ENGR 376: Project

2022 Winter Term I

Heat Treatment Project

Prepared by:

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Objective

Design a heat treatment by selecting the appropriate material and suitable heat treatment process to optimize Time, Temperature, and Pressure with the goal of minimizing the overall cost.

Design Criteria

The design criteria for a gear used in an excavation drill gearbox are as follows:

1. Minimum hardness throughout the component: 40 HRC
2. Maximum hardness at center: 50 HRC
3. Range of diameter: 15-22 mm
4. Maximum heat treatment time: 4 hours
5. Minimum hardness 0.2 mm below the surface: 62 HRC
6. Quenching medium: Agitated water or Oil
7. Available alloys: 8610, 8620, 8630, 8640, and 8660
8. The relationship between pressure and carbon content is given as follows: P: in Pascal
9. Maximum allowable pressure: 170 psi
10. Maximum achievable temperature: 950 C°
11. Cost criteria:
    - 11.1General operation costs $1 /min (You could assume at any given temp. and pressure)
    - 11.2Every degree increases in Temp. Costs an additional 9.5 ¢ per hour
    - 11.31 System pressure costs an additional $0.75 psi/hour.

Determining Appropriate Material and Quenching Medium

The first step to determining the appropriate material and quenching medium for a gear used in an excavation drill gearbox was to plot the maximum and minimum hardness on the hardenability curves for; 8620, 8630, 8640, 8660 alloy. From here the equivalent Jominy distance from the quenched edge can be determined as shown in table 1 and 2.

Graph 1: Minimum and Maximum Allowable Hardness vs distance from quenched edge

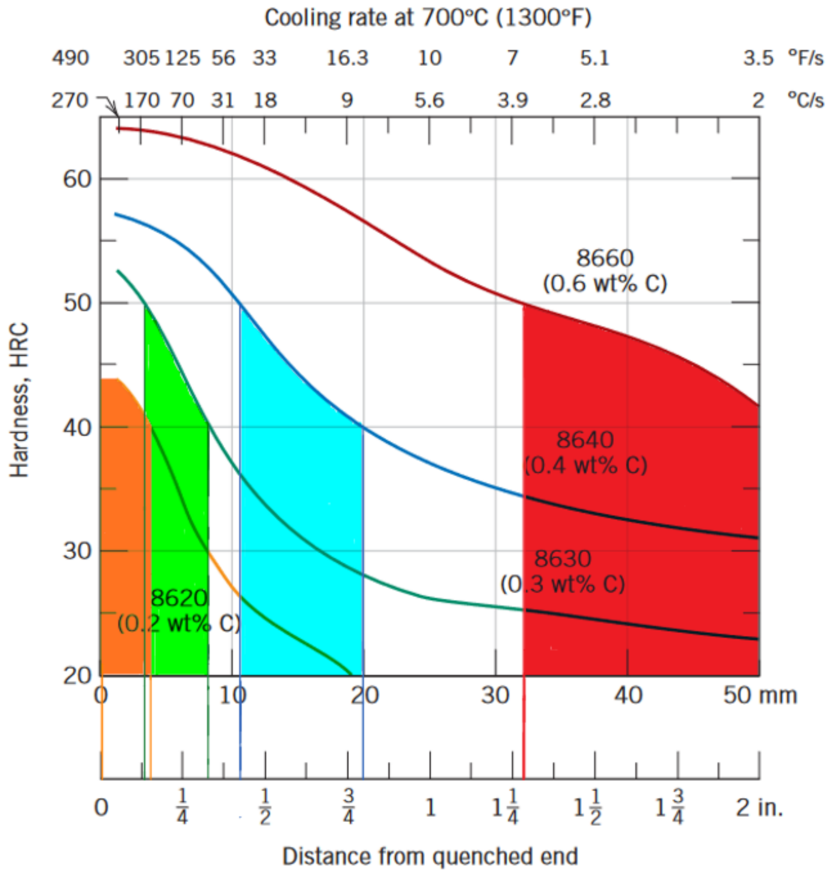
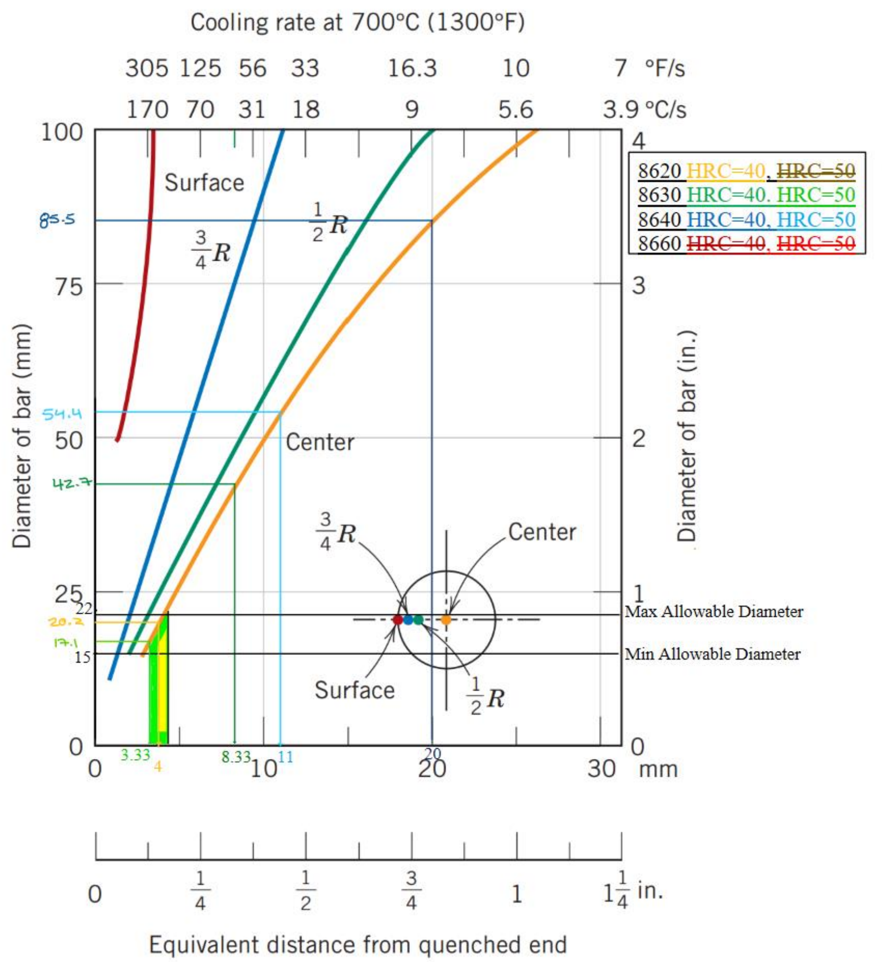


