Effect of Temperature on the Toughness of Locally Manufactured Low Alloy Steel SUP9 Used for Manufacturing Leaf Springs

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ABSTRACT

The effect of heat treatment on locally manufactured low alloy steel grade SUP9 most frequently used in making leaf springs for automobiles was studied. While for determination of toughness and hardness Charpy impact testing machine and Rockwell hardness tester were used. The cryogenic test temperatures were achieved by soaking the samples in liquid nitrogen and temperature was measured using digital thermometer capable of reading the temperature from -40-200°C. Hardening, tempering and austempering treatments were conducted using muffle furnace and salt bath furnace. After heat treatment samples were quenched in oil.

The results of present work confirmed that toughness and hardness are inversely related with each other and are highly dependent on the type of heat treatment employed. Highest toughness was measured after austempering at 450°C. Effect of test temperature revealed that toughness of the samples increased significantly with decreasing temperature. DBTT (Ductile to Brittle Transition Temperature) of the austempered samples was observed at -10°C, whereas, that of tempered samples could not be determined.

Based on the test results authors wish to recommend the 600°C tempering temperature in place of 450°C where normally tempering is practiced in Alwin industry Karachi during manufacturing of leaf spring.

Key Words: Hardening, Temperimg, Austempering, Toughness, Ductile-Brittle Transition Temperature.

1. INTRODUCTION

Materials are continuously explored and developed for attaining best mechanical properties for almost uncountable number of applications in the field of engineering. Most solicited properties in the components where performance is of prime importance include improved durability, sufficient damage tolerance, efficiency, reliability, ease of manufacture and cost effectiveness [1]. In order to support the load of vehicle, leaf springs are commonly used in automobiles as suspension components. Apart from that, they are also utilized as the struts to anchor the axles to the vehicle during the starting and braking torque and

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other sudden load fluctuations [2]. The efficiency and performance of leaf spring depends on the loading conditions of a commercial vehicle and on the smoothness and or roughness of the roads on which they are being driven. Mechanical properties in general and toughness in particular is governed by the factors including, chemical composition of an alloy, processing, microstructure, operating temperature and loading rate [3-5]. On the other hand, introduction of engineering notches, increase in part thickness and lower operating temperatures are found to be detrimental to ductility and toughness of the material [6]. Therefore, in present work, effect of various heat treatments on low alloy steel (SUP9) on the mechanical properties and microstructure were studied and an attempt has also been made to determine the ductile to brittle transition temperature using two widely recognized methods i.e. rapid loss in toughness and fracture mode.

2. EXPERIMENTAL WORK

2.1 Material

A rectangular bar of 15x12mm^2, normally used for manufacturing of leaf spring was received from Landhi Engineering Industry, Karachi. The chemical composition of material used in the present work is given in Table 1. Optical spark emission spectrometer (Model: MAXX-LMM14) was used for elemental analysis of the SUP9 leaf spring steel.

2.2 Sample Preparation

A total number of forty one specimens of 10x10x40mm^3 for Charpy impact test were machined using abrasive cutter and lathe machine. Standard cutter was used for machining the notch of 2.5mm depth at 45^o. During machining water was used as coolant to avoid excess heating of samples. After manufacturing required number of specimens, the unique number was stamped to each sample on their ends. To smooth the specimen surface and remove micro surface stress raiser samples were roughly polished using 500μm emery paper.

TABLE 1. CHEMICAL COMPOSITION OF SUP9 LEAF SPRING STEEL

Element	Weight (%)	Element	Weight (%)	Element	Weight (%)
C	0.271	Cr	0.867	Nb	0.003
Si	0.265	Mo	0.048	V	0.004
Mn	0.762	Al	0.004	Ti	0.001
P	0.012	Cu	0.197	Fe	97.167
Ni	0.213	Co	0.025		

2.3 Heat Treatment

In present work following heat treatment processes were applied to each group of samples to investigate their effect on performance of the leaf spring. The details of the heat treatment processes are given below.

