Project 1

MEEN 687: Additive and Subtractive Processes in Custom Manufacturing

Group: Team 2	
Victor De La Parra Echaverria	827007731
Carlos Navarro Naranjo	726003363
Diego Martinez	127006189
Luis A. Rodriguez	525000917

“An Aggie does not lie, cheat, or steal, or tolerate those who do.”

Introduction

This project is intended to demonstrate the difference in values between theoretical and experimental calculations of power consumption and surface roughness in CNC turning machining. Specifically, aluminum alloy and cast iron pieces are cut with a carbide insert while spindle power and surface roughness are sampled and tabulated. Each material is tested twice, with each trial conducted at different cutting speeds. Experimental machining power and surface roughness can be determined with the comma separated value data. With the following parameters, theoretical machining power and surface roughness can also be estimated.

Constant Parameters:

- Major cutting edge angle, $k_r = 95°$
- Minor cutting edge angle, $k'_r = 30°$
- Nose radius, $R = 0.1\, mm$
- Feed per revolution, $f = 0.1\, mm$
- Depth of cut, $a_p = 0.5\, mm$
- $undeformed\ chip\ thickness,\ a_c = f sin k_r = 0.1\, mm \cdot sin(95°) = 0.095831\, mm$

Table 1: Trial-Dependent Parameters

	Test 1	**Test 2**	**Test 3**	**Test 4**
Material	Aluminum	Aluminum	Cast Iron	Cast Iron
Speed (m/min) [v]	75	120	30	50

Calculations

A. Calculate theoretical machining power and surface roughness for all the four cases.

Case 1: Aluminum, 75 m/min

$$Machining\ Power\ (P) = Material\ Removal\ Rate\ (Z) \cdot Specific\ Cutting\ Energy\ (p_s)$$

$$Z = a_p \cdot f \cdot v = 0.5\,mm \cdot 0.1\,mm \cdot 75\,m/min \cdot \frac{1\,m^2}{1000^2\,mm^2} \cdot \frac{1\,min}{60\,s} = 6.25 \cdot 10^{-8}\,m^3/s$$