Table 1: Distance from quenched edge at given Hardness

Hardness	8620	8630	8640	8660
40 HRC	4 mm	8.33 mm	20 mm	n/a
50 HRC	n/a	3.33 mm	11 mm	32 mm

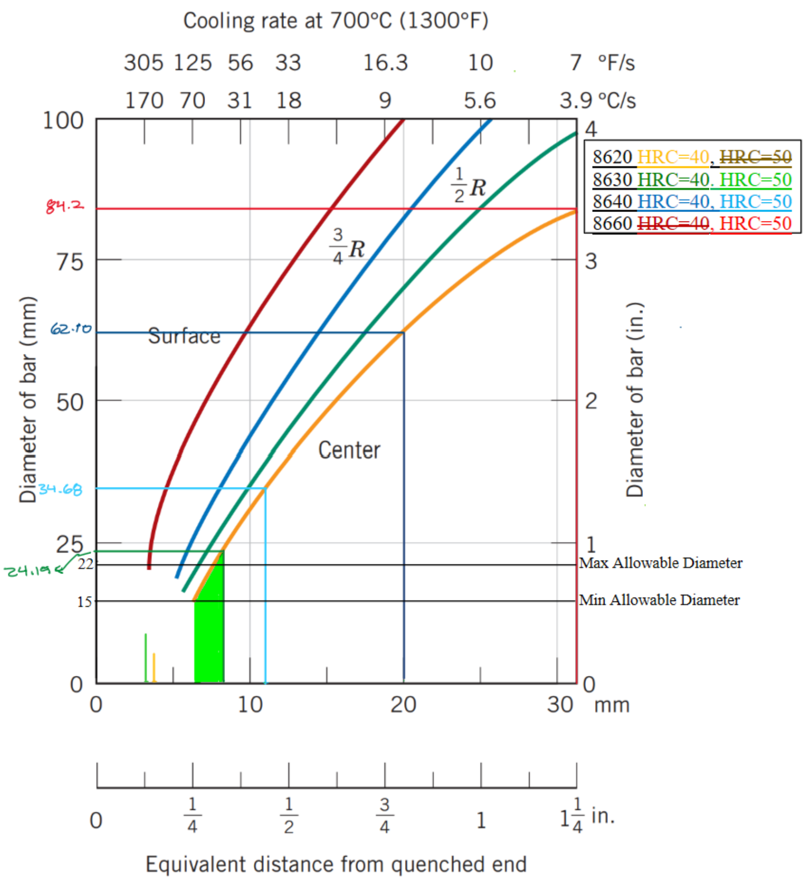
The next step in determining the appropriate material and quenching medium for a gear used in a excavation drill gearbox is to take the equivalent Jominy distances for the harnesses specified above and use them to determine what the range in diameters would be for each of the given materials.

Graph 2: Agitated water, diameter of bar vs. equivalent distance from edge



(a)

Graph 3: Agitated oil, diameter of bar vs. equivalent distance from edge



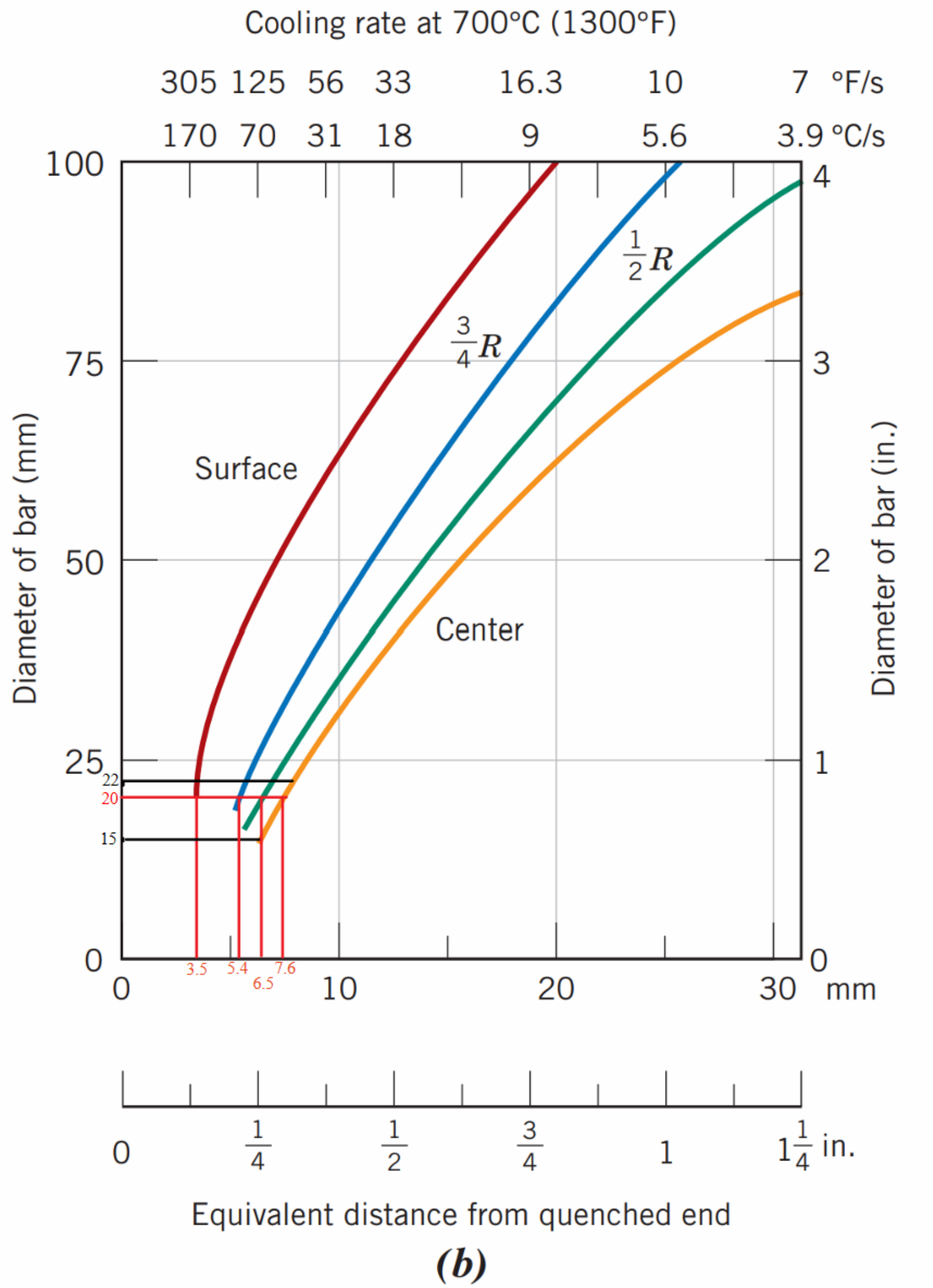
(b)