2.4 Hardening Followed by Tempering

For hardening sixteen specimens were austenitized in preheated muffle furnace set at 900^{o}C. The specimens were soaked for 20 minutes at that temperature and quenched in oil bath. After hardening, surface hardness was measured and then one set of eight specimens was tempered at 480^{o}C and other set of eight specimens at 600^{o}C. At each tempering temperature samples were soaked for 3 hours and subsequently quenched in oil. Samples hardened followed by tempering at 480 and 600^{o}C were identified as HT_480, HT_600 respectively.

2.5 Austempering

For austempering twenty four specimens were heated for 20 minutes above the upper critical temperature (i.e. 900^{o}C) and a batch of eight samples were then transferred into salt bath set at temperatures ranging from 350, 400, and 450^{o}C for 2 hours and quenched in oil, to obtained lower, medium and upper bainite microstructure respectively. Specimen austempered at 450, 400 and 350^{o}C were identified as AT_450, AT_400 and AT_350 respectively.

2.6 Hardness Measurement

After heat treatment, hardness of each sample was measured using Rockwell Hardness testing machine with diamond indenter. Minor and major loads used during Rockwell hardness testing were 10 and 160kg respectively.

2.7 Toughness Measurement

Toughness was measured using Charpy impact testing machine at temperatures ranging from 30, 20, 10, 0, -5, -10, and -20°C. Cryogenic test temperatures were attained by quenching the samples in liquid nitrogen for 20 minutes. Immediately after soaking time samples were placed at working table of the Charpy impact tester. The surface temperature of samples was continuously monitored using the digital thermometer capable of measuring the temperature ranging form -40-200°C. As soon as the specimen reached the desired surface temperature the impact test was conducted just releasing the pendulum already set at standard lift angle.

2.8 Fractography

In order to determine the mode of fracture after impact test the surface of fractured specimens were examined using digital camera.

2.9 Metallography

To examine the microstructure one sample from each category was prepared using standard metallographic procedure. After mounting and grinding specimens were polished using slurry of aluminum powder. Polished specimens were finally etched in Nital solution containing 2% HNO_3.

3. RESULTS AND DISCUSSION

The results pertaining to the effect of different heat treatment conditions and microstructure on hardness, toughness and DBTT of low alloy steel is extensively evaluated in present section.

3.1 Hardness

Effect of heat treatment on hardness is shown in Table 2. Table 2 indicates and confirms that hardness of the steel is strongly dependent on the type of heat treatment. Maximum hardness is achieved with hardening followed by tempering at 480°C, whereas, material attained minimum hardness when it is austempered at 450°C.

About 20% decrease in hardness with increasing the tempering temperature from 480-600°C is observed. With increasing tempering temperature decreasing trend in hardness is well documented in literature [7-9] and is basically attributed with morphological change in martensite lathes. Fig. 1 (a-b) clearly exhibit the coarsening effect of martensite laths with increasing the tempering temperature from 480-600°C.

Effect of austempering temperature on steel hardness indicates that steel becomes harder with decreasing the temperature. This is basically due to transformation of austenite into bainitic structure, since bainite is harder than pearlite. The maximum hardness by austempering process is attained at 350°C where lower bainite is expected to transform and minimum hardness is obtained at 450°C where upper bainite is likely to form. Transformation of austenite into upper, medium and lower bainite in present case can be witnessed from microstructures shown in Fig. 2. Literature [10-11] pertaining to properties and transformation of bainite indicates that upper and lower bainite resembles the features of fine pearlite and martensite respectively. This means that hardness of lower and upper

TABLE 2. EFFECTS OF HEAT TREATMENT ON HARDNESS OF LOW ALLOY SPRING STEEL

Heat Treatment Condition	Rockwell HRC No.
HT_480	42.68
HT_600	34
AT_450	28.18
AT_400	34.44
AT_350	37.93
AR	22.75

bainite would be close to that of martensite and pearlite respectively. Interestingly hardness values of steel austempered at 350 and 450°C obtained in present work is very close to the hardness measured from the specimens which were hardened and tempered and in as received condition respectively.

