also demonstrated in Figure 8.19*b*.

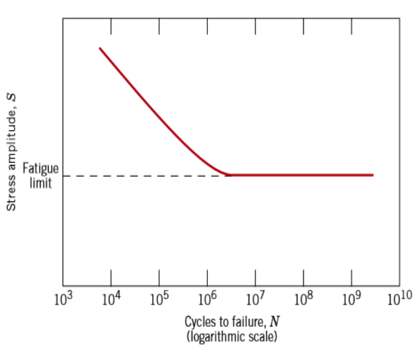
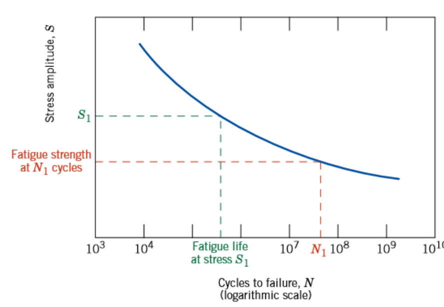


Figure 8.19 Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (*a*) a material that displays a fatigue limit and (*b*) a material that does not display a fatigue limit.



[7]

In the field of solid mechanics, **torsion** is the twisting of an object due to an applied torque. Torsion is expressed in either the Pascal (Pa), an SI unit for newtons per square metre, or in pounds per square inch (psi) while torque is expressed in newton metres (N·m) or foot-pound force (ft·lbf). In sections perpendicular to the torque axis, the resultant shear stress in this section is perpendicular to the radius.

In non-circular cross-sections, twisting is accompanied by a distortion called warping, in which transverse sections do not remain plane.[1] For shafts of uniform cross-section unrestrained against warping, the torsion is:

$$T = \frac{J_{\mathrm{T}}}{r}\tau = \frac{J_{\mathrm{T}}}{\ell}G\varphi$$