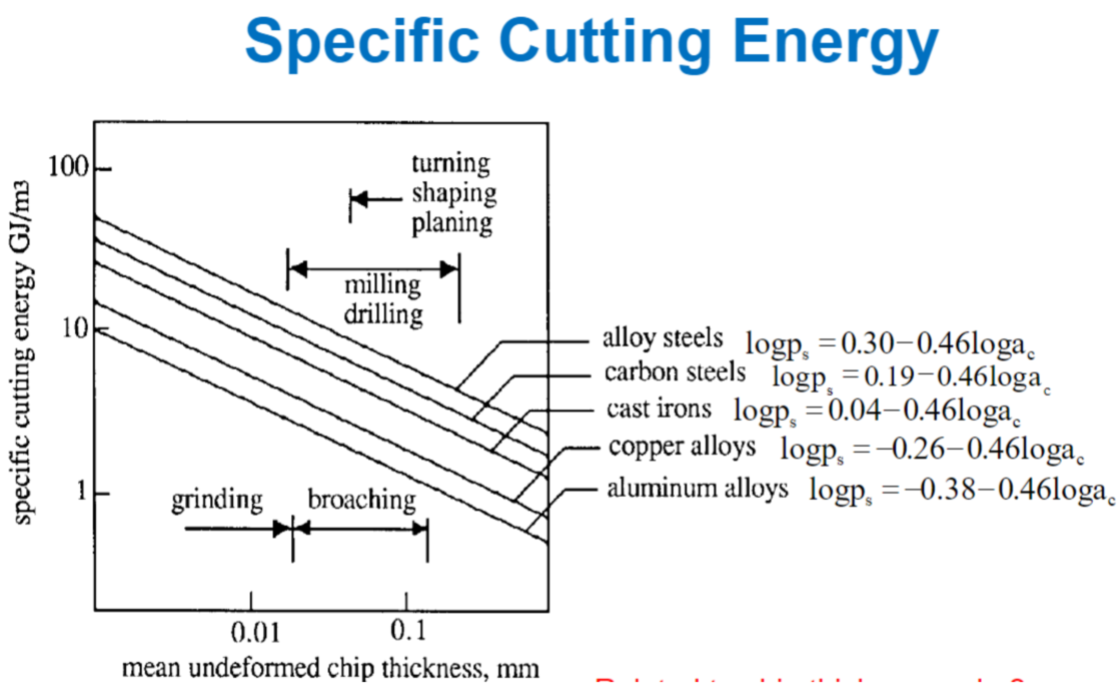

Figure 1: Specific Cutting Energy (GJ/m^3) vs undeformed chip thickness (mm)

Case 2: Aluminum, 75 m/min

$$p_s = 10^{-0.38-0.46\log(a_c)} = 10^{-0.38-0.46\log(0.095831)} = 1.226049\ GJ/m^3$$

$$P = Z \cdot p_s = 6.25 \cdot 10^{-8}\,m^3/s \cdot 1.226049\ GJ/m^3 \cdot \frac{10^9\,J}{1\,GJ} \cdot \frac{1\,W}{1\,J/s} = 76.63\,W$$

Surface roughness can be calculated using insert nose radius, or major/minor cutting edge angles. For an ideal, sharp tool:

$$Ra = \frac{f}{4(\cot(k_r) + \cot(k'_r))} = \frac{0.1\,mm}{4(\cot(95°)+\cot(30°))} \cdot \frac{1000\,\mu m}{1\,mm} = 15.2\,\mu m$$

Considering nose radius:

$$Ra \ = \frac{f^2}{32\,R} = \frac{(0.1\,mm)^2}{32\,(0.1\,mm)} \cdot \frac{1000\,\mu m}{1\,mm} = 3.125\ \mu m$$

Case 2: Aluminum, 120 m/min

$$P \ = \ Z \ \cdot \ p_s$$

$$Z \ = \ a_p \cdot f \cdot v = 0.5\,mm \ \cdot 0.1\,mm \cdot 120\,m/min \ \cdot \frac{1\,m^2}{1000^2\,mm^2} \cdot \frac{1\,min}{60\,s} = 1 \cdot 10^{-7}\,m^3/s$$

For Aluminum alloys: $p_s = 10^{-0.38-0.46log(a_c)} = 10^{-0.38-0.46log(0.095831)} = 1.226049\ GJ/m^3$

$$P \ = \ Z \ \cdot \ p_s = 1 \cdot 10^{-7}\,m^3/s \ \cdot 1.226049\,GJ/m^3 \ \cdot \frac{10^9\,J}{1\,GJ} \cdot \frac{1\,W}{1\,J/s} = 122.6\,W$$

For an ideal, sharp tool:

$$Ra \ = \ \frac{f}{4(cot(k_r) + cot(k'_r))} = \frac{0.1\,mm}{4(cot(95°)+cot(30°))} \cdot \frac{1000\,\mu m}{1\,mm} = 15.2\ \mu m$$

Considering nose radius:

$$Ra \ = \frac{f^2}{32\,R} = \frac{(0.1\,mm)^2}{32\,(0.1\,mm)} \cdot \frac{1000\,\mu m}{1\,mm} = 3.125\ \mu m$$

Case 3: Cast Iron, 30 m/min

$$P \ = \ Z \ \cdot \ p_s$$

$$Z \ = \ a_p \cdot f \cdot v = 0.5\,mm \ \cdot 0.1\,mm \cdot 30\,m/min \ \cdot \frac{1\,m^2}{1000^2\,mm^2} \cdot \frac{1\,min}{60\,s} = 2.5 \cdot 10^{-8}\,m^3/s$$