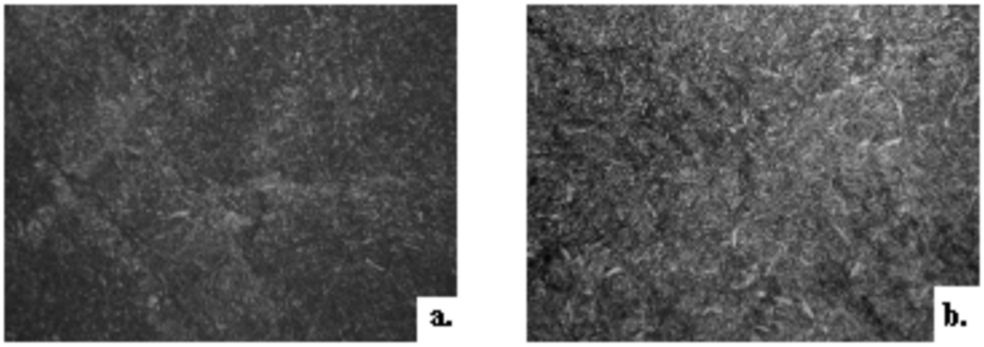
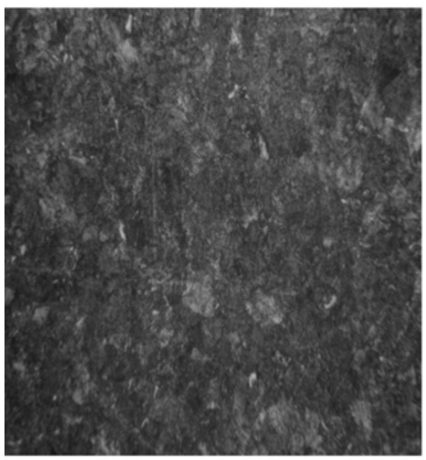


FIG. 1. MICROGRAPHS RECORDED AFTER TEMPERING AT (a) 480°C AND (b) 600°C X400



(a) PEARLITE IN AS RECEIVED SAMPLE

(b) UPPER BAINITE IN A SAMPLE AUSTEMPERED AT 400°C

(c) MEDIUM BAINITE IN A SAMPLE AUSTEMPERED AT 350°C

(d) LOWER BAINITE IN A SAMPLE AUSTEMPERED AT 300°C

FIG. 2. EFFECT OF AUSTEMPERING TEMPERATURE ON BAINITE MORPHOLOGY X400

3.2 Toughness

Effect of heat treatment on Charpy impact toughness is given in Table 3. Table 3 indicates that toughness of the steel either decreases or increases depending on the type of heat treatment applied and microstructure i.e., upper, medium and lower bainite as has been exhibited in Fig. 2.

In case of hardening followed by tempering toughness increases with increasing the tempering temperature.

TABLE 3. EFFECT OF HEAT TREATMENTS ON TOUGHNESS OF LOCALLY MANUFACTURED LEAF SPRING STEEL

Heat Treatment Condition	Toughness (Nm)
HT_480	0.953
HT_600	2.546
AT_450	1.4631
AT_400	0.854
AT_350	0.370
AR	2.103

About 62.5% increase in toughness is obtained just by increasing the tempering temperature from 480-600^{o}C. The basic reason behind this significant increase in toughness is the decrease in hardness values.

Incase of austempering decreasing trend in toughness values with decreasing austempering temperature is resulted. The basic reason behind decreasing trend in toughness is the transformation of austenite into upper bainite to lower bainite. Since lower bainite is too harder than upper bainite therefore variation in toughness are encountered respectively.

