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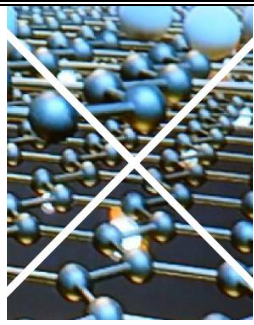

EFFECTS OF VARIOUS HEAT TREATMENT PROCEDURES ON THE TOUGHNESS OF AISI 4140 LOW ALLOY STEEL

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Abstract

In this paper, through literature search, effects of various heat treatment procedures on toughness of commercially available AISI 4140 low alloy steel were investigated. Variables affecting a material's mechanical properties were discussed briefly and details of AISI 4140 steel were delivered. Different heat-treating routes and approaches from various reports were considered and compared. Utilizing a materials properties database, a number of reported results were gathered and discussed. An effort has been put into keeping all the variables affecting the results constant other than heat treatment procedures for the purpose of observing only the effects of those procedures. Double quenching and tempering in the range of 600-900℃ as well as full annealing at around 860℃ were found to be resulting with the highest toughness values. A proposal was also made for furtherly improving the toughness values of these heat-treated samples.

Keyword: Maximum toughness, heat treatment, AISI 4140 steel.

1.Introduction

1.1. Variables Affecting a Material's Mechanical Properties

For many years the influence of materials' microstructures on mechanical properties has been extensively researched; engineers have been pressed to enhance the properties of alloys to develop stronger and lightweight materials. By designing with stresses which are below the yield strength of a high ductility material, designers can generally avoid failure. However, the same practice does not properly function on newly developed high strength and low ductility alloys as there were a lot of catastrophic failures reported. For this exact reason, a material's toughness came forward in design parameters.

In materials science, toughness indicates a material's ability to absorb energy before the rupture.

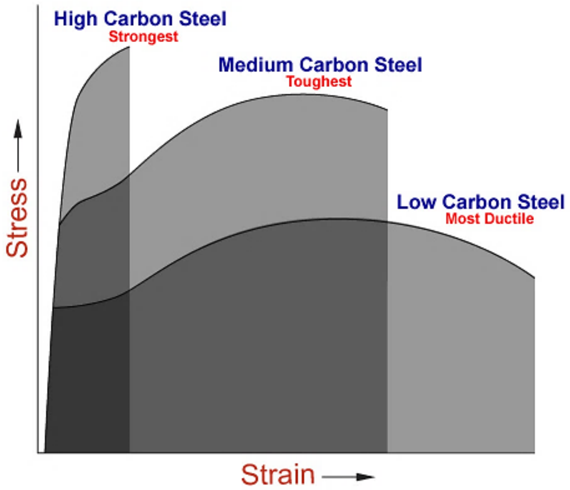

Figure 1. Typical Stress - Strain curves for different material compositions [1].

One another definition of a materials toughness is the amount of energy that a material can absorb and plastically deform without fracture. So, by definition, as a material's toughness value increases, the area under its stress-strain curve increases, or vice versa. This is pictured above in Figure 1.

There are a number of variables that affect a material's toughness and some of which can be listed as [1]:

- Working temperature
- Notch effect
- Loading rate (strain rate)
- Loading type
- Geometry of the sample

For example, a specific material under a static load may be satisfactory but may not perform well under a cyclic loading; it can exhibit a high toughness behavior when loaded at room temperature but at relatively low temperatures this may change abruptly. Thus, to obtain reliable toughness data, different test types have been developed throughout the years such as low temperature or high temperature impact testing.

Besides testing conditions, composition of a material plays a huge role on its physical properties. Even addition of trace amounts of alloying elements affects a material's properties directly. In this consideration, there are countless alloys and among these there are many materials which are appropriate for maximum toughness heat treatments and there are many which are not. These are referred as heat-treatable and non-heat-treatable alloys, respectively. AISI 4140 alloy steel is one of those heat-treatable materials.

Here, in this text, these types of variables will be held as constant as possible in order to investigate only the effects of heat treatment procedures on AISI 4140 alloy steel's toughness values.

1.2. AISI 4140 Alloy Steels:

4140 grade steels (ASTM A29 equivalent) are heat-treatable low-alloy steels having the chemical compositions indicated in Table 1. Their typical applications consist of oil and gas drilling equipment, fishing tools, high and moderately stressed components for automobile industry, screws and etc. similar to AISI 4130 chrome moly steel but only with a slightly higher carbon content. This higher amount of carbon content gives the steel greater strength as well as better heat treatment capability which is a very crucial property for this maximum toughness approach.

Table 1. Composition of a 4140-steel [2][3].

	C	Mn	Si	Cr	Ni	Mo
AISI 4140 standard limits	0.38 - 0.43	0.75 – 1.00	0.15 – 0.35	0.80 – 1.10	-	0.15 – 0.25
Typical 4140	0.42	0.97	0.27	1.04	0.13	0.18

To shed some light on the properties of this alloy, Table 2 was constructed and given below. Here, these values were obtained from the test results of a standard 4140 steel after its production without a special heat treatment procedure and may vary with applied treatments.

Table 2. Various properties and their values of AISI 4140 standard alloy steel [4].

Properties	**Values**
Density	7.85 g/cm^3
Melting point	1416°C
Tensile strength	655 MPa
Yield strength	415 MPa
Bulk modulus (typical for steel)	140 GPa
Shear modulus (typical for steel)	80 GPa
Elastic modulus	190-210 GPa
Poisson's ratio	0.27-0.30
Elongation at break (in 50 mm)	25.70%
Hardness, Brinell	197
Hardness, Knoop (converted from Brinell hardness)	219
Hardness, Rockwell B (converted from Brinell hardness)	92
Hardness, Rockwell C (converted from Brinell hardness. Value below normal HRC range, for comparison purposes only)	13
Hardness, Vickers (converted from Brinell hardness)	207

Having sufficient knowledge about the materials behavior is critical in heat treatment processes. Below, Continuous Cooling Curves (Figure 2) and Time-Temperature-Transformation diagrams (Figure 3) are given. Further comments and discussions will be based on these two diagrams.

Heat treatment of steels is a group of processes applied to alter a material's physical and/or chemical properties for a specific application or for general purpose usage. These techniques include the followings:

- Tempering
- Carburizing
- Nitriding
- Annealing
  - Homogenization Annealing
  - Full Annealing
  - Normalizing
  - Process (Recrystallization) Annealing
  - Spheroidizing
  - Stress-relief Annealing
- Quenching (or hardening)
- Cryogenic treatments etc.

For achieving maximum toughness values from a steel sample, tempering, annealing (full annealing or normalizing) and quenching processes are mainly utilized.

1.3. Heat Treatment of Steels:

1.3.1. Tempering of Steels:

Tempering is a type of heat treatment procedure used to alter a material's mechanical properties such as hardness and ductility. During a tempering process internal stresses are relieved and entrapped carbon in the martensitic microstructure (if present) is dispersed.