Table 2: Diameter of bar for specific; alloy, hardness, and quenching medium

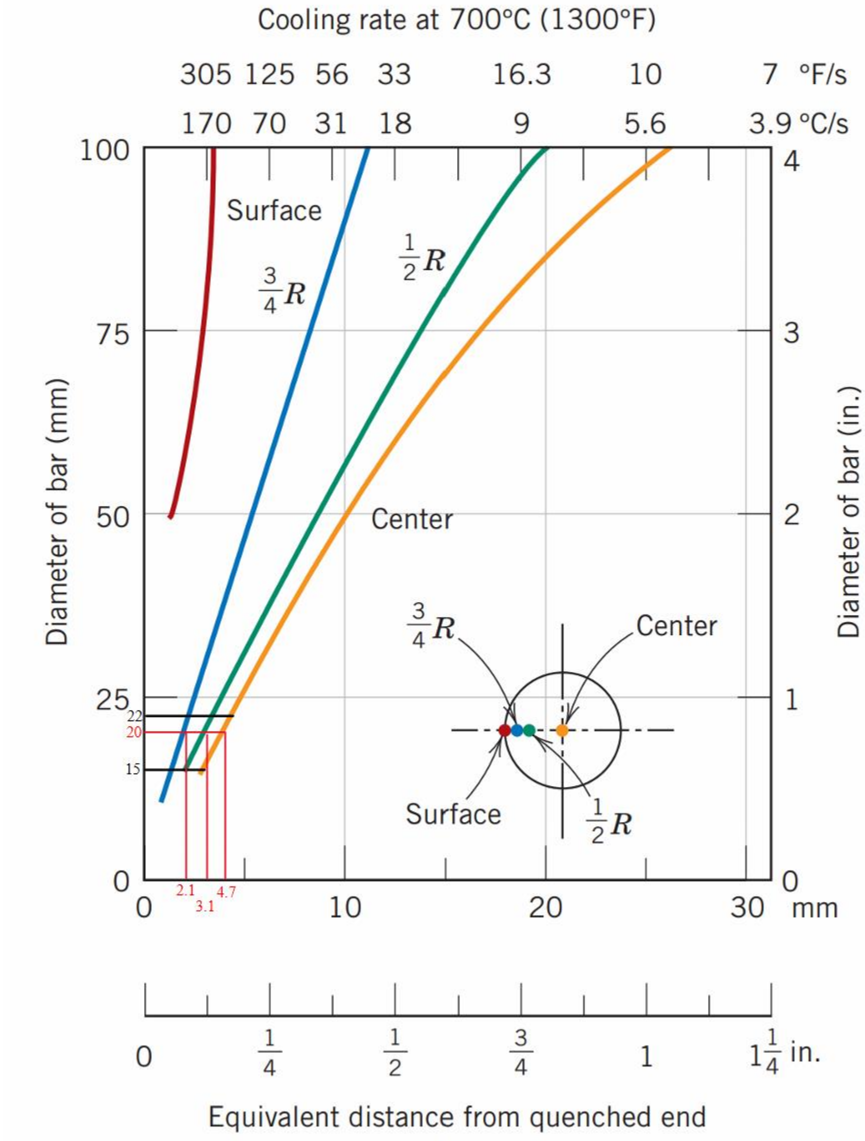
		Alloy	8610	8620	8630	8640	8660
Agitated Oil	HRC = 50	Diameter of Bar	To Small	To Small	To Small	34.68	84.2
	HRC = 40	Diameter of Bar	To Small	To Small	24.19	62.1	To Big
Agitated Water	HRC = 50	Diameter of Bar	To Small	To Small	17.1	54.4	To Big
	HRC = 40	Diameter of Bar	To Small	20.2	42.7	85.5	To Big

From the data acquired from Graph 2 and Graph 3, represented in Table 2, if agitated water were to be used as the quenching medium an 8620 or 8630 alloy would be able to produce a rod that achieves a minimum hardness of 40 HRC with a diameter range from 15-22mm. If agitated oil were to be used as the quenching medium only an 8630 alloy would produce a rod that achieves a minimum hardness of 40 HRC throughout the component within the required diameter range.