The increasing trend of toughness either in case of tempering or austempering treatments is quite in agreement with the decreasing trend of hardness shown in Table 2. Furthermore improvement in toughness with increase in tempering and austempering temperature is fully supported with the published data in literature [12-15]. The more

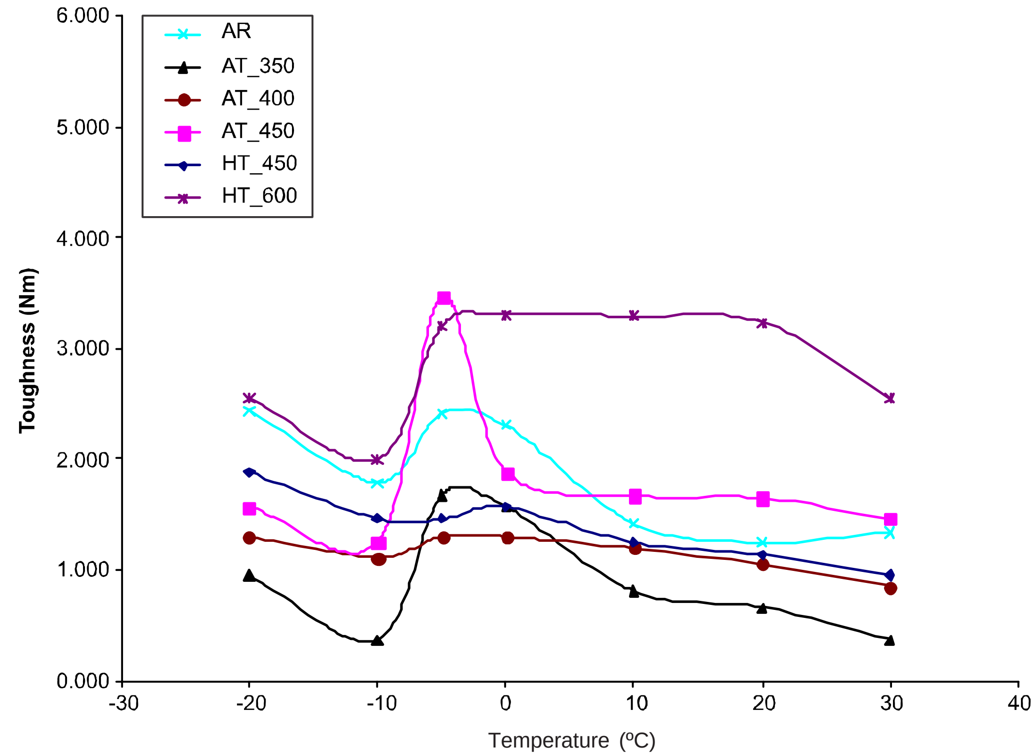


FIG. 3. EFFECT OF TEST TEMPERATURE (ºC) ON CHARPY IMPACT TOUGHNESS OF LOW ALLOY STEEL

interesting thing that can be deduced from the hardness and toughness results shown in Tables 2-3, is that among the parameters which governs the toughness of the material microstructure play significant role than hardness. Tables 2-3 indicates that hardness of steel hardened followed by tempering at 600°C and steel austempered at 400°C is approximately same, while their toughness is quite different. The significant difference of about 66% in toughness between austempered and tempered steel strongly attest the important role of microstructure in tuning the mechanical properties. Similarly, wide difference in toughness values in between steel austempered at 450°C and steel tempered at 600°C further confirms the critical role of microstructure though former steel is too soft as compared to latter.

Effect of test temperature on toughness of low alloy steel was further studied. The results are shown in Fig. 3. Fig. 3 indicates almost slightly decreasing trend in toughness with increasing the temperature. The steel austempered at 450 and 350°C almost tailors similar fashion of toughness variation except that former has higher toughness values than latter.