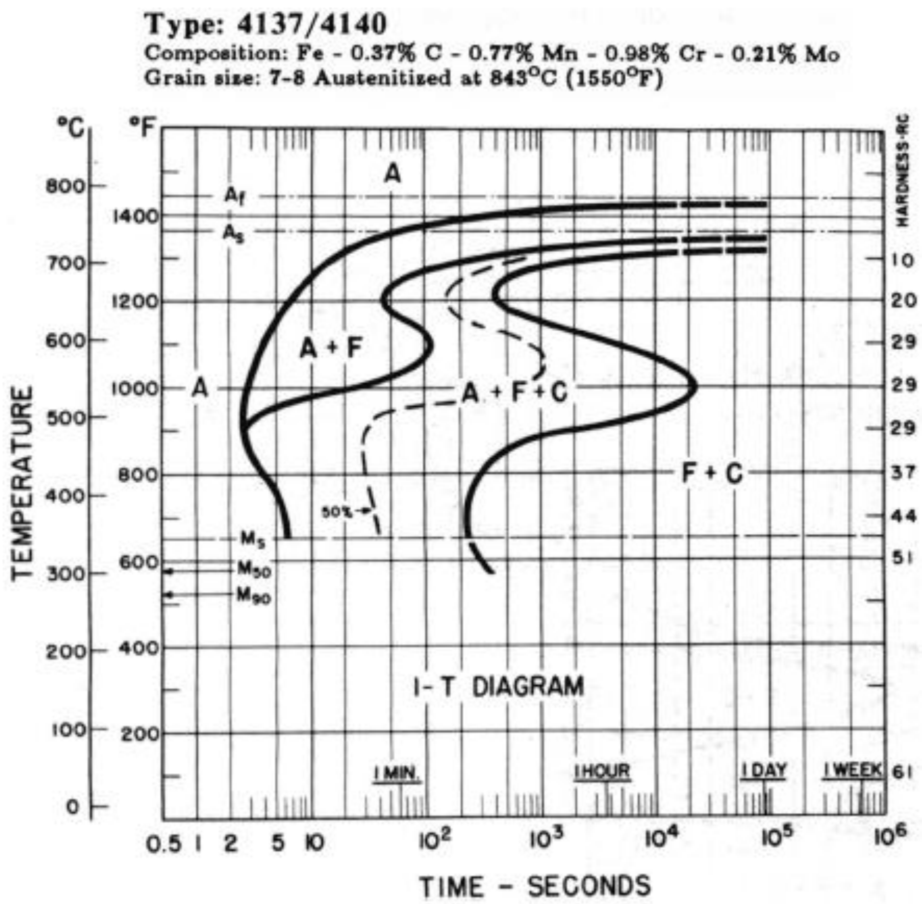

Figure 2. Isothermal Time-Temperature-Transformation (TTT) curve for AISI 4140 low alloy steel [6].

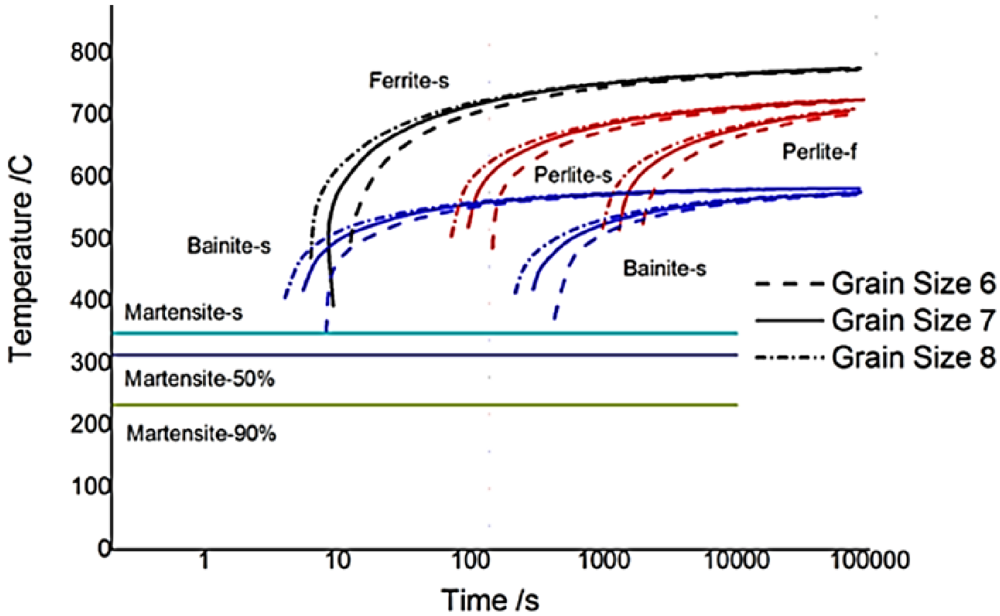

Figure 3. 4140 CCT diagram based on different grain sizes [5].

Tempering is performed by basically heating the steel part below its lower critical temperature, holding it at this temperature for a sufficient time (depends on the type of the metal and the expected properties) and then cooling at a specific rate down to a specific temperature. While diffusion of alloying elements and carbon is time and temperature dependent, during tempering, holding temperature is more critical than holding time.

As stated earlier tempering process is done to relieve internal stresses and increasing ductility of a component. However, for alloys having some specific impurities such as S, Sb, P, Sn and As, toughness values may drop drastically and the material exhibits brittle fracture behavior. This is due to a phenomenon called temper embrittlement which stems from impurity segregation into grain boundaries during the process. While the best way of avoiding this phenomenon is reducing the amount of impurities, this effect can also be inhibited by the addition of Mo and W elements or by heating the part above 600°C and quenching below 300°C [7].

The effects of alloying elements are not limited only with temper embrittlement. They may also retard the softening rate of a part during tempering and not only that, but they may also increase the hardness by forming alloy carbides at higher temperatures. This effect is referred as secondary hardening and as stated by Liu, B. et.al., it is closely related to the carbide precipitation and transformation [8]. Effect of tempering temperature on the secondary hardening is shown in Figure 4.

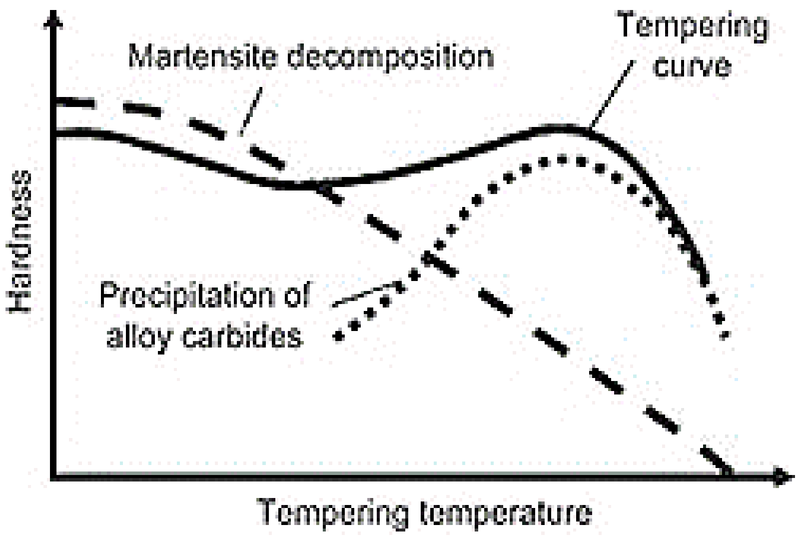

Figure 4. Effect of tempering temperature on secondary hardening [9].

