Optimization of Tempering Process Parameters of AISI 3140 Low Alloy Steel to Conserve Furnace Energy using Tukey’s Honestly Significant Difference Test

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Abstract. Quenching and Tempering of AISI 3140 alloy steel is a necessary heat treatment process to attain desired hardness and toughness. However the tempering process consumes remarkable amount of energy in furnace. One of the usual tempering processes of AISI 3140 steel is performed by heating it to a temperature of 425°C in crucible furnace and holding at that same temperature for 2 hours. Furnace energy consumption may be reduced by increasing tempering temperature to 540°C and holding for a relatively lesser duration. Therefore, 20 specimens of AISI 3140 steel are oil quenched. Few specimens are tempered at lower temperature of 425°C for 2 hours. Remaining specimens are tempered in 4 batches at higher temperature of 540°C for various holding time of 50 minutes, 40 minutes, 30 minutes and 20 minutes respectively. The heat treated specimens are subjected to Izod’s Impact test and Rockwell Hardness test. Test results are statistically analyzed using Tukey’s Honestly Significant Difference Test and it is found that impact toughness and hardness attained by tempering at 425°C for 2 hours is significantly equal to that attained at 540°C for 30 minutes. It is observed that the furnace energy consumed is decreased significantly by increasing furnace temperature and reducing holding time during tempering process while other process parameters are kept identical. Thus energy and time are conserved without compromising the vital mechanical properties by optimizing tempering process parameters.

1. Introduction
The low alloy steel AISI 3140 has wide applications in areas such as aircraft landing gears, gear shafts, power transmitting shafts and connecting rods. Based on the requirements of intended application, the desired mechanical properties are attained by quenching and tempering processes[1], [2]. It is a well established fact that in tempering process, the properties of specimen such as hardness and toughness that have been attained employing a longer time period at a lower temperature can also be attained by holding it for a shorter time period at higher temperature[1]. Tempering time and temperature plays major role in determining the toughness and hardness[3]. Toughness increases at the cost of hardness. At the same time, either extreme toughness or extreme hardness is always undesirable. The increase in both tempering temperature and tempering time generally increases the toughness but decreases the hardness[1], [3], [4]. Hence while altering the parameters of the tempering
process, tempering temperature can either be increased while decreasing the holding time or be decreased while increasing the holding time, in order to achieve the same mechanical properties[2]. For AISI 3140 steel, tempering temperature of 425°C and tempering time of 2 hours is one among the conventional tempering process parameters to attain certain desired toughness and hardness[1], [3]. But the same mechanical properties may be attained by increasing the tempering temperature and decreasing the tempering time[1], [2]. Energy consumed during tempering process is a factor of both time and temperature. By operating furnace over a shorter time period, the energy consumed can be well reduced, which will eventually lead to the conservation of energy as an aid to the globally challenging energy shortage.

2. Materials and Methods
AISI 3140 steel specimens are procured from different lots to attain randomness in sampling. 20 numbers of specimens of AISI 3140 are prepared for Izod’s impact test in standard dimensions as prescribed by ASTM[3]. Each specimen has a cross section of 10mm×10mm and a length of 75mm with a 2mm 45° V-notch on one face[3]. All 20 specimens are kept in a crucible furnace for 1 hour at 840°C and subsequently oil quenched to room temperature to harden the specimens. Since all the specimens are hardened with identical process parameters, they can be treated to be identical in the aspects of mechanical properties[1], [2]. The specimens are randomly grouped into 5 batches each consists of 4 specimens. One batch is tempered for 2 hours at 425°C in crucible furnace. Other 4 batches are tempered for 50 minutes, 40 minutes, 30 minutes and 20 minutes respectively, all at same temperature of 540°C. All specimens are tested with both Izod’s impact test and successively Rockwell hardness test. The observed values of Izod impact toughness and Rockwell hardness number are tabulated in table 1 and table 2 respectively corresponding to the tempering temperature and tempering time.