Similarly steel tempered at 450 and 600°C resembles the toughness variation trend with change in temperature likewise austempered steels except two contrasts. In case of steel tempered at 450°C the toughness value remained almost intermediate; secondary the increasing trend in toughness with decreasing temperature continued up to -20°C. Whereas the austempered steels had shown substantial increase in toughness between 0 and -5°C and significant decrease between -5 and -10°C. The toughness variation trend of steel tempered at 600°C indicated that toughness value increased significantly with decreasing the test temperature from 30-20°C. Moreover no further change in toughness is resulted till the -5°C. Beyond -5°C the toughness value decreased sharply.

As has been discussed earlier that microstructural changes, which occur due to different heat treatments also influence the mechanical properties such as toughness and hardness of the low alloy steel used to manufacture leaf spring.

The increasing trend of toughness with decreasing temperature is principally totally against the normally believed principle and shows an artifact. It is widely accepted and experimentally proved that toughness increases with increasing temperature and vice versa. Therefore it is very hard to support the findings of present work with published work. However the possible reasons that could be argued behind this indirect relationship between toughness and temperature are as follows.

Firstly the contraction of micro cracks would have happened with decrease in temperature due to which the detrimental effect of local stress concentration points is most probably reduced. Thus resistance to fracture is increased with decreasing the temperature, because rate of crack propagation has direct relation with temperature.

Secondly the MnS present in the grain boundaries is supposed to liquefy the grains at higher temperatures and adds brittility in the grains at normal temperature. With decreasing temperature the detrimental effect of MnS phase eliminates.

Based on above postulations the increasing trend of toughness with decreasing temperature can be defended to some extent. The validity of these postulations need a detailed surface analysis of the fracture surface under scanning electron microscope.

At extremely low temperatures (i.e. -10 to -20°C) the significant drop in toughness values of austempered steel may be attributed with ductile to brittle transition characteristic of the material.

3.3 Ductile to Brittle Transition Temperature

For the DBTT the toughness values and fracture texture at the test temperatures viz. 30, 20, 10, 0, -5, -10, and -20^{o}C was used. The evaluation of transition temperature in present study is made on the basis of most widely recognized methods including rapid loss in toughness and fracture mode evaluated by considering the significant variation in toughness.

Generally three approaches are used for determination of ductile to brittle transition temperature. The first approach is based on the determination of a temperature point or range where sharp decrease in toughness takes place. Some steels do not show sharp change in toughness with temperature but rather show significant difference in failure mode (i.e. cleavage or ductile) at transition temperature. For this examination of fracture surface of specimen tested at different temperatures is made and then percentage of ductile and brittle fracture is estimated. The temperature at which fracture surface shows 50% ductile (i.e. fibrous) and 50% cleavage (crystalline) is regarded as FATT (Fracture Appearance Transition Temperature). Other criteria used for determination of ductile to brittle transition temperature is to use an arbitrary energy absorbed. In this case 20J an arbitrary value for low strength ship steels is used.

In present work first two approaches were attempted to determine ductile to brittle transition temperature. Fig. 3 depicts that steel tempered at 450^{o}C (HT_450) do not exhibit sharp toughness variation, while steel tempered at 600^{o}C (HT_600) and austempered steel samples AT_350 and at_450 exhibit marginal drop in toughness value at -10^{o}C. Therefore no one test temperature can be regarded as ductile to brittle transition temperature for steel tempered AT 450^{o}C (HT_450), whereas, -10^{o}C could be assumed as DBTT according to first criteria for the rest of the samples. The slight increase in toughness below transition temperature (i.e. -10^{o}C) may be due to error in measuring the test temperature.