To overcome the limitations of regular tempering procedure, martempering and austempering processes were developed throughout the years. The main difference between these two processes is that in austempering the quenching step is stopped at a higher temperature than for martempering, so, it is actually a bainitic transformation [10].

Martempering (Marquenching):

In this process martensite transformation is ensured to take place at the same time throughout the metal body. Quench is interrupted at a temperature above martensite transformation region for the metal body's center to cool down to the same temperature as the surface. The cooling is then continued in martensite region followed by conventional tempering [10]. This procedure is depicted in Figure 5.

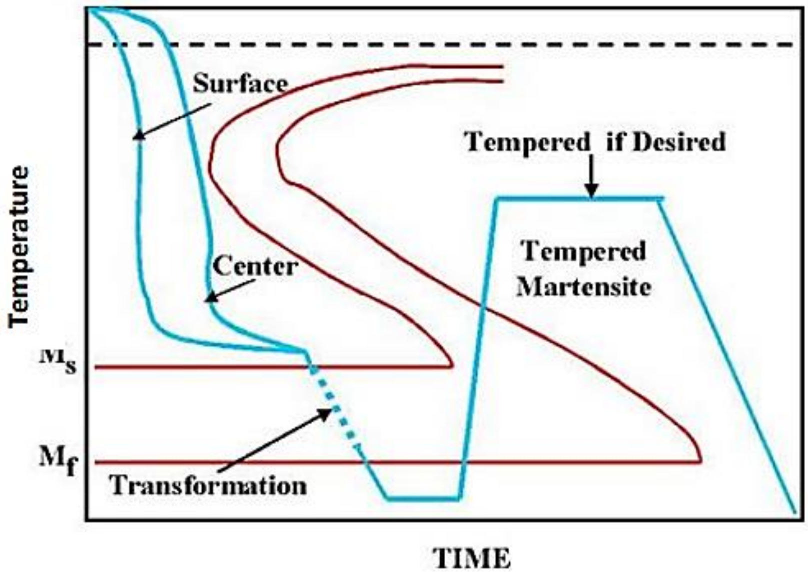

Figure 5. Cooling diagram of martempering process [10].

The advantage of martempering lies in the reduced thermal gradient between the part's surface and center during cooling. Thus, residual stress development is lower which reduces or even eliminates the susceptibility to crack formation.

Generally, any steel that can be quenched in an oil quenchant can be martempered including AISI 4140 alloy steel. The success of the procedure depends on the knowledge of the TTT characteristics of the material. Two events may come into play: Martensite transformation region gets wider and the martensite transformation temperature decreases as the carbon content increases, and the martensite range of single (or double) alloys are usually higher than that of triple alloy steels. Thus, it is important to obtain sufficient knowledge on the cooling behavior of the heat-treating material prior to the procedure [10].

Austempering:

Compared to martempering, the quenching step is interrupted at a higher temperature in austempering. Before cooling to room temperature, both the surface and the center of the part is allowed to transform into bainite (Figure 6). The purpose of interrupting the quench remains the same, reducing the thermal gradient between the surface and the center of the part [10].

As it can be seen in the Figure 6, as opposed to martempering there is no need for a final tempering which turns out to be energy efficient and less time consuming. There is also less distortion and crack formation compared to martempering as there is no austenite to martensite transformation. In austempering ductility and toughness results are also improved relative to conventional tempering and quenching [10].

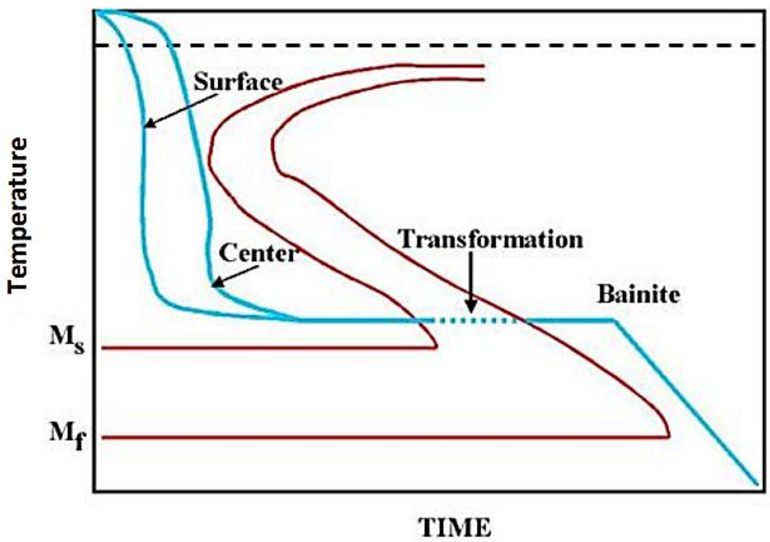

Figure 6. Cooling diagram of austempering process [10].

Here, the final product is fully bainite. This transformation limits the application of austempering on some materials which have their bainitic transformation line postponed due to the addition of alloying elements. As the bainitic transformation takes too much time, maintaining the furnace at sufficiently high temperatures decreases energy efficiency. Thus, in practice, austempering is only appropriate for materials with short bainitic transformation periods [10].

1.3.2. Normalizing of Steels:

Normalizing is an annealing procedure improving a part's strength, hardness and toughness to some extent. It provides grain size uniformity throughout the structure by simply heating the part above its recrystallization temperature (shown in Figure 7), holding there for a sufficient amount of time and letting it to cool down to room temperature in still air. This moderate cooling rate results in fine pearlite formation in the microstructure which is the main difference between normalizing and full annealing. In full annealing treatment the part is cooled in a furnace (slow cooling rate), so the resultant microstructure is coarse pearlite which exhibits higher ductility but lower hardness and strength relatively [11].

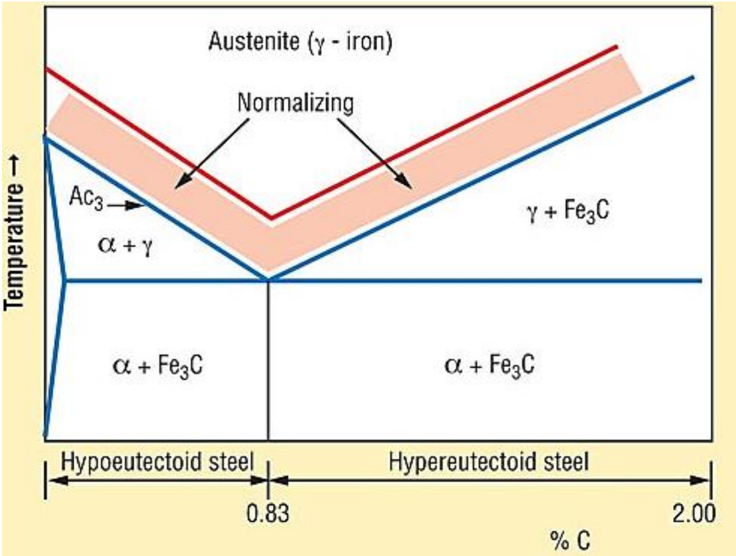

Figure 7. Normalizing temperature range superimposed on the standard phase diagram of steels [11].