For Cast Iron: $p_s = 10^{0.04-0.46log(a_c)} = 10^{0.04-0.46log(0.095831)} = 3.224839\ GJ/m^3$

$$P \ = \ Z \ \cdot \ p_s = 2.5 \cdot 10^{-8}\,m^3/s \ \cdot 3.224839\,GJ/m^3 \ \cdot \frac{10^9\,J}{1\,GJ} \cdot \frac{1\,W}{1\,J/s} = 80.62\,W$$

For an ideal, sharp tool:

$$Ra \ = \ \frac{f}{4(cot(k_r) + cot(k'_r))} = \frac{0.1\,mm}{4(cot(95°)+cot(30°))} \cdot \frac{1000\,\mu m}{1\,mm} = 15.2\ \mu m$$

Considering nose radius:

$$Ra \ = \frac{f^2}{32\,R} = \frac{(0.1\,mm)^2}{32\,(0.1\,mm)} \cdot \frac{1000\,\mu m}{1\,mm} = 3.125\ \mu m$$

Case 4: Cast Iron, 50 m/min

$$P = Z \cdot p_s$$

$$Z = a_p \cdot f \cdot v = 0.5\, mm \cdot 0.1\, mm \cdot 50\, m/min \cdot \frac{1\, m^2}{1000^2\, mm^2} \cdot \frac{1\, min}{60\, s} = 4.17 \cdot 10^{-8}\, m^3/s$$

For Cast Iron: $p_s = 10^{0.04-0.46 log(a_c)} = 10^{0.04-0.46 log(0.095831)} = 3.224839\, GJ/m^3$

$$P = Z \cdot p_s = 4.17 \cdot 10^{-8}\, m^3/s \cdot 3.224839\, GJ/m^3 \cdot \frac{10^9\, J}{1\, GJ} \cdot \frac{1\, W}{1\, J/s} = 134.4\, W$$

For an ideal, sharp tool:

$$Ra = \frac{f}{4(cot(k_r) + cot(k'_r))} = \frac{0.1\, mm}{4(cot(95°)+cot(30°))} \cdot \frac{1000\, \mu m}{1\, mm} = 15.2\, \mu m$$

Considering nose radius:

$$Ra = \frac{f^2}{32\, R} = \frac{(0.1\, mm)^2}{32\, (0.1\, mm)} \cdot \frac{1000\, \mu m}{1\, mm} = 3.125\, \mu m$$

Table 2: Theoretical Machining Power & Ra

	Test 1	**Test 2**	**Test 3**	**Test 4**
Machining Power	76.63 W	122.6 W	80.62 W	134.4 W
Ra (Ideal sharp tool)	$15.2\, \mu m$	$15.2\, \mu m$	$15.2\, \mu m$	$15.2\, \mu m$
Ra (Nose radius)	$3.125\, \mu m$	$3.125\, \mu m$	$3.125\, \mu m$	$3.125\, \mu m$

B. Use the data provided to calculate machining power and Ra for the four cases.

When spindle power for each test is graphed, it becomes apparent that power readings vary greatly in the machine's idle state, and during cutting and non-cutting regions. Power versus time graphs for each case are shown below.

