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Full Length Research Paper

Measuring the stress, strain and strain-rate in heat treated medium carbon steel samples and finding the constituited material related properties

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Mechanical failure of component parts as well as in build up structures can be prevented if proper quality control is carried out at point of component's manufacture. Engineers are known to analyze samples from which accurate predictions are made about the properties of the materials that are produced for the purpose of component and structural processing. This work had produced and tested heat treated 1030 steel by pulling them in tensometer to fracture. The tensometer was connected to a computer which plotted graphs from which data of true stress and strain were analyzed for the various heat treated specimens. The analysis of data was done using none regression analysis, SPSS soft ware, to obtain the materials related properties for each of the specimen. The yield strength (σ_y) and ultimate tensile strength (σ_u) of the specimens were significantly different. The highest and lowest σ_y was annealed specimen 450 MPa and normalized specimen 220 MPa respectively. The highest and lowest σ_u was hardened specimen 608 MPa and normalized specimen 320 MPa respectively. With a strain-rate sensitivity C of 0.0562, normalized specimen was less ductile than hardened specimen which had a C value of 0.0083. By the analysis, normalized and tempered specimen which had the strain hardening parameter n of 0.1270 and 0.1240 respectively were less ductile than hardened and annealed specimens with n values of 0.0439 and 0.0571 respectively.

Key words: Yield strength, ultimate tensile strength, 1030 steel.

INTRODUCTION

The failure of metals in service, either through direct collapse from overload, or through fatigue as a result of cyclic stresses, or from bending and buckling, or by critical and crippling load, or by crushing, do occur as a daily phenomenon even after very careful manufacturing processes. The same failures do take place in machine components, very often in parts that are remotely located, which require disassembling before inspection and replacement or repair. The engineers' way around these problems is to take samples of the materials at the point of manufacture and put then through quality control tests. One of these tests was experimented by Ozel and Zeren (2004). This present work went beyond what Ozel did to use experimental and analytical method to develop constituted materials related properties for heat treated 1030 steel. These properties together with the empirical relationship were used to predict how the materials will behave in service.

Oxley (1989) used the Johnson and Cook constitutive model to describe the flow stress of materials as a product of strain, strain rate and temperature effect that are individually determined. He also used shear failure model to develop an equation for strain at fracture. Sharma (2003) modeled the primary deformation zone as a parallel-sided shear zone and the secondary zone which also caused further plastic deformation in machining. Murarka et al. (1981) investigated the influence of strain, strain-rate and temperature on the flow stress in primary deformation zone when cutting metal. Chapman (1972) developed equations which converted engineering

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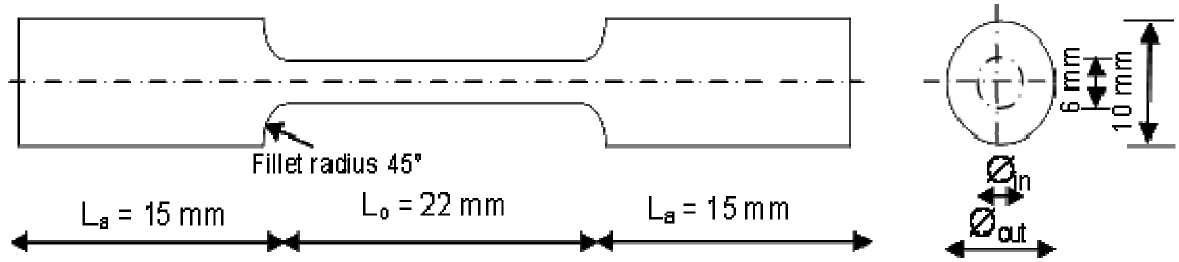

Figure 1. Test specimen from medium carbon steel.

stress and strain to true stress and strain.

The information from researchers mentioned will be used to develop empirical relationship between true stress and true strain for heat treated 1030 steel. The true stress and true strain data will be analyzed to obtain material related property for each of the heat treated specimen. It will then be possible to predict how the materials from which the specimen were made, will behave in service.

DESCRIPTION OF MACHINE AND EQUIPMENT USED

The following machines and equipment were used; the English Hythe Colchester Lathe, the Standard Universal Testing Marching (UTM) or tensometer calibrated in S.I. Unit, a computer system attached to the UTM, and 50 heat treated specimen of medium carbon steel (1030 steel).

The Hythe Colchester Lathe was a variable speed machine that turned the specimen to the dimensions shown on Figure 1. The tensometer had two jaws, the lower fixed jaw and upper movable jaw, which were used to secure the specimen in position before it was pulled. The tensometer was connected to a computer which was programmed to analyze and print out the result of all the variables of interest. The strain rates operated were 200, 500, 1000, 1500 and 1750 mm/min. The heat treated specimen were normalized, tempered, annealed, hardened and “as received” or untreated.

THEORETICAL ANALYSIS

The flow stress or instantaneous yield strength at which the work piece starts to deform plastically or flow is mostly influenced by the cutting force, temperature, strain strain-rate and other process variables such as tool geometry, shear angle, rake angle and work materials properties. Flow stress model are highly important in investigating the work piece constitutive behavior when machining on a lathe.

Ozel et al. (2004) observed that for now, it is better to use semi-empirical constitutive models rather than use sound theoretical model based on atomic level materials behaviour which are still not well understood.

The general form of heat flow equation in 3 dimensions with a moving heat source is given by Komandun et al. (2001) as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - \frac{R_T}{t_u}\frac{\partial T}{\partial x} = \frac{R_T}{V t_u}\frac{\partial T}{\partial t} \quad (1)$$

where R_T is thermal number , V is the cutting speed , t_u is the undeformed chip thickness, and T is the temperature. Also Komanduri et al. (2001) proposed that the moving band heat source is a combination of infinitely small differential segment dl, each of which is considered to be an infinitely long moving line source. Thus at any points on the machining work piece the temperature as a result of the differential segment dl, is given by:

$$T_1 = \frac{q_l}{2\pi\lambda} e^{-\frac{XV}{2a}} K_o\left(\frac{RV}{2a}\right) \quad (2)$$

where q_l is the heat liberation intensity of moving line source, X is the co-coordinating axis, a is the thermal diffusivisity, K_o is the zero order Bessel function which determined the location of the nodal points, R is the distance between the moving line heat source and the point where the temperature rise is assessed, λ is the thermal conductivity, K_o is given as,

$$K_o = 1 - \left(\frac{l_i}{2}\right)^2 + \frac{1}{2!2!}\left(\frac{l_i}{2}\right)^4 - \frac{1}{3!3!}\left(\frac{l_i}{2}\right)^6 \quad (3)$$

where $l_c \le x \le l_{AB}$ and li is the instantaneous point of interest on the shear plane, l_{AB} the line along shear plane AB. Also

$$T_I = \frac{q_{pl}}{2\pi\lambda}\int_{-l}^{+l} e^{-V(X-l_i)Cos\phi/2a} K_o\left[\frac{V(X-l_i)}{2a}\right] dl_i \quad (4)$$

and

$$T_l = \frac{q