There are three stages in a normalizing process [11]:

- Recovery Stage: Driven by the free energy stored in point defects and dislocations; internal stresses are relieved.
- Recrystallization Stage: Driven by the free energy stored in dislocations; strained grains are replaced by new strain-free grains.
- Grain Growth Stage: Driven by the free energy stored in grain boundaries; new grains grow continuously. This stage is restrained to some degree is normalizing in order to get fine pearlite in the final microstructure and not coarse pearlite

1.3.3. Quenching:

Quenching is the process to rapidly cool a steel part down to desired temperatures using a quench media referred as quenchant. Common quenchant materials are salt/fresh water, oil, forced air, special polymers etc. When the aim is to have the highest rate of cooling, water is very effective as a quenchant whereas oil provides a relatively slower rate.

Quenching is often done to obtain a martensitic microstructure; however, it may also be applied to cool down materials that have already finished their phase transformations at high temperatures for their safe handling. Quenching can be interrupted as in austempering and martempering in order to decrease the temperature gradient within a part.

2. Experimental Data in The Literature

Although there are not many reports specifically investigating the maximum toughness values of AISI 4140 steel in the literature, data obtained from a number of them provide sufficient knowledge about the outcomes of different heat treatment approaches. In this chapter, findings from this literature search will be presented and discussed.

As mentioned earlier, to obtain maximum toughness values from a steel part conventional normalizing, tempering and quenching heat treatment processes are usually applied. To investigate further, Sanij, K. et. al. proposed a double quenching and tempering procedure [12]. In their paper, effects of conventional quenching and tempering (denoted as CQT) and double quenching and tempering (denoted as DQT) processes on 4140 steel are evaluated. Heat treatment procedures are given below [12]:

CQT procedure:

25 mm Φ specimens were heated to 860℃ in a furnace for 60 minutes, followed by hot oil quenching at 80℃. Final tempering step was done at 600℃ for 30 minutes.

DQT procedure:

25 mm Φ specimens were heated to 860℃ in a furnace for 60 minutes, followed by hot oil quenching at 80℃. The first tempering step was carried out at 300℃ for 60 minutes followed by 80℃ hot oil quenching. The samples were heated to 860℃, held there for 60 minutes followed by a hot oil quenching at 80℃ again. The final tempering step was at a higher temperature of 600℃ for 30 minutes. The samples were hot oil quenched to 80℃ finally.

Below, in Figure 8, Time-Temperature graphs of these two processes are drawn:

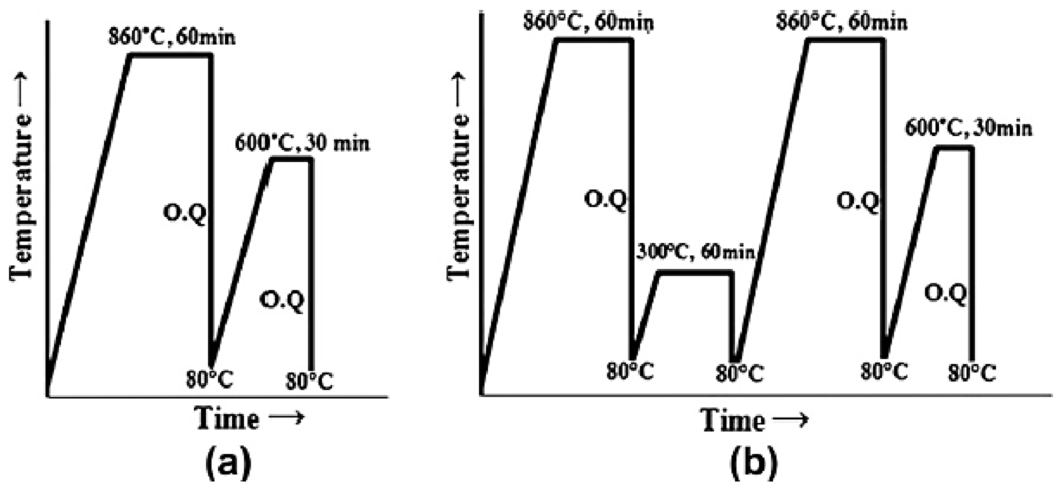

Figure 8: Time-Temperature lines of heat treatment processes: (a) CQT and (b) DQT [12].

To investigate the effects of double quenching and tempering, in the DQT procedure as described above, the second tempering step was carried out at 600℃ for 30 minutes so the only difference here is that there is an additional 300℃ for 60 minutes tempering step. Mechanical tests of these samples were done in Sanij, K. et. al. work [12], and the results were given in Table 3.

Table 3. Variation in mechanical properties and prior austenite grain size as a function of heat treatment processes [12].

Heat Treatment	0.2% yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction in area (%)	Impact Energy (J)	Hardness (RC)	Grain size (µm)
CQT	975	1136	12.8	47	61	33	11.4
DQT	1000	1185	17	54	79	32.25	5.8

Here, from the table, it can be seen that the samples produced following the DQT processing route exhibited improved mechanical properties with only a small drop in the hardness value compared to the parts produced via CQT route. Regarding the toughness of the samples, a 29.5% increase was observed in the absorbed impact energy values. This is also accompanied by increase in the UTS and the yield strength of these samples. In Figure 9, engineering stress and strain graphs of these samples also show this property enhancement. This improvement is rationalized to be due to the austenite grain refinement (nearly 50% increase) that was observed in DQT samples. Below, Figure 10 shows the prior austenite grain boundaries present in the samples.