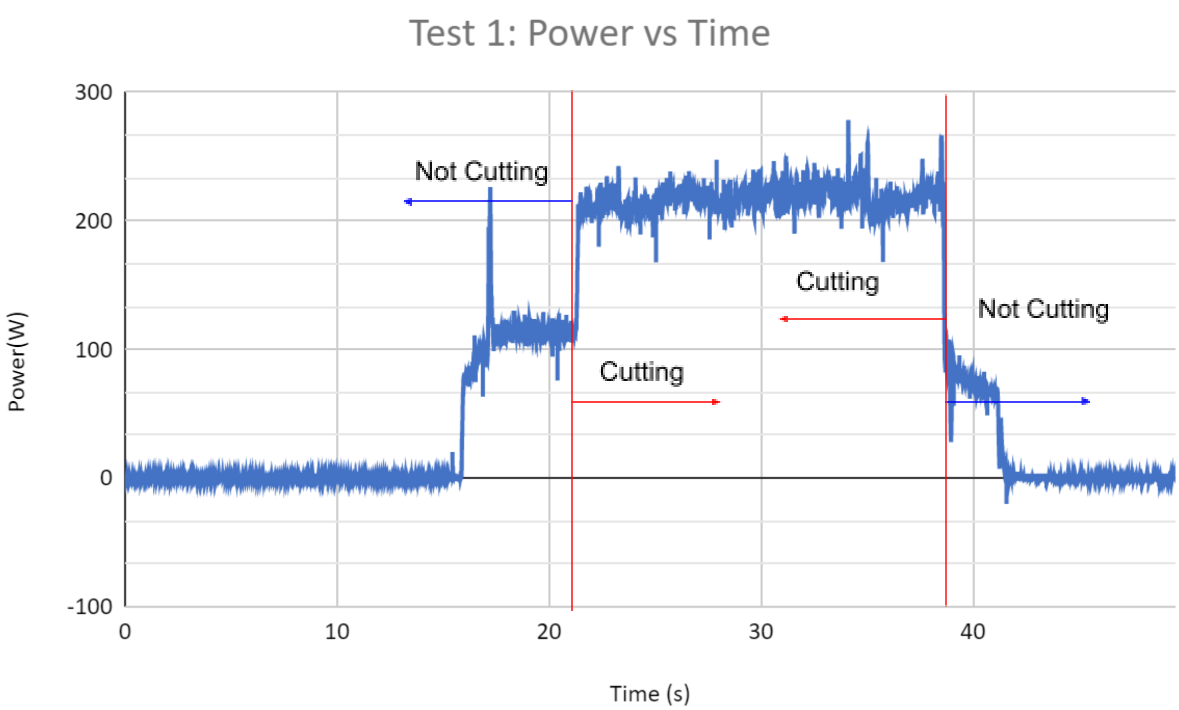

Figure 2: Test 1 Spindle power graph

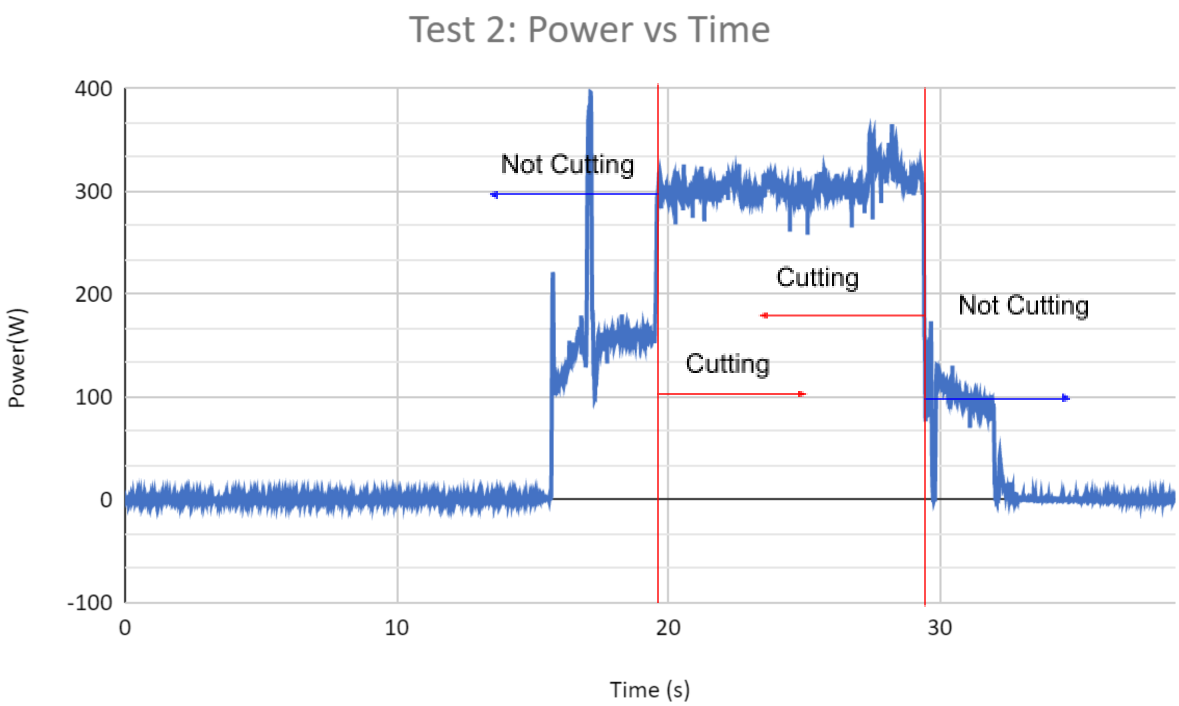

Figure 3: Test 2 Spindle power graph

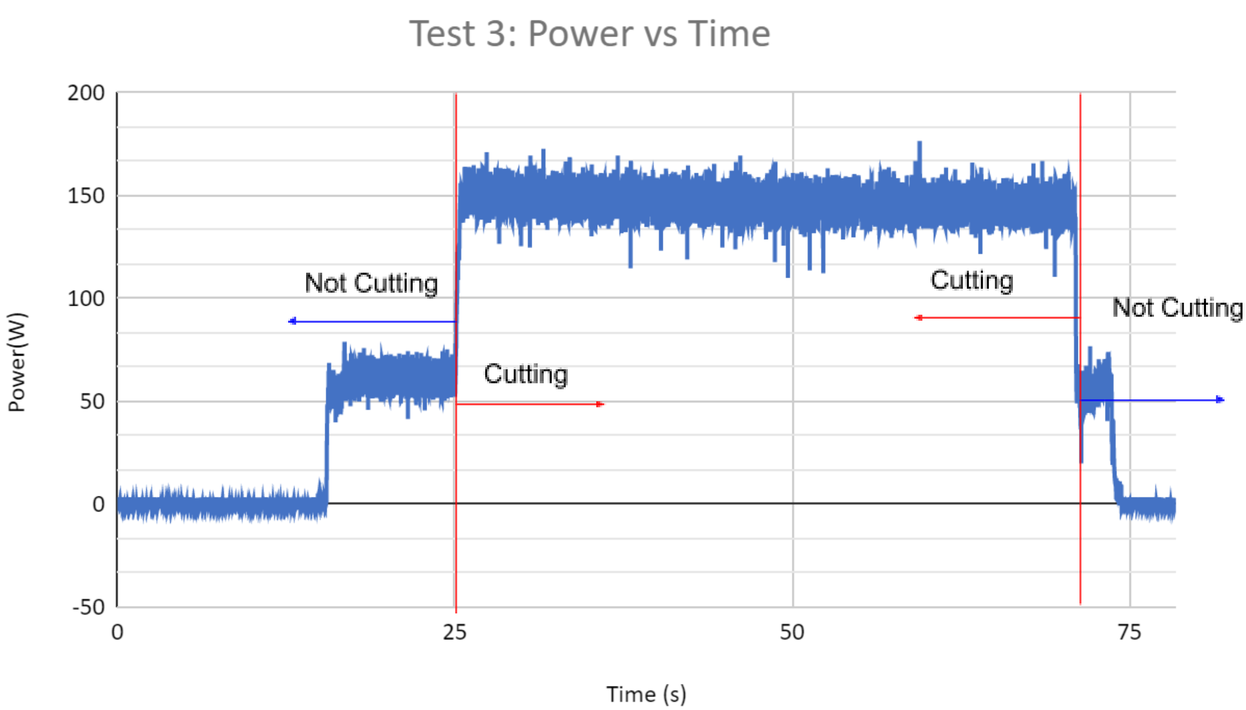

Figure 4: Test 3 Spindle power graph

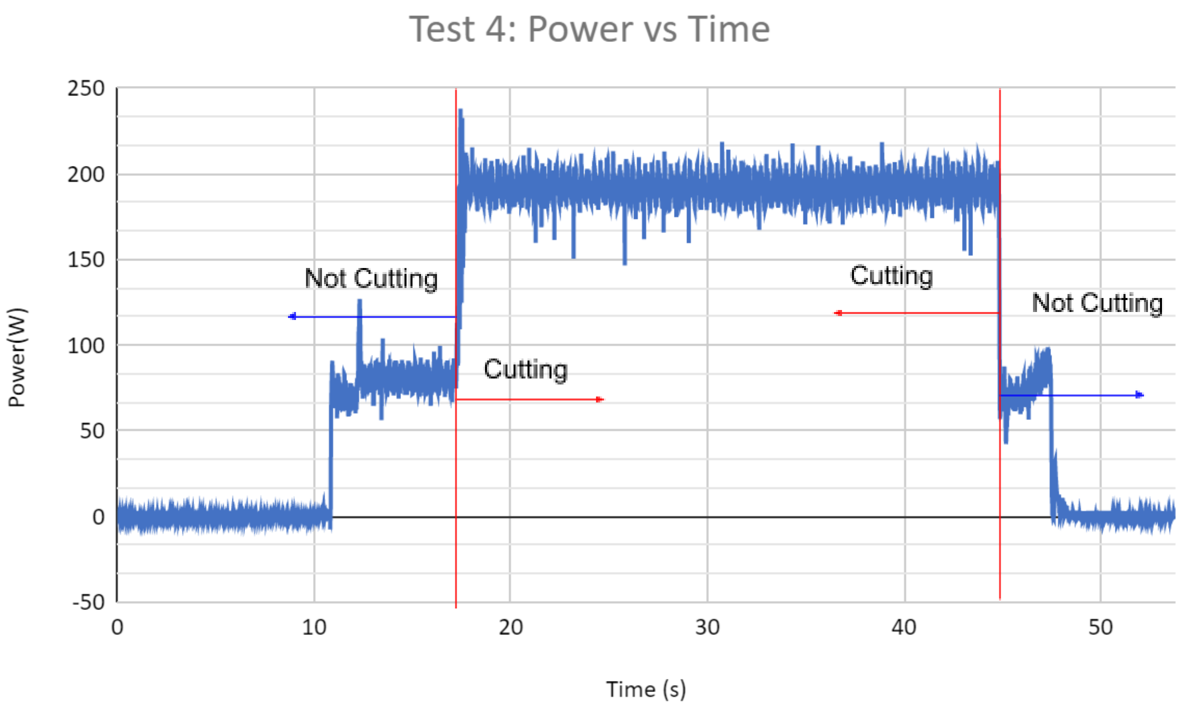

Figure 5: Test 4 Spindle power graph

The regions of interest to our experimental power calculation is the average of the cutting region minus the average of the non cutting region. That way we will obtain the actual machining power.

Table #: Experimental Machining Power

	Test 1	Test 2	Test 3	Test 4
Cutting Time range (s)	15.87 - 41.69	19.5 - 29.42	25.05 - 71.03	17.51 - 44.82
Mean Actual Machining Power (W)	83.5	180.87	89.34	115.27

Surface roughness can be experimentally obtained by using its mathematical definition shown below.

$$R_a = \frac{1}{L}\int_0^L \left| y(x) - \left(\frac{1}{L}\int_0^L y(x)dx \right) \right| dx$$

Here, the Ra is obtained by calculating the average h and subtracting it from each surface profile point value. Then taking the absolute value of each of these results and later on averaging them . These results are tabulated below.