Graph 4: Agitated oil, determining a useable diameter



Graph 5: Agitated water, determining a useable diameter



(a)

It is known that; the smaller the diameter of material that is quenched results in a higher hardness in said component, and the heat treatment under design requires a minimum hardness of 62 HRC 0.2 mm below the surface. After further analysis, it can be shown in Graph 4, that the minimum diameter that meets the required hardness and assumption stated above would be 20mm. The next step in determining the appropriate material and quenching medium for a gear used in an excavation drill gearbox, is to use the known diameter to determine the approximate hardness throughout the component, as to confirm that design specifications are met.

Graph 6: 8600 Alloys, Hardenability Curve, (diameter = 20mm) equivalent edge vs. Hardenability

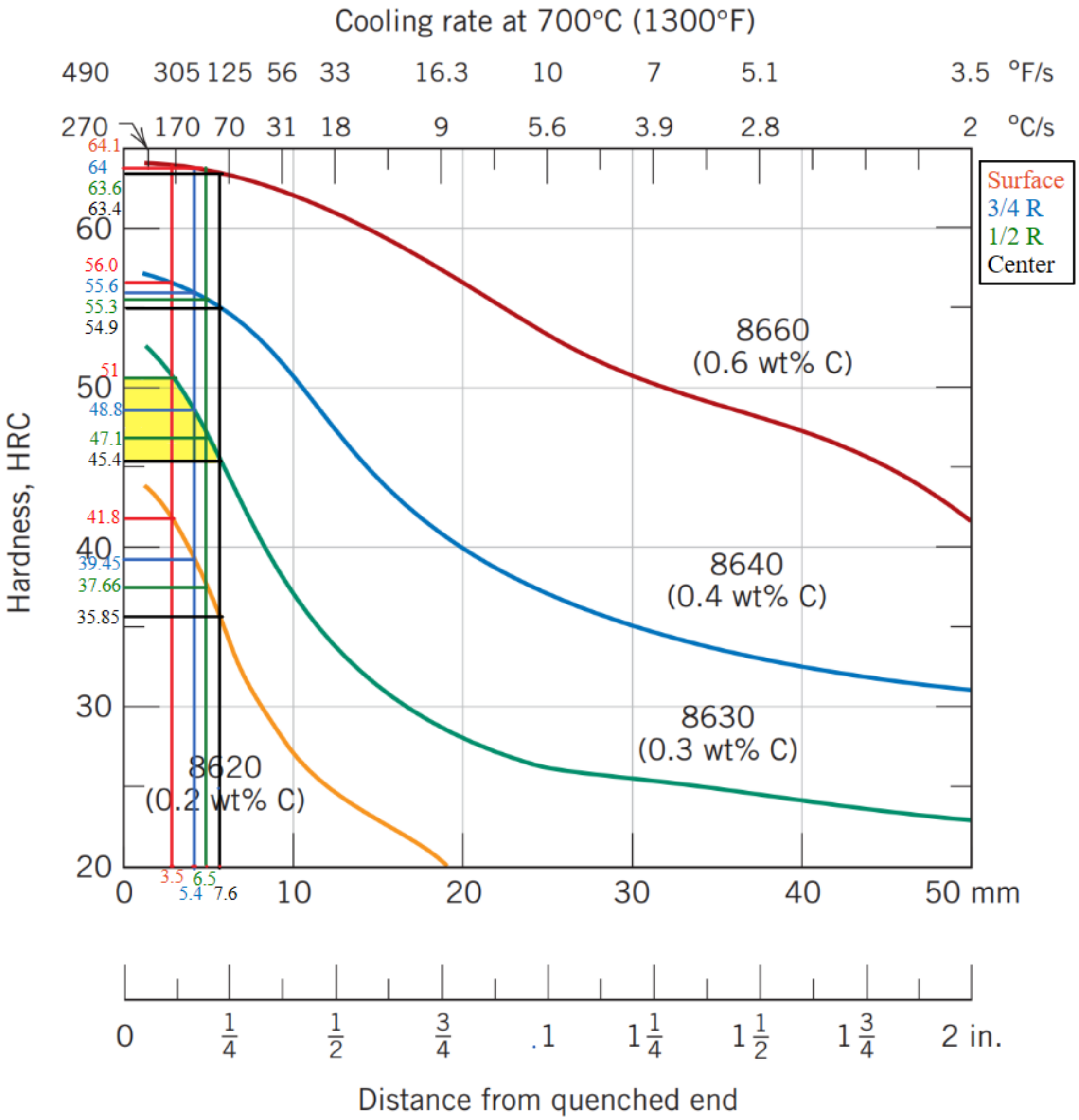


Table 3: Analysis of 8600 Alloys, Hardenability Curve for diameter = 20mm

Agitated Oil					
Alloys	Hardness Center (mm)	Hardness 1/2 R (mm)	Hardness 3/4 R (mm)	Hardness S (mm)	Diameter (mm)
8620	35.85	37.66	39.45	41.8	20
8630	45.4	47.1	48.8	51	20
8640	54.9	55.3	55.6	56	20
8660	63.4	63.6	64	64.1	20

Graph 7: 8600 Alloys, Hardenability Curve, (diameter = 20mm) equivalent edge vs. Hardenability