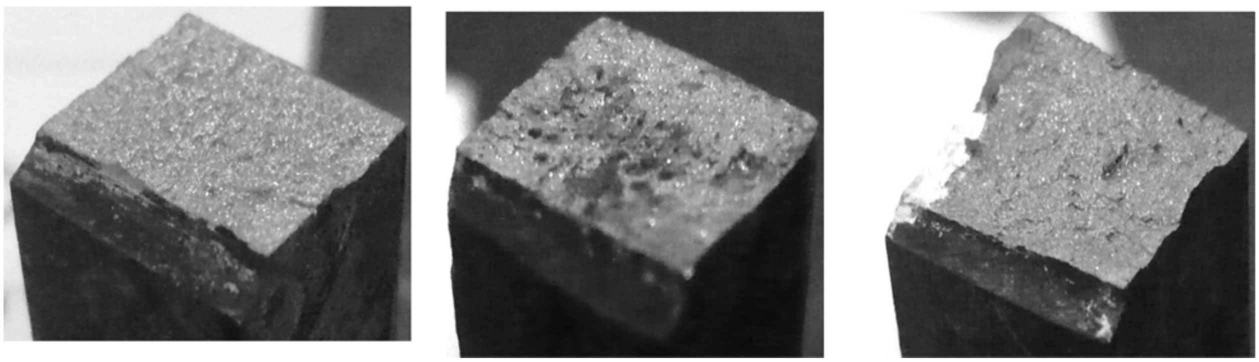
To validate the transition temperature of austempered steel samples and to determine the transition temperature of tempered steel, examination of fracture surfaces was made. For this fracture surfaces of tempered (HT_600) and austempered specimens at 30, -5 and -10^{o}C were examined. Whereas fracture surfaces of steels tempered at 450^{o}C (HT_450) at all test temperature were studied. Fracture surfaces of austempered steel samples are shown in Figs. 4-5 and that of tempered steels are shown in Figs. 6-7.

Figs. 4-5 clearly shows the effect of temperature on fracture mechanism of AT_450 and AT_350 austempered steel respectively. Fig. 4 (a and c) very clearly depicts the crystalline failure at 30 and -10^{o}C whereas Fig. 4(b) illustrates the fibrous fracture at -5^{o}C of AT_450 austempered steel. Similarly fracture surfaces shown in Fig. 5 indicate that AT_350 austempered steel is fractured by crystalline mechanism when test temperature is set at 30 and -10^{o}C and fibrous at -5^{o}C.

The DBTT of austempered steel can therefore, be conceived from fibrous and crystalline fracture surfaces at -5 and -10^{o}C respectively. Thus it would be right to conclude that DBTT of austempered steel most probably exist at -10^{o}C. Sharp change in toughness value and fracture surface appearance at -10^{o}C temperature validates and support to each other.

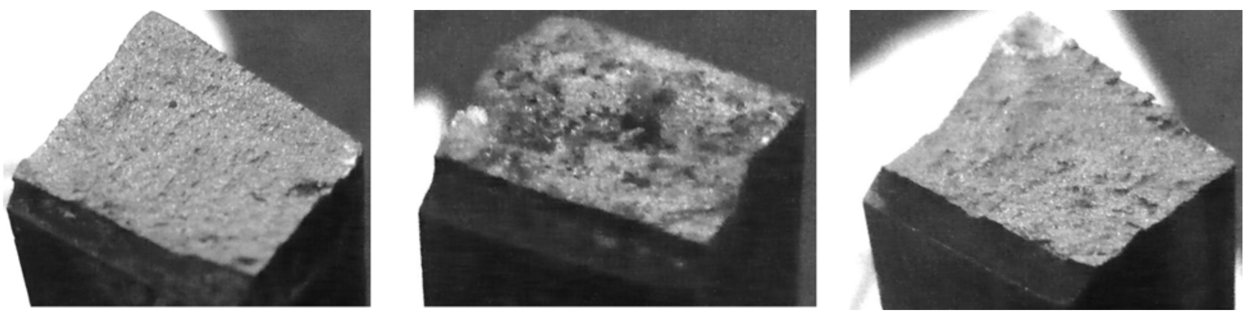
Fracture surfaces of steel tempered at 600^{o}C shown in Fig. 6 indicated almost fibrous fracture texture in all specimens. However marginal change in fibrous appearance is noted at different test temperatures.