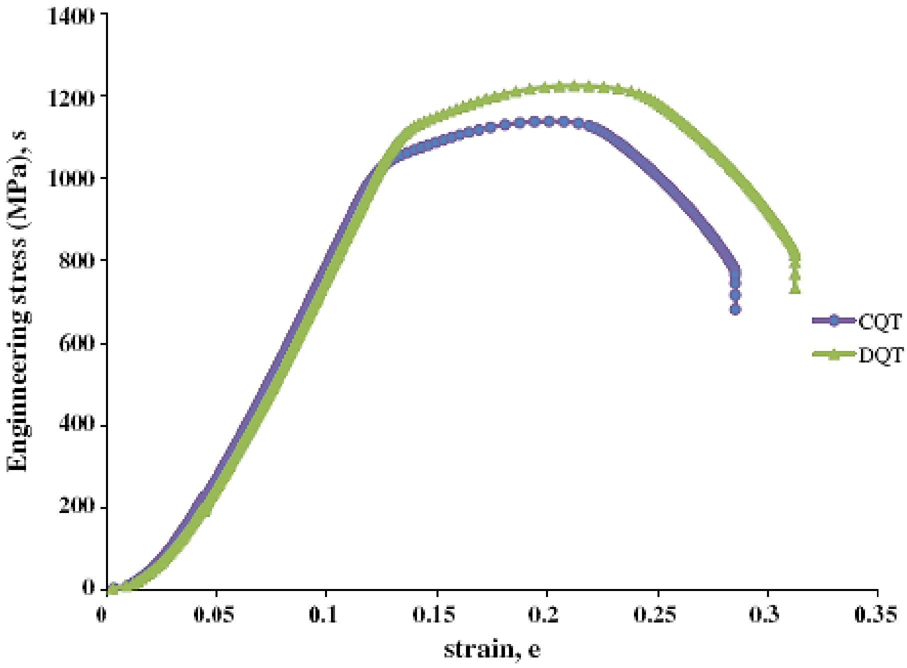

Figure 9. The engineering stress–strain behavior of CQT and DQT specimens [12].

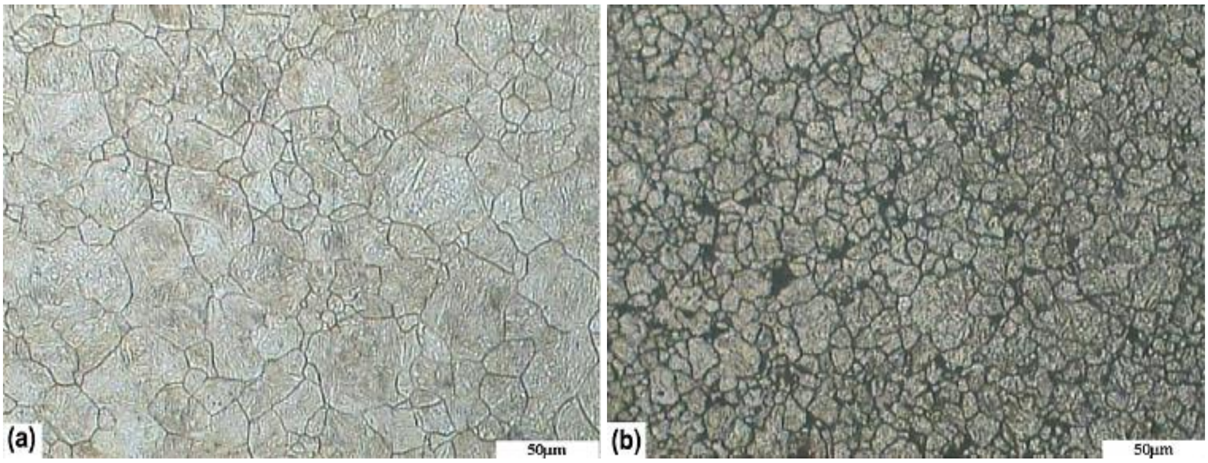

Figure 10. The prior austenite grain boundary networks developed from the specimens treated as: (a) CQT and (b) DQT heat treatments [12].

Here, packets of martensitic laths can be seen in both of the light microscopy images. Table 3 shows the austenite grain size measurements and from these results it is apparent that in DQT the austenite grain size of the specimen is 50% finer than that of the CQT samples. SEM analysis of these samples is also consistent with this observation as the packet sizes of the laths can clearly be seen as decreasing comparing CQT samples with DQT samples in Figure 11 [12].

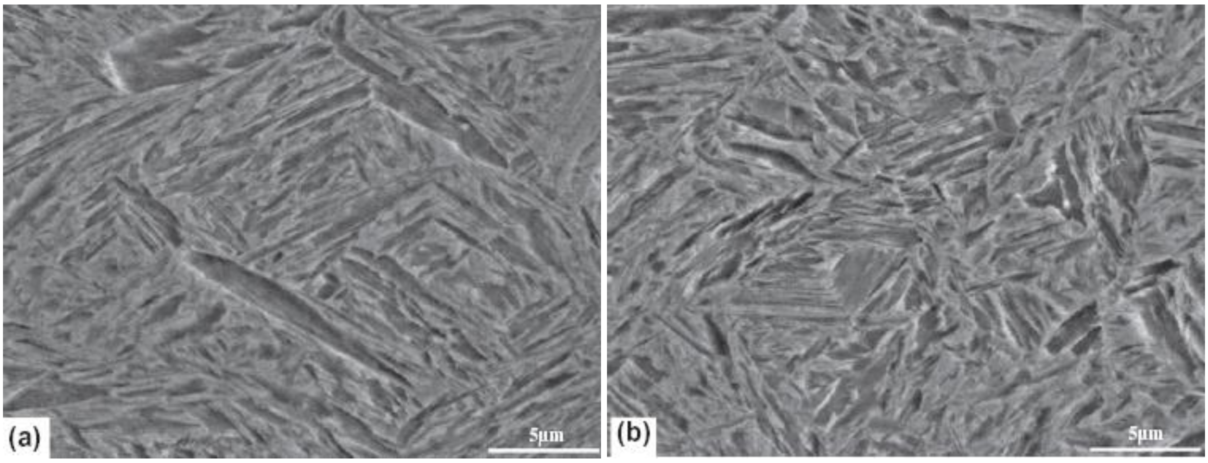

Figure 11. SEM micrographs showing the martensitic packets in the heat-treated specimens: (a) CQT and (b) DQT conditions [12].

It is, therefore, proved that grain boundaries are beneficial in low alloy martensitic steels as they retard cleavage crack propagation, improving impact toughness and also ductility in DQT processing samples. In Sanij, K. et. al. report, austenite grain size refinement phenomenon was associated with the precipitation of fine carbides in martensitic matrix during the first tempering step in DQT [12]. These carbide particles act as nucleation sites for austenite grains and, thus, grain refinement of austenite phase takes place.

EDS line scan analysis was done on the samples to observe the behavior of troublemaker impurity atoms mentioned as elements that cause temper embrittlement in section 1.3.1 in this text such as Sulfur and Phosphorus. The results indicate that S and P concentrations were higher near grain boundaries for both of the CQT and DQT samples. However, as increasing grain boundary area in DQT process means a more uniform distribution and dispersion of these impurities, the grain boundary segregation level was significantly lowered compared to CQT condition. Therefore, excess amounts of S and P impurities near grain boundaries were decreased and the impact toughness was increased in DQT heat-treated samples [12].

In another report, Chuang, J.H. et. al. (1998), investigated crack growth behavior of austempered and tempered AISI 4140 grade steel samples [13]. Although this work is about crack propagation under cyclic loading, it carries valuable information about how tempering (or austempering) temperature affects the toughness of a material. Below, along with heat treatment procedures, mechanical properties of these samples were tabulated.

Table 4. Heat treatment procedures and resultant mechanical properties of heat-treated specimens [13].

Specimen ID	Heat Treatment Procedure	UTS (MPa)	YS (MPa)	Elongation (%)	Hardness (HrC)
QT230	850°C/40 min + oil quench + 230°C/1 h tempered	1899	1533	12.0	52.4
QT300	850°C/40 min + oil quench + 300°C/1 h tempered	1720	1528	11.9	50.0
QT370	850°C/40 min + oil quench + 370°C/1 h tempered	1614	1470	12.3	46.6
QT450	850°C/40 min + oil quench + 450°C/1 h tempered	-	-	-	43.7
QT550	850°C/40 min + oil quench + 550°C/1 h tempered	-	-	-	39.6
AT230	850°C/40 min + 230°C/1 h austempered	1823	1568	12.5	52.3
AT300	850°C/40 min + 300°C/1 h austempered	1701	1474	13.0	50.1
AT370	850°C/40 min + 370°C/1 h austempered	1308	1116	16.0	41.5

Here, QT230 - AT230 and QT300 - AT300 specimen pairs gave very close test results in terms of UTS, yield strength and percent elongation as well as hardness as reported in Chuang, J.H. et. al. discussion. This trend could not be observed between QT370 and AT370 pair as austempering at higher temperatures (370°C) reduced the sample's hardness and strength values and increased its percent elongation substantially. As previously shown in Figure 2, the martensite transformation (Ms temperature) of 4140 steel is approximately 350°C. Thus, austempering below 350°C could not achieve 100% bainitic structure [13].

Toughness values of these samples were also tested by Charpy impact test in Chuang, J.H. et. al. work and the results are given in Figure 12. For the conventional QT samples tempered between 230–370°C range, it is apparent that there is a drop in their toughness values. This was interpreted by Chuang as the tempering range coincides with the temper embrittlement range of AISI 4140 steels, the specimens were weak against impact loading types. While QT samples went through a temper embrittlement event, AT samples did not which prevented a toughness drop in these samples [13]. Thus, if one was to utilize a tempering process in this temperature range it would be wise to apply austempering rather than a conventional tempering procedure to avoid temper embrittlement.

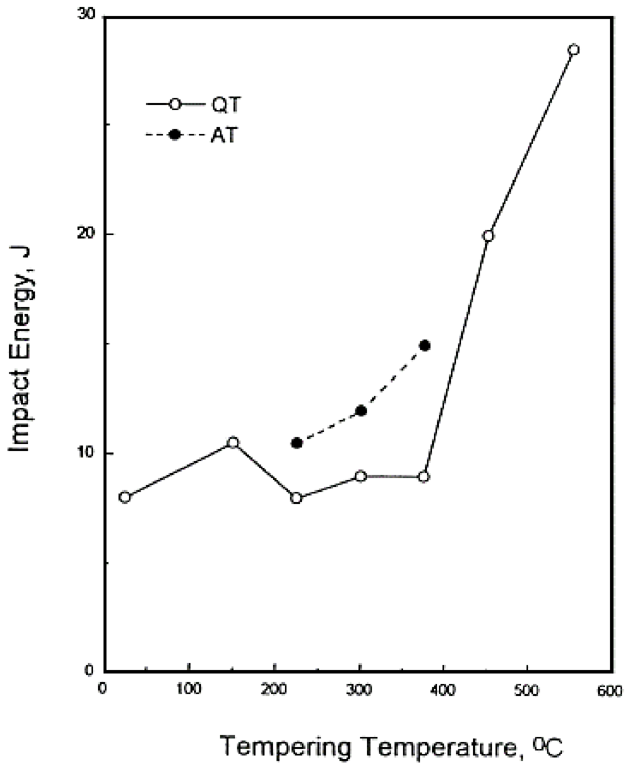

Figure 12. Charpy impact values of 4140 specimens according to tempering temperature [13].

Figure 12 also shows that as the tempering temperature increases impact energies of samples also increase in the range of 370-550°C. Thus, along with double quenching and tempering route as suggested by Sanij, K. et. al., increasing the tempering (or austempering) temperature is also proved to increase toughness values of 4140 steel parts [12][13]. However, to obtain maximum toughness, 4140 steel's heat treatment limits should be tested by performing processing routes such as full annealing.

In 2014, Abdel Wahab, A. et.al., conducted a series of experiments involving tempering, full annealing and stress relief annealing to observe the effects of heat treatment on the fracture toughness of AISI 4140 grade steel specimens [14]. Below, the heat treatment procedures of this work are given:

- A: Stress relief at 500, 600 and 660°C for 30 minutes; air cooling.
- B: Full annealing at 800, 860 and 900°C for 30 minutes; furnace cooling.
- C: Austenitizing at 850-870°C for 30 minutes followed by oil quenching; tempering at 200, 370 and 540°C for 1 hour; air cooling.

Heat treated specimens were tested only by tensile testing and their fracture toughness values were calculated from these results employing a semi-empirical relationship developed by Hahn-Rosenfield. The equation was given as:

$$K_{IC} = \sqrt{\frac{0.05}{3} E \sigma_{YS} \epsilon_F n^2} \quad (1)$$

where E is the modulus of elasticity, σ_{YS} is the yield stress, ϵ_F is true strain at fracture of a smooth tensile bar and n is the strain hardening exponent. Calculated K_{IC} values of the samples are shown below in Table 5 and according to these data a Fracture Toughness-Temperature graph was constructed and shown in Figure 13 [14].

Table 5. Calculated K_{IC} values of heat-treated samples and as received sample [14].

Heat Treatment	Heat Treatment Temperature (°C)	K_{IC} (MPa$\sqrt{m}$)
As Received Condition	25	48
A: Stress Relief	500	51.4
	600	61.5
	660	73
B: Full Annealing	800	117
	860	151
	900	123
C: Quench and Tempering	200	32.7
	370	42.4
	540	66

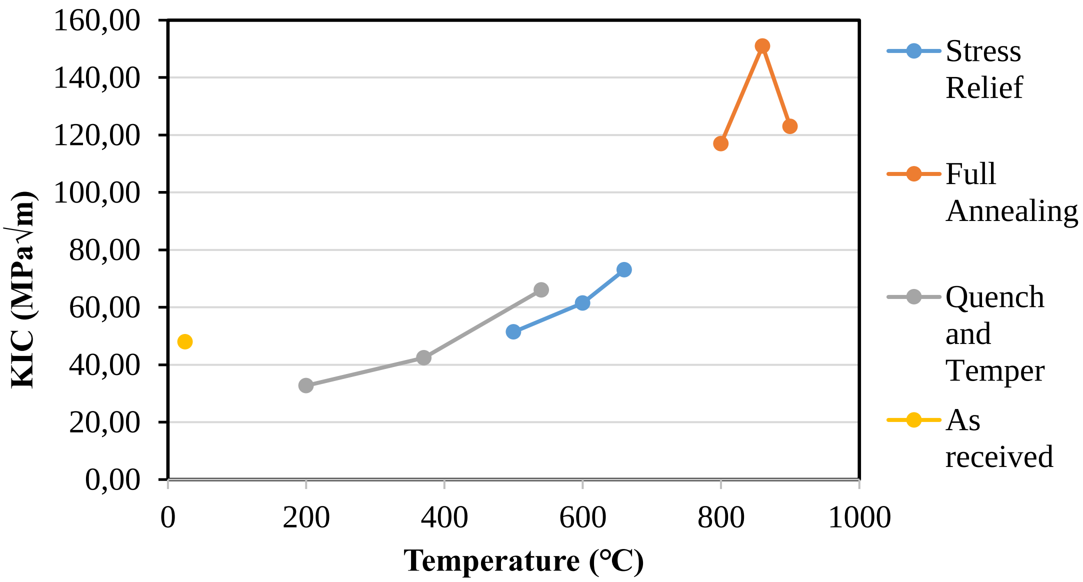

Figure 13. Fracture Toughness-Temperature graph of heat-treated samples [14].