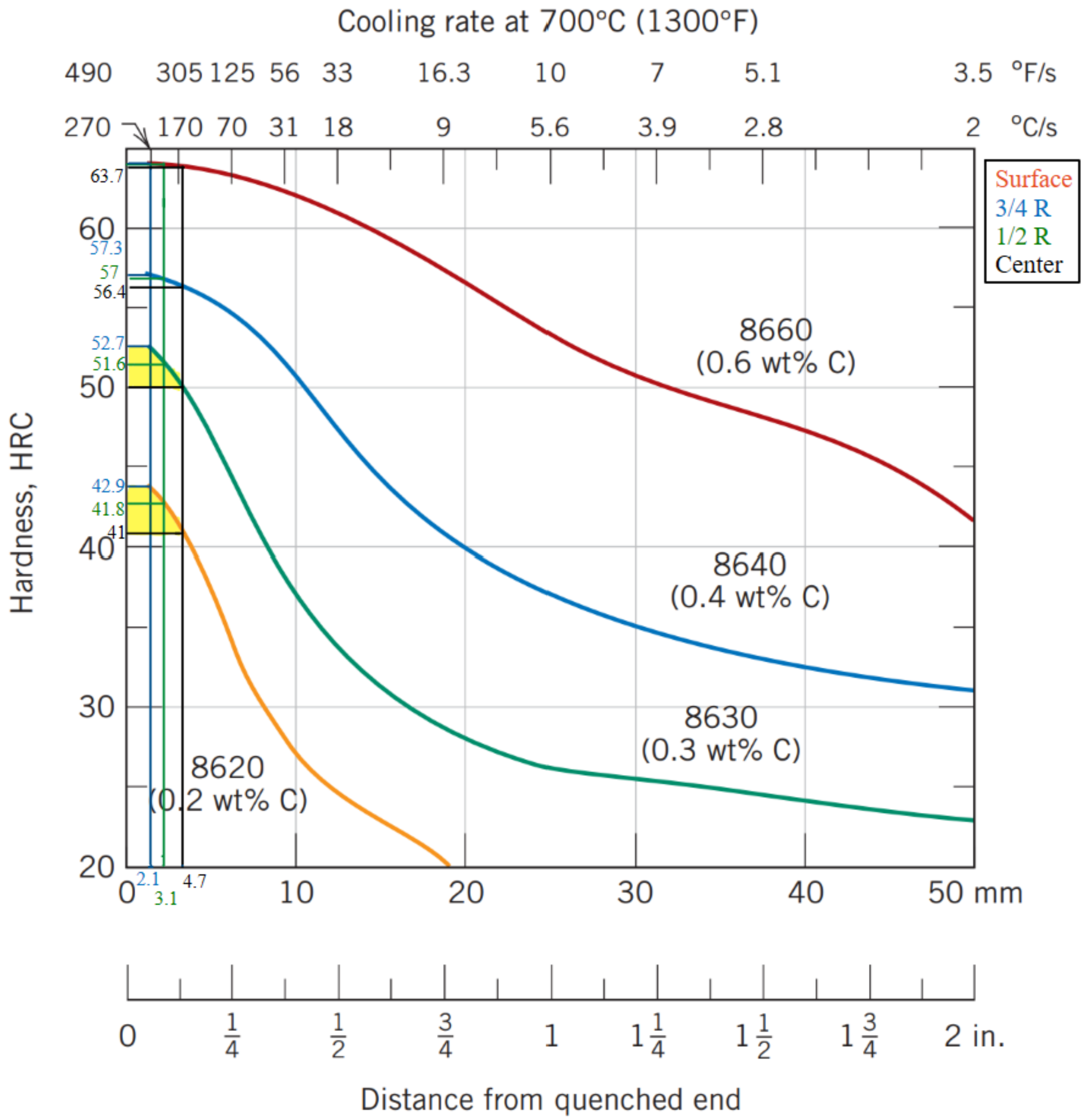


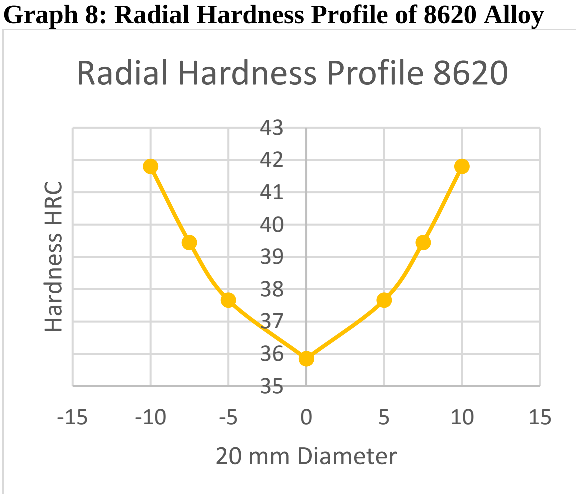
Table 4: Analysis of 8600 Alloys, Hardenability Curve for diameter = 20mm

Agitated Water					
Alloys	Hardness Center (mm)	Hardness 1/2 R (mm)	Hardness 3/4 R (mm)	Hardness S (mm)	Diameter (mm)
8620	41	41.8	42.9	Does Not Exist	20
8630	50	51.6	52.7	Does Not Exist	20
8640	56.4	57	57.3	Does Not Exist	20
8660	63.7	63.8	64	Does Not Exist	20

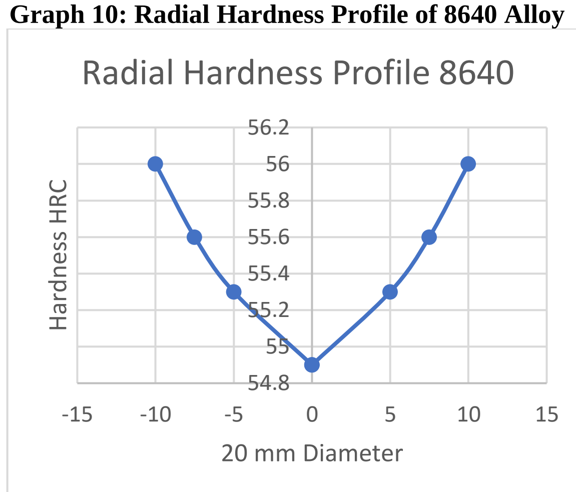
It can be noted that it is assumed that if a center, ½ R, ¾ R, and surface measurement cannot be taken for a given hardness that the quenching medium will be too severe because cracking and warping may be produced. Keeping this assumption in mind, and looking at Graph 2, a quenching medium consisting of agitated water would be considered too severe. Looking at Graph 3, as shown above, it can be shown that an 8630 alloy can be quenched in agitated oil and meet the minimum hardness of 40 HRC throughout the component within the required diameter range.

The information gathered from Graph 5, represented in Table 3, can now be used to determine what the hardness of the specimen will be without conducting a heat treatment process. Knowing that the diameter of the specimen at hand is 20mm, it can be shown that ¾ R = 2.5mm, ½ R = 5mm, Center (R) = 10mm. Therefore, after analyzing Table 3, it is can be shown that the hardness of the component, at a radial distance less then 2.5mm into the specimen, will be greater then 48.8 HRC. This can further be shown in the following graphs.