Table #: Ra Calculations

	Test 1	**Test 2**	**Test 3**	**Test 4**
Average h-datum (μm)	$-\ 7.23 \cdot 10^{-2}$	$-\ 5.43 \cdot 10^{-3}$	$-\ 1.91 \cdot 10^{-2}$	$-\ 2.79 \cdot 10^{-2}$
Experimental Ra (μm)	3.185	1.851	4.207	5.129

The overall results from parts A-B are summarized in the table below.

Table #: Theoretical and Experimental Machining Power/Surface Roughness

	Test 1	**Test 2**	**Test 3**	**Test 4**
Theoretical Power (W)	76.63	122.6	80.62	134.4
Experimental Power (W)	83.5	180.87	89.34	115.27
Theoretical Ra, ideal/nose radius (μm)	15.2 3.125	15.2 3.125	15.2 3.125	15.2 3.125
Experimental Ra (μm)	3.185	1.851	4.207	5.129

C. *Compare the machining powers (of Parts a and b) and you will see some discrepancies. Explain possible causes for the over- or underestimated power prediction. Be specific on* *the answers provided instead of generic reasons like sample variations, human factors, etc.*

Table #: Theoretical and Experimental of Machining Power

	Test 1	**Test 2**	**Test 3**	**Test 4**
Theoretical Power (W)	76.63	122.6	80.62	134.4
Experimental Power (W)	83.5	180.87	89.34	115.27

According to [1], the reason the experimental power recorded by the machine is higher than the theoretical values calculated is because of the additional power required for the acceleration of the spindle to keep up with the machining process. The spindle needs to accelerate from when it first starts to when it is cutting the workpiece. This would explain why the experimental values are higher than the theoretical values. According to [2], a possible reason on why the theoretical values are higher than the experimental results of the machining power we collected is because of the accuracy of the machines database during the idle faces of the CNC machine. For example, since the machine has to ramp up to a certain power before machining and then increase its power to actually machine the material, the idle period of the machine will drop the power average. Liu's findings made sense for one of our power theoretical calculations because it was higher than the experimental results. Both of these findings seem to contradict themselves with one another through one stating that the acceleration of the spindle during the machining process can cause the spindle power to increase, while the other states how the inaccuracy of the machine to detect is power during idle speeds can cause the power output to be lowered. Shao et al., on the other hand, does point out how a worn out tool piece can increase the machining power by as much as 50% when compared to a similar machining process with a new tool piece [3].

D. *Now compare the roughness values (of Parts a and b). Since the feed is the same, the theoretical Ra should also be the same. However, likely you will see discrepancies for these cases. Explain possible causes for these discrepancies and their dependency on speed and material.*

Table #: Theoretical and Experimental of Surface Roughness

	Test 1	**Test 2**	**Test 3**	**Test 4**
Theoretical Ra, nose radius (μm)	3.125	3.125	3.125	3.125
Experimental Ra	3.185	1.851	4.207	5.129

(μm)				

According to [4], a possibility for a smoother finish (smaller Ra) value is a slightly used tool piece, up until a certain point before the tool loses its prime edge and starts producing higher Ra values. Another study [5], investigated the effects of cutting speed, feed rate, and depth of cut on surface roughness. Results showed that feed rate highly affected the Ra while an increase in cutting speed increased the Ra. The former study could explain why the second aluminum case had a much lower Ra value than the first, and the former study could explain why the second cast iron case had much higher Ra value than the 1st. Arbizu et al. discovered in his study [6], that there is a certain cutting speed that can minimize the Ra of a material. This could shed some light on the possibility as to why a smaller Ra value was achieved for the second aluminum case (120 m/min) than the 1st case. Another interesting study conducted by Munoz-Escalona [7] revealed that as machining parameters were held constant such as feed rate, depth of cut, and nose radius, for the single turning of four different steels. He found that as the material gets softer, the surface finish improves i.e. reduces Ra. This finding completely agrees with our findings as we were able to achieve smaller Ra values for aluminum than cast iron.

E. References

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