Optical metallography results showed that the microstructure of the as received specimen was consisting of lath martensite along with some amount of ferrite similar to stress relieved specimens which consist of slightly larger ferrites. The ferrite content in stress relieved specimens increased with increasing process temperature. This outcome was interpreted as being the reason for the incremental increase in toughness values of stress relieved specimens. Fully annealed specimens yielded a typical ferrite and pearlite phases in their structures with increasing pearlite content with increasing temperature. Quenched and tempered specimens exhibited cementite and ferrite formation characterized by cementite plates in ferrite matrix. At 200℃, at martensite grain boundaries Fe_2C carbide precipitation event takes place [14].

According to these results, as the full annealing temperature is between 800℃ and 860℃ the fracture toughness of the specimens increases as the processing temperature increases. However, above this range, fracture toughness decreases with increasing temperature as it can be seen from Figure 13. The reason for this decrease was the extensive softening (lowering strength and increasing ductility) of the steel parts which retards the ability of the material to absorb energy before rupturing. The effect of this over-softening can be seen in Figure 1 also.

Further literature search in material database systems served great amount of data about the toughness of 4140 steels heat treated with various routes. A number of different trial sets were done on 4140 steel specimens having various diameters in the mentioned databases and to ensure the similarity between the samples only the ones with 1inch diameters were selected for this investigation. Below, these screened heat treatment procedures are listed.

From Figures 14 and 15, it is apparent that as the UTS or Hardness values of the specimens decrease, their impact toughness values increase. With the help of Table 6, this trend can also be translated into “as the processing temperature increases for a particular heat treatment procedure, toughness of the material increases”. This trend was already confirmed by Abdel Wahab, A. et.al. in their work [14]. The only exception for this phenomenon occurs in the range of 200-370°C (samples 1-2 and 7-8) where temper embrittlement for the steels takes place as previously confirmed by Chuang, J.H. et. al [13].

Another interesting finding from these data can be interpreted by comparing sample pairs 1-6, 2-8, 3-10, 4-12, 5-14. Comparing these samples, e.g. 5-14, while toughness values are close to each other there is a deviation in UTS and hardness values. While sample 5 is stronger, sample 14 is harder. So, for the sake of energy efficiency, applying only a tempering process on an oil quenched sample would be the wise choice. The only reason for picking the 14^{th} route (normalizing prior to tempering) would be for obtaining a relatively harder part.

From the graphs, it can be deducted that tempering below 600°C does not yield a toughness value as high so it does by going above 600°C. Combining this data with the one from Abdel Wahab, A. et.al. report [14], keeping the processing temperature between 600-900°C gives the maximum toughness ability to AISI 4140 steel. In this temperature range, utilizing double quenching and tempering for maximum toughness along with retarded temper embrittlement or utilizing a full annealing around 860°C results in the maximum amount of toughness for AISI 4140 steel [12][14][15].

Table 6. Test results of heat-treated specimens (AISI 4140; 1inch diameter, round) [15].

	Heat Treatment Procedure	**Brinell Hardness**	**IZOD Impact (J)**	**UTS (MPa)**
1.	Oil quenched, 205°C temper	520	14	1795
2.	Oil quenched, 315°C temper	455	9	1585
3.	Oil quenched, 425°C temper	385	22	1380
4.	Oil quenched, 540°C temper	320	61	1140
5.	Oil quenched, 650°C temper	255	110	931
6.	Normalized at 870°C, reheated to 845°C, oil quenched, 205°C temper	578	15	1965
7.	Normalized at 870°C, reheated to 845°C, oil quenched, 260°C temper	534	11	1860
8.	Normalized at 870°C, reheated to 845°C, oil quenched, 315°C temper	495	9	1725
9.	Normalized at 870°C, reheated to 845°C, oil quenched, 370°C temper	461	15	1595
10.	Normalized at 870°C, reheated to 845°C, oil quenched, 425°C temper	429	28	1450
11.	Normalized at 870°C, reheated to 845°C, oil quenched, 480°C temper	388	46	1295
12.	Normalized at 870°C, reheated to 845°C, oil quenched, 540°C temper	341	65	1150
13.	Normalized at 870°C, reheated to 845°C, oil quenched, 595°C temper	311	94	1020
14.	Normalized at 870°C, reheated to 845°C, oil quenched, 650°C temper	277	115	896
15.	Normalized at 870°C, reheated to 845°C, oil quenched, 705°C temper	235	135	807