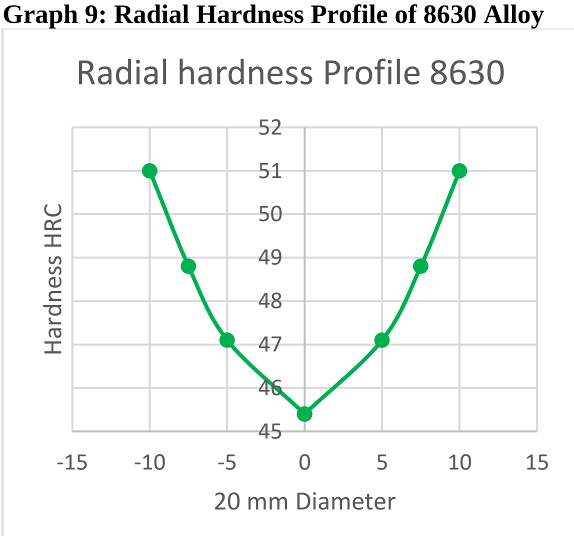
Graph 8: Radial Hardness Profile of 8620 Alloy



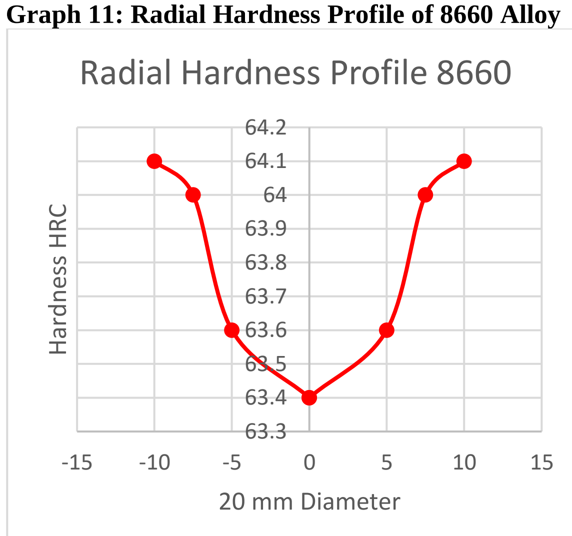
Graph 10: Radial Hardness Profile of 8640 Alloy



Graph 9: Radial Hardness Profile of 8630 Alloy



Graph 11: Radial Hardness Profile of 8660 Alloy



It can be shown from the Radial Hardness graphs plotted above that the 8630 alloy is the only material that achieves the minimum hardness throughout the component without going over the maximum allowable hardness at the center. It can also be shown, in graph 8, that the hardness 2mm below the surface does not reach 62 HRC for the 8630 alloy. Looking at graph 10, it can be shown that the hardness throughout the component at the same diameter will achieve a hardness greater then 62 HRC. With this information the next step in determining the appropriate material and quenching medium for a gear used in an excavation drill gearbox is to design a suitable heat treatment in order to achieve a hardness greater then 62 HRC 0.2mm below the surface.

Selecting Suitable Heat Treatment

The first step in selecting a suitable heat treatment for the specimen at hand is to determine variables for the following equations.

- $\frac{C(x,t)-C_0}{C_s-C_0} = 1 - \operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$
    - $C(x,t) = 0.6$
    - $C_0 = 0.3$
    - $x = 0.2mm = 0.0002m$
    - $t_{max} = 14400\ s$
- $D = D_0 + \exp\left(-\frac{Q_d}{RT}\right)$
    - $Q_d = ?$
    - $D_0 = ?$
- $C_s = 7 \times 10^{-3}\sqrt{P}\exp\left(-\frac{20000}{RT}\right)$
    - $T_{min} = 1180\ Kelvin$
    - $P_{max} = 170\ psi$
    - $R = 8.314\,\frac{J}{molK}$

- $t = \left(\frac{x}{2 \times inerf\left(1 - \frac{C_x - C_0}{C_s - C_0}\right)}\right) \times \left(\frac{1}{D}\right)$

- Cost=(60($)+(0.095($)×T(kelvin))+(.75($)×Psi)) × Time(hours)Cost=60$+0.095 $×T(kelvin)+.75$×Psi × Time(hours)

Graph 12: Iron-Carbon Phase Diagram: Selecting Appropriate Austenizing Temperature