**Table 1**. Impact Toughness of AISI 3140 steel for Different Tempering Temperature and Time.

| Tempering temperature (°C) | 425 | 540 | 540 | 540 | 540 |
|---------------------------|-----|-----|-----|-----|-----|
| Tempering time (minutes)  | 120 | 50  | 40  | 30  | 20  |
| Impact Toughness (Joules) | 69  | 78  | 70  | 64  | 59  |
| Sample 1                  |     |     |     |     |     |
| Sample 2                  | 66  | 76  | 71  | 65  | 63  |
| Sample 3                  | 64  | 79  | 73  | 68  | 56  |
| Sample 4                  | 65  | 76  | 75  | 68  | 58  |

**Table 2**. Hardness of AISI 3140 steel for Different Tempering Temperature and Time.

| Tempering temperature (°C) | 425 | 540 | 540 | 540 | 540 |
|---------------------------|-----|-----|-----|-----|-----|
| Tempering time (minutes)  | 120 | 50  | 40  | 30  | 20  |
| Hardness (HRC)            | 40  | 34  | 40  | 42  | 44  |
| Sample 1                  |     |     |     |     |     |
| Sample 2                  | 40  | 36  | 37  | 41  | 47  |
| Sample 3                  | 41  | 35  | 38  | 42  | 46  |
| Sample 4                  | 43  | 34  | 37  | 40  | 44  |

The energy consumed by the crucible furnace $E$ (Joules) during each of tempering process is determined by considering the tempering temperature $T_r$ (K), room temperature $T_a$ (K), holding time $t_o$ (s), initial time to reach tempering temperature $t_i$ (s), number of specimen $N$, volume of specimen $V$ (m³), density of specimen $\rho$ (kg/m³), specific heat capacity of specimen $C$ (J/kg/K) and furnace heat loss rate $q$ (J/s/K).

Energy consumed by furnace is the sum of energy required to reach the tempering temperature and the energy required to maintain at that temperature. However energy required to reach the tempering temperature is negligible for mass production since the furnace once heated to operating temperature is maintained at that temperature for many batches of heat treatments[5], [6]. Energy consumed by the furnace to maintain the same tempering temperature is equal to the heat loss in furnace. Hence furnace
energy consumption for a specific tempering process is mainly affected by the furnace heat loss rate, holding time and holding temperature.

\[ E = q t_o T_o \]  

(1)

3. Results and Discussions

The values obtained for various specimens can be statistically analyzed to arrive at a decision of comparing different process parameters and the resulting mechanical properties. In addition, furnace energy consumption for different tempering processes can be calculated mathematically and the results can be compared.

3.1. Statistical Analysis of Izod Impact Toughness

The various values of Izod impact toughness for different parameters and different specimens are visualized using Scatter Plot of Python against tempering temperature and time as shown in figure 1. The variations in the values of Izod impact toughness can be statistically analyzed using Tukey’s Honestly Significant Difference (HSD) Test to spot whether two different process parameters result in significantly same mechanical properties[7]. In order to reject the pairs of process parameters which do not establish significantly same mechanical properties, 0.05 level of significance is incorporated. Tukey’s HSD Test sets a null hypothesis that the mean values of Izod impact toughness for all different pairs are significantly equal[7]. Pair-wise comparison is conducted for all tempering processes. The statistical test is carried out on the Izod impact toughness using Python and the results are tabulated in table 3.

![Figure 1. Scatter Plot of impact toughness for different tempering temperature and time.](image1)

![Figure 2. Scatter Plot of hardness for different tempering temperature and time.](image2)

Results of Tukey’s HSD Test on Izod impact toughness yield a view on comparisons of different tempering process parameters in a pair-wise manner. Columns 1 and 2 under heads group1 and group2 show the pair which undergo statistical test for the instance. Column 3 gives the value of difference in the mean of data spread for the pair. Column 4 gives the probability value as a result of statistical analysis for each pair. This probability value yields the lead to arrive at statistical decision by comparing it with the level of significance 0.05. In the case of probability value lying below 0.05, the null hypothesis proposed may summarily be rejected. On the other hand, probability above 0.05 may eventually result in acceptance of null hypothesis. Final column of table 3 under head ‘reject’ summarises the statistical decision made for each pair. It briefly indicates the rejection of null hypothesis and may contain any of two possible outcomes, namely True and False. If ‘reject’ is True, Izod impact toughness values corresponding to the two different tempering processes under test are significantly unequal. If ‘reject’ is False, Izod impact toughness values corresponding to the two different tempering processes under test are significantly equal.
Table 3. Results of statistical analysis of izod impact toughness for all different pairs $^a$.

| group1 | group2   | meandiff | p-adj | lower   | upper   | reject |
|--------|----------|----------|-------|---------|---------|--------|
| 425celsius_120min | 540celsius_20min | -7.0    | 0.0036 | -11.8585 | -2.1415 | True   |
| 425celsius_120min | 540celsius_30min | 0.25    | 0.9   | -4.6085 | 5.1085 | False  |
| 425celsius_120min | 540celsius_40min | 6.25    | 0.0092 | 1.3915  | 11.1085 | True   |
| 425celsius_120min | 540celsius_50min | 11.25   | 0.001 | 6.3915  | 16.1085 | True   |
| 540celsius_20min | 540celsius_30min | 7.25    | 0.0027 | 2.3915  | 12.1085 | True   |
| 540celsius_20min | 540celsius_40min | 13.25   | 0.001 | 8.3915  | 18.1085 | True   |
| 540celsius_20min | 540celsius_50min | 18.25   | 0.001 | 13.3915 | 23.1085 | True   |
| 540celsius_30min | 540celsius_40min | 6.0     | 0.0125 | 1.1415  | 10.8585 | True   |
| 540celsius_30min | 540celsius_50min | 11.0    | 0.001 | 6.1415  | 15.8585 | True   |
| 540celsius_40min | 540celsius_50min | 5.0     | 0.0423 | 0.1415  | 9.8585 | True   |

$^a$ as generated by Tukey’s HSD Test of Python

On observation, the rejection of statement that ‘all the mean Izod impact toughness values for different parameters are the same’ is found to be true for all pairs except the pair of 425°C at 120 minutes and 540°C at 30 minutes. In other words, the Izod impact toughness is significantly same for the later pair. It can be observed that the probability value for that pair is 0.9, which is much higher than the criterion value of 0.05. Therefore, the method of tempering at 425°C, 2 hours can be well replaced by tempering at 540°C, 30 minutes to attain the same impact toughness. Other tempering timings of 20 minutes or 40 minutes or 50 minutes for the same tempering temperature of 540°C cannot be a substitute for tempering at 425°C, 2 hours, because they result in significantly different Izod impact toughness.

3.2. Statistical Analysis of Hardness

The hardness values in Rockwell Hardness Scale presented in table 2 are visualized in figure 2 using the Scatter Plot of Python to get better insight on spread of values. The analysis of variations in the hardness and pair-wise comparison of the hardness obtained by different tempering process parameters can be performed by means of Tukey’s HSD Test with a level of significance of 0.05. The test sets a null hypothesis that mean values of hardness for all different pairs are significantly equal. The results of Tukey’s HSD Test using Python are presented in table 4.

From the results of Tukey’s HSD Test run on hardness values of different tempering process parameters, shown in table 4, it can be observed that the probability value 0.9 for the pair of 425°C, 120 minutes and 540°C, 30 minutes is higher than the level of significance 0.05. For all other pairs the probability values lie below 0.05. From the last column of results, it is observed that the rejection is false for the statement that the mean hardness for the process at 425°C, 120 minutes is significantly same as the mean hardness for the process at 540°C, 30 minutes. For all other pairs, the rejection is significantly true. Therefore the method of tempering at 425°C, 2 hours can be replaced by tempering at 540°C, 30 minutes to attain the same hardness. Other tempering time durations of 20 minutes or 40 minutes or 60 minutes for the same tempering temperature of 540°C cannot be employed in place of tempering at 425°C, 2 hours, because they result in significantly different hardness.
Table 4. Results of statistical analysis of hardness for all different pairs \(^b\).