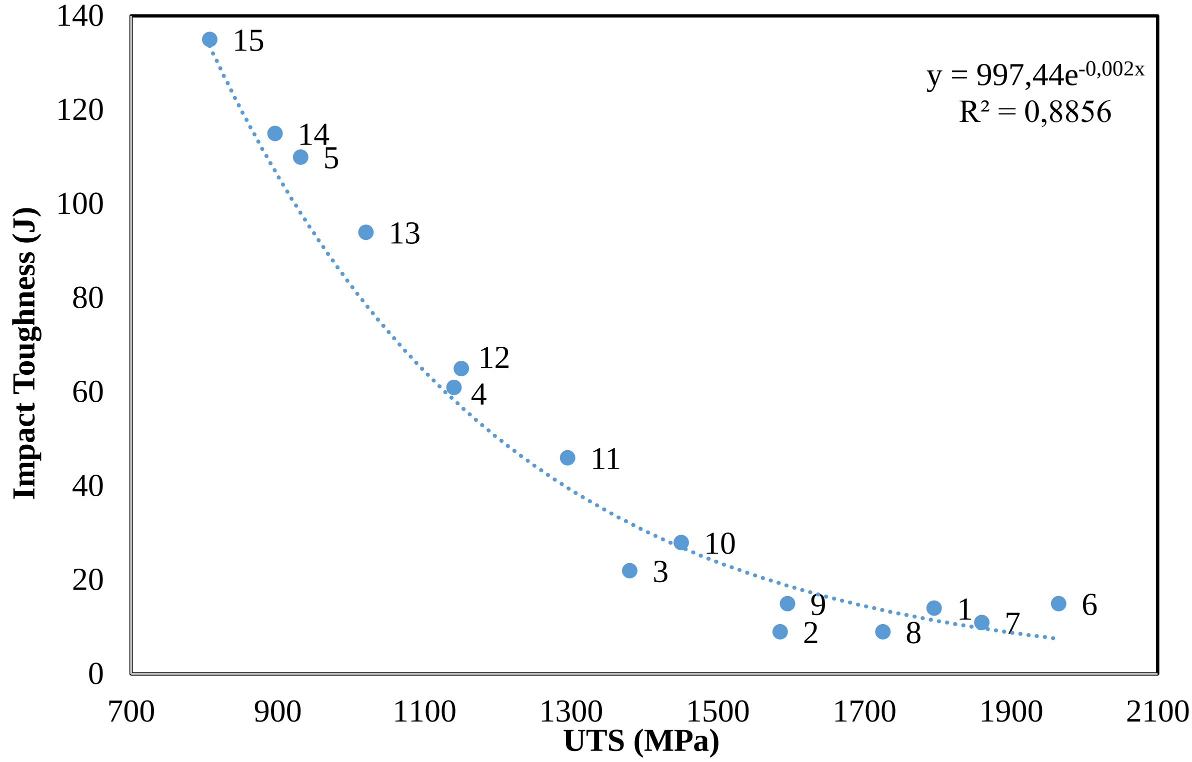

Figure 14. UTS vs Impact Toughness graph of the specimens [15].

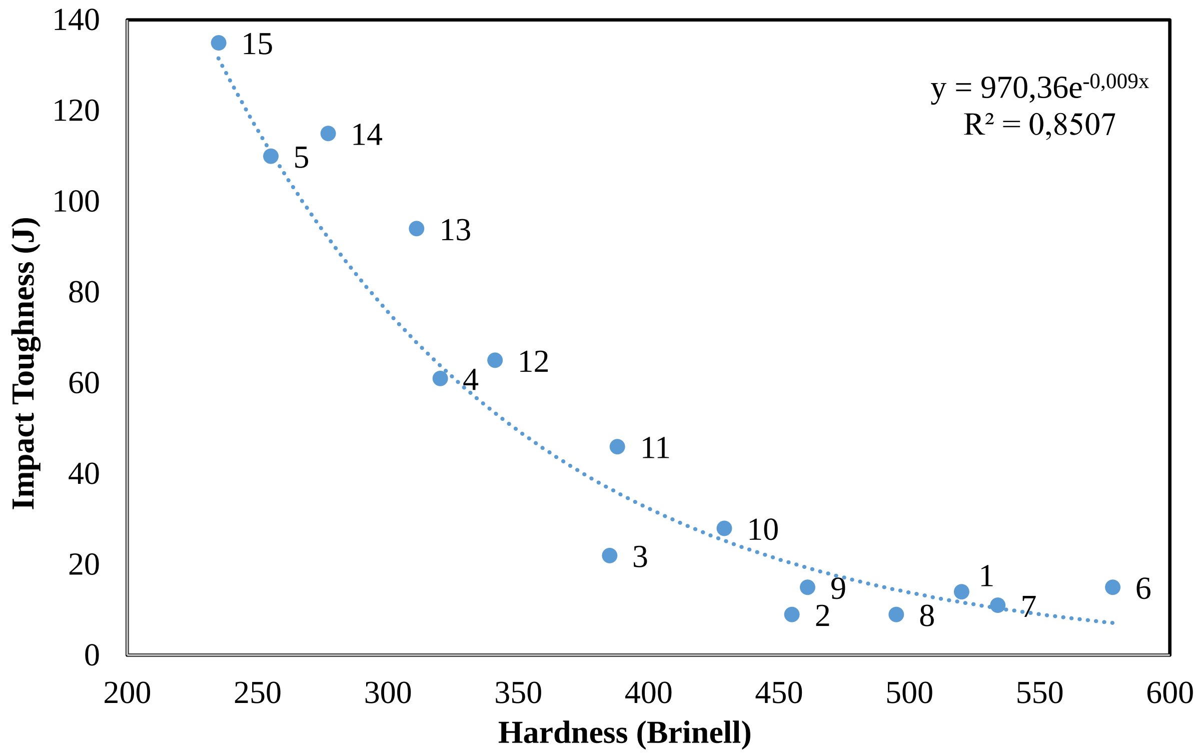

Figure 15. Hardness vs Toughness graph of the specimens [15].

3. Conclusion & Procedure Proposal to Achieve Maximum Toughness

In this writing, a number of reports were investigated to observe and compare the effects of various heat treatment procedures on toughness of commercially available AISI 4140 low alloy steel. In Sanij, K. et. al. study, double quenching and tempering technique was found to be improving the materials toughness by 29.5% compared to conventional quenching and tempering process [12]. In Chuang, J.H. et. al. work, increasing tempering temperature and employing austempering process were found to be beneficial in order to increase toughness and decrease temper embrittlement [13]. In Abdel Wahab, A. et.al. report, increasing processing temperature was once again proved to be beneficial up to a point. Especially in full annealing heat treatment process the test samples yielded the highest toughness values when treated in the range of 800-870℃. However, going above this range, due to over softening, resulted in a decrease in the toughness of the samples [14]. The data obtained from a materials properties database showed that there is no significant toughness change between applying a normalizing step prior to tempering and utilizing only a tempering process on an as received specimen (when the tempering temperatures are the same) [15]. While making these points, an effort has been put into keeping all the variables affecting the results constant other than heat treatment procedures for the purpose of observing only the effects of these procedures. Double quenching and tempering in the range of 600-900℃ as well as full annealing at around 860℃ were found to be resulting with the highest toughness values.

In this text, combining all the reports investigated, a proposal can be made by employing the maximum toughness approach: Double quenching and tempering process with an increased secondary temper temperature alongside with a decreased tempering time. As mentioned earlier, double quenching and tempering method proved itself in increasing toughness and decreasing the susceptibility to temper embrittlement by grain refinement mechanism. Increasing the second tempering step’s holding temperature may increase the toughness even more by increasing ductility as observed in both Abdel Wahab, A. et.al. work, in Chuang, J.H. et. al. report and in the data obtained from the material database. However, the working principle of this double quenching and tempering process is based on the grain refinement event and this would be inhibited by the increase in temperature as the rate of grain growth increases. Additionally, the mobility of the impurities would increase and their segregation to grain boundaries would be faster/easier. These two negative effects of increasing tempering temperature may be avoided by decreasing the holding time without affecting this step’s advantages because as it was already mentioned in Chapter 1.3.1., in tempering, holding temperature is much more critical than holding time. Thus, while ductility increases as a result of the higher holding temperature, there is no sufficient time for excessive grain growth and impurity segregation to the grain boundaries. As a result, the toughness increases without promoting temper embrittlement or excessive grain growth. To see if this proposed method would yield higher toughness values than full annealing at around 860℃, however, a series of experiments should be done with varying second temper holding temperature and time.

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