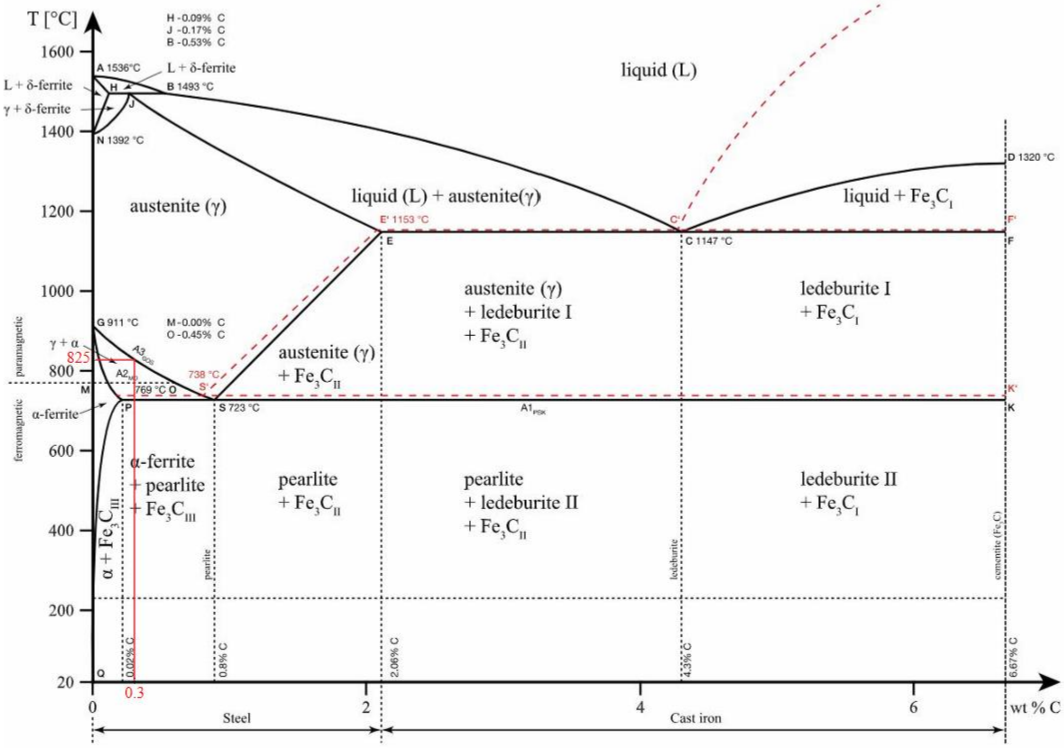


Table 5:

Diffusing Species	*Host Metal*	$D_0(m^2/s)$	*Activation Energy Q_d* *kJ/mol*	*eV/atom*	*Calculated Values* *T(°C)*	$D(m^2/s)$
Fe	α-Fe (BCC)	2.8×10^{-4}	251	2.60	500 900	3.0×10^{-21} 1.8×10^{-15}
Fe	γ-Fe (FCC)	5.0×10^{-5}	284	2.94	900 1100	1.1×10^{-17} 7.8×10^{-16}
C	α-Fe	6.2×10^{-7}	80	0.83	500 900	2.4×10^{-12} 1.7×10^{-10}
C	γ-Fe	2.3×10^{-5}	148	1.53	900 1100	5.9×10^{-12} 5.3×10^{-11}
Cu	Cu	7.8×10^{-5}	211	2.19	500	4.2×10^{-19}
Zn	Cu	2.4×10^{-5}	189	1.96	500	4.0×10^{-18}
Al	Al	2.3×10^{-4}	144	1.49	500	4.2×10^{-14}
Cu	Al	6.5×10^{-5}	136	1.41	500	4.1×10^{-14}
Mg	Al	1.2×10^{-4}	131	1.35	500	1.9×10^{-13}
Cu	Ni	2.7×10^{-5}	256	2.65	500	1.3×10^{-22}

Source: E. A. Brandes and G. B. Brook (Editors), *Smithells Metals Reference Book,* 7th edition, Butterworth-Heinemann, Oxford, 1992.

As shown in Graph 11, the minimum Austenizing temperature is equal to approximately 825 degrees Celsius or 1098 kelvin (absolute temperature). Not knowing if the specimen contains impurities, or due to other unknown factors, it is advisable to use a temperature at least 10% greater then the minimum Austenizing temperature. Using Table 5, it is shown that the Diffusion Coefficient and the Activation Energy are 2.8×10^{-4}(m^2/s) and 148 kJ/mol respectively. With this information known it is now required to write a code that will optimize the time, temperature, and pressure with the goal of minimizing cost.

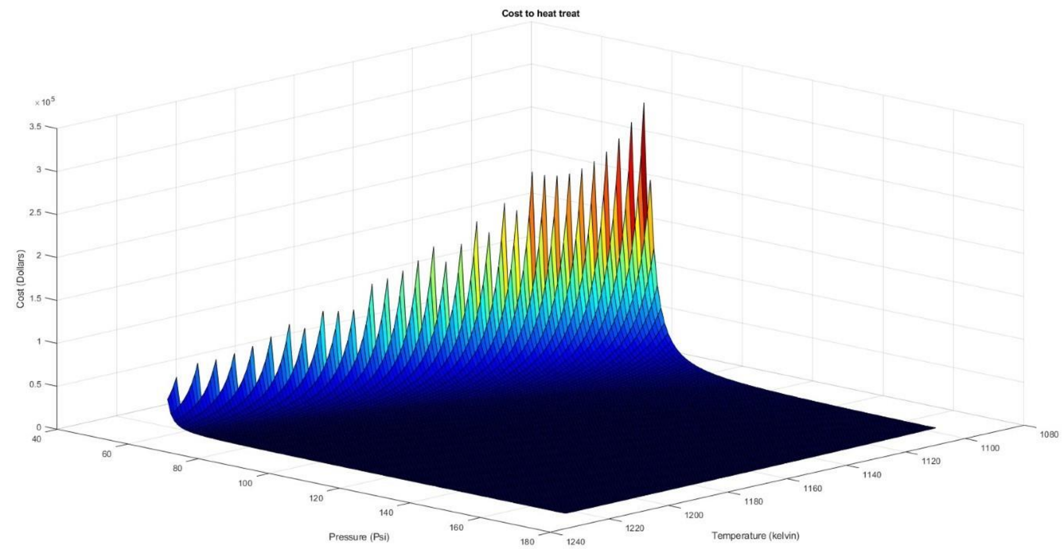
Figure 1: Matlab code for optimizing Time, Temperature, and Pressure with the goal of minimizing the cost

```
%variable decloration

Cx=0.6;                       %Carbon concentration we are looking to reach
Co=0.3;                       %Materials original carbon concentration
Do = 2.3 * 10^-5;             %Diffusion coefficient for carbon in austenite
x=2*10^-4;                    %Depth of ideal carbon concentration
Qa=148000;                    %Activation energy of carbon in austenite
Psi = 0:1:170;                %Pressure vector for all acceptable Psi
Psi_vertical_vector = Psi';   %Creation of a vertical Psi vector
P = Psi .* 6894.76;           %Psi to Pascal conversion
P = P';                       %Changing pressure vector into a vertical vector
T = 1098:1:1223;              %Temperature vector for all aceptable temperatures

%Calculations

Cs=7.*10^-3 .* sqrt(P) .* exp(-20000./(8.314 .* T));    %Atmospheric carbon concentration as a function of temperature and pressure
Cs(Cs<.61) = NaN;                                        %Elimination of all Cs values less than .61
D = Do .* exp(-Qa./(8.314.*T));                          %Diffusion as a function of temperature
inverf_value = erfinv(1-((Cx-Co)./(Cs-Co)));             %Intermitant calcuation
t= ((x ./ (2 .* inverf_value) ) .^2 ) ./ D;              %Time as a function of atmospheric pressure concentration and diffusion
t_hours = t ./ 3600;                                     %Conversion of time from seconds to hours

%Cost as a function of Time, Pressure and Temperature

cost = (60 + (0.095 .* T) + (0.75 .* Psi_vertical_vector )) .* t_hours;

%Finding lowest cost

lowest = min(cost);           %Finds lowest cost for each degree of temperature
lowest_cost = min(lowest)     %Finds the lowest cost within the lowest cost for each temperature and displays lowest cost
surf(T,Psi,cost)              %3d graph with X: Temperature, Y: Pressure, and Z:cost
title('Cost to heat treat')
xlabel('Temperature (kelvin)')
ylabel('Pressure (Psi)')
zlabel('Cost (Dollars)')
colormap(jet(50))
```