| group1                  | group2                  | meandiff | p-adj | lower     | upper     | reject |
|-------------------------|-------------------------|----------|-------|-----------|-----------|--------|
| £425celcius_120min      | £540celcius_20min       | 4.25     | 0.0021| 1.4734    | 7.0268    | True   |
| £425celcius_120min      | £540celcius_30min       | 0.25     | 0.9   | -2.5266   | 3.0266    | False  |
| £425celcius_120min      | £540celcius_40min       | -3.0     | 0.0313| -5.7766   | -0.2234   | True   |
| £425celcius_120min      | £540celcius_50min       | -6.25    | 0.001 | -9.0266   | -3.4734   | True   |
| £540celcius_20min       | £540celcius_30min       | -4.0     | 0.0037| -6.7766   | -1.2234   | True   |
| £540celcius_20min       | £540celcius_40min       | -7.25    | 0.001 | -10.0266  | -4.4734   | True   |
| £540celcius_20min       | £540celcius_50min       | -10.5    | 0.001 | -13.2766  | -7.7234   | True   |
| £540celcius_30min       | £540celcius_40min       | -3.25    | 0.0184| -6.0266   | -0.4734   | True   |
| £540celcius_30min       | £540celcius_50min       | -6.5     | 0.001 | -9.2766   | -3.7234   | True   |
| £540celcius_40min       | £540celcius_50min       | -3.25    | 0.0184| -6.0266   | -0.4734   | True   |

\(^b\) as generated by Tukey’s HSD Test of Python

3.3. Comparison of Furnace Energy Consumption

Since tempering at 425°C, 120 minutes can suitably be replaced by tempering at 540°C, 30 minutes to attain the same hardness and impact toughness, these two tempering processes alone can be considered for the further analysis of furnace energy consumption. Furnace energy consumptions during other tempering processes parameters such as 20 minutes or 40 minutes or 50 minutes all at 540°C are discarded as unnecessary for further calculations and discussions.

Therefore furnace energy consumption for the two tempering processes of 425°C, 2 hours and 540°C, 30 minutes can be calculated and compared. Furnace loss rate \( q \) (J/s/K) is a constant for a specific crucible furnace. The unique process parameters for former method are tempering temperature \( T_o = 425°C = 698K \) and tempering time \( t_o = 120\times60 = 7200s \), and that for latter method are tempering temperature \( T_o = 540°C = 813K \) and tempering time \( t_o = 30\times60 = 1800s \).

From equation (1),

\[
\text{Energy consumed by former method, } E_{425C,120m} = q \times 698 \times 7200 = 5025600q
\]

(2)

Energy consumed by latter method, \( E_{540C,30m} = q \times 813 \times 1800 = 1463400q \)

(3)

By comparing equations (2) and (3), it is observed that the latter method is highly energy conserving. Percentage savings in energy can be calculated as the ratio of reduction in energy consumption to energy consumption by conventional tempering process.

\[
\text{% savings} = \frac{(E_{425C,120m} - E_{540C,30m})}{E_{425C,120m}} \times 100
\]

Therefore

\[
\text{% savings} = \frac{(5025600q - 1463400q)}{5025600q} \times 100 = 70.88\%
\]
It can be found that the relatively lesser holding time at a relatively little higher tempering temperature in furnace lead the tempering process in saving a drastic amount of furnace energy.

4. Conclusions
The method of tempering at 425°C for 2 hours can be replaced by tempering at 540°C for 30 minutes for AISI 3140 low alloy steel without compromising vital mechanical properties such as hardness and impact toughness. The furnace energy consumed by tempering at 540°C for 30 minutes is much lesser than that consumed by tempering at 425°C for 2 hours with a savings in energy of 70.88%. It can also be concluded that by increasing tempering temperature and correspondingly decreasing tempering time, any desired mechanical properties can be achieved at relatively lesser furnace energy consumption. This energy conserving principle for tempering process can be applied to any other furnaces employing different types of energy inputs such as solid fuel, furnace oil and gaseous fuel.

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