Fracture surfaces of steel tempered at 450^{o}C shown in Fig. 7 do not show significant difference, therefore it is very difficult to conceive the DBTT of tempered steel. To obtain substantial difference in fracture mechanism and to conceive the DBTT. A detailed study of specimens tempered at 450^{o}C under scanning electron microscope is required. Hence digital camera used for fractography of tempered steel does not provide sufficient information so that any test temperature can be regarded as DBTT. This is also possible, that the DBTT of tempered steel do not exist at the test temperatures used in present work, because most of the low alloy steels exhibit DBTT at quite low temperatures depending on their microstructure. Thus DBTT of AR (As Received) steel could not be conceived neither from charpy impact values nor from the appearance of fracture surfaces. Fig. 3 indicates that AR steel do not exhibit the constant toughness variation trend either decreasing or increasing with decreasing the temperature. Quite possible reason for that may be the significant diffence in microstructure which has been caused during the specimen preparation, since the AR samples were not normalized before testing. Specimen preparation has long been recognized to play a significant role in inducing the



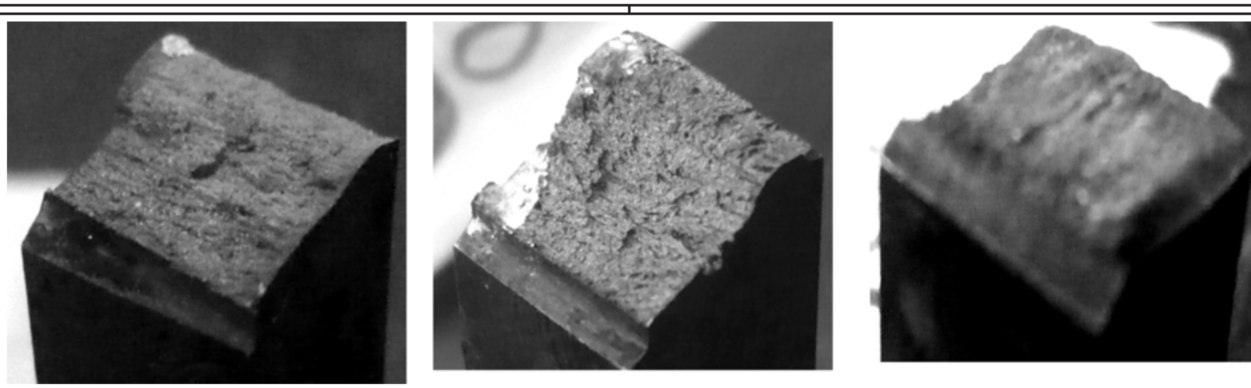
(a) AT_450_30°C *(b) AT_450_-5°C* *(c) AT_450_-10°C*

FIG. 4. FRACTURE SURFACES OF SAMPLES AUSTEMPERED AT 450°C AND IMPACT TESTED AT DIFFERENT TEMPERATURES



(a) AT_350_30°C *(b) AT_350_-5°C* *(c) AT_350_-10°C*

FIG. 5. FRACTURE SURFACES OF SAMPLES AUSTEMPERED AT 350°C AND IMPACT TESTED AT DIFFERENT TEMPERATURES



(a) HT_600_30°C *(b) HT_600_-5°C* *(c) HT_600_-10°C*

FIG. 6. FRACTURE SURFACES OF SAMPLES TEMPERED AT 600°C AND IMPACT TESTED AT DIFFERENT TEMPERATURES

thermo-mechanical stresses into material, thereby influencing the behavior of material substantially.

4. CONCLUSIONS

After extensive evaluation of the effect of test temperature and heat treatment on toughness and DBTT on low alloy SUP9 steel used in manufacturing of leaf spring the following conclusions are made.

(i) The toughness of the steel is widely affected with varying the heat treatment. The maximum increase in toughness is observed in steel tempered at 600°C sample at the cost of hardness.

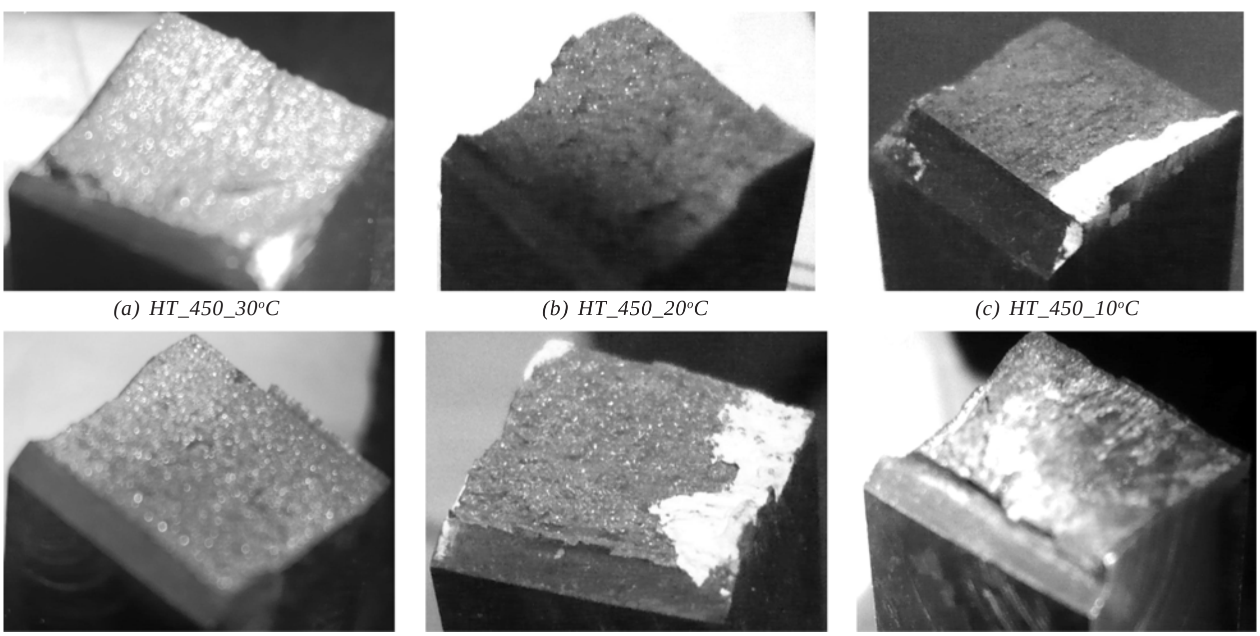
(ii) Loss of 33.33% in hardness with 36.6% increase in toughness values between tempered at 480°C and austempered at 450°C suggest approximate linearly inverse relationship between the two properties of the steel used in the present work.

(iii) Ductile to brittle transition temperature observed was found to be difficult to evaluate using significant toughness change at particular temperature. However using fracture appearance approach DBTT of tempered and austempered specimens is noted at -10°C.

(iv) Increase in toughness with decrease in test temperature was observed. Maximum increase in toughness is measured at -5°C in austempered samples.

5. RECOMMENDATIONS

Studying the effect of heat treatment on toughness of low alloy leaf spring steel a significant increase in toughness with employing tempering treatment at 600°C and austempering suggested that optimization of heat treatment process is imperative. Based on the results of the present work it would be worth to recommend the tempering at 600°C as a suitable substitute of tempering at 450°C which is most frequently employed during manufacturing of leaf spring in Alwin industry Karachi.



(a) HT_450_30°C *(b) HT_450_20°C* *(c) HT_450_10°C*

(d) HT_450_0°C *(e) HT_450_-5°C* *(f) AT_450_-10°C*

FIG. 7. FRACTURE SURFACES OF TEMPERED SPECIMENS AND IMPACT TESTED AT 30, 20, 10, 0, -5, AND -10°C DIFFERENT TEMPERATURE

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