Important notes on the code

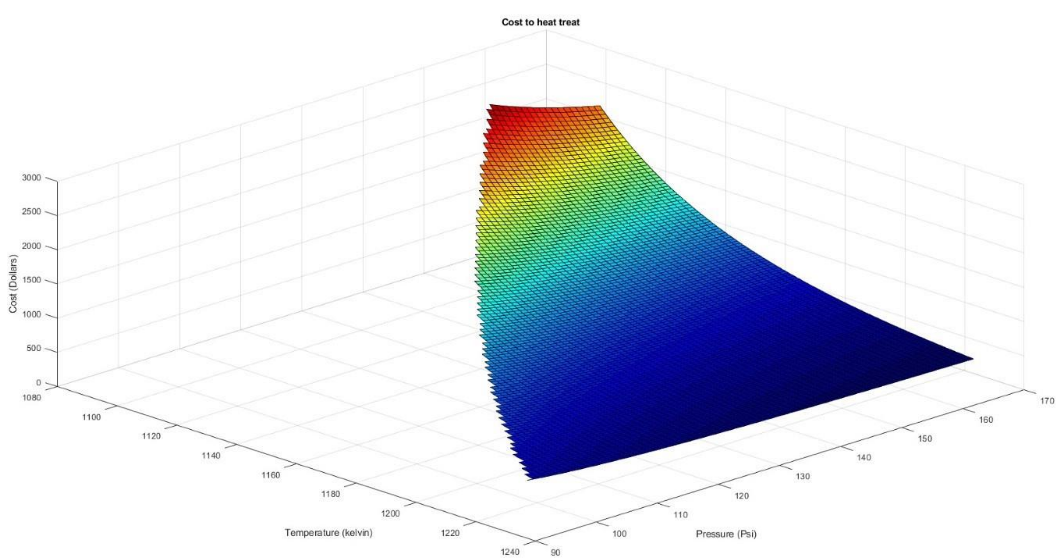
- Cs is cut off at 0.61%, for all values less than .61% NaN takes their place.
- Temperature is set as a horizontal vector going from 1093 - 1223 degrees kelvin.
- Pressure is set as a vertical vector going from 0 -170 Psi.
- Time is a matrix.
- Cost is a matrix.

Graph 13: Cost vs Pressure, Temp and Time



This graph shows the cost when the tolerance for Cs is set to 0.61%. As Cs approaches 0.6% the cost approaches an infinite amount because as the atmospheric carbon concentration approaches the ideal carbon concentration for the gear the time approaches infinity. Because of this phenomenon, it is difficult to visualize the cost. But we can observe the trend that greater pressure and greater temperatures result in a lower cost. To have a better understanding of how the pressure and temperature affect the cost of the heat treatment changing the scope of the atmospheric carbon pressure to a higher value to effectively crop the graph only to display lower cost values.

Graph 14: Cropped Cost vs Pressure, Temp and Time



Note: The X and Y axis are rotated for better visualisation of the slope.
This graph better shows the relationship between the temperature and pressure to the cost. Pressure seems to increase the cost linearly, while temperature seems to increase the cost exponentially.

$$C_s = 7 \times 10^{-3}\sqrt{P}\,\exp\left(-\frac{20000}{RT}\right)$$

I believe the temperature has an exponential effect because it appears in the exponent of the carbon concentration equation, while pressure is square rooted.
The lowest cost can be observed at the highest temperature and highest pressure. This makes sense as the cost is calculated from the time, pressure per hour, and temperature per hour.

Cost=(60($)+(0.095($)×T(kelvin))+(.75($)×Psi)) × Time(hours)Cost=60$+0.095$×T(kelvin)+.75$×Psi × Time(hours)

Since time is a multiplicand of both time, pressure, and general operations it has the biggest impact on the resulting cost. This means the lowest cost is going to be a result of the shortest heat treatment process. The shortest heat treatment process occurs when the pressure and temperature are at their highest. This is observable in the graph as the cost trends downward while temperature and pressure increase.

Conclusion

From the observation made above regarding how the cost decreases as the pressure and time increase, we can find the cheapest heat treatment by taking the maximum value of temperature and maximum value for pressure and calculating the time required to reach a concentration of 0.6%. Then calculate the cost from the three variables. Thankfully with MATLAB we can do this automatically with MATLAB using the min() function we can find automatically the lowest value within the cost matrix, which is at the max temperature and max pressure.

Overall to achieve the desired criteria for a gear used in an excavation drill gearbox it is recommend to use a 20mm bar of 8630 Alloy. And then conduct a heat treatment process held at a temperature of 950 degrees Celsius at a pressure of 170 psi for 42 minuets. Under these conditions there will be a 0.6wt%C at 0.2mm below the surface. Then the rod is quenched in agitated oil, this results in a surface hardness greater then 62 HRC and a center hardness of 45.5 HRC. The resulting cost of this heat treatment procedure is $212.2.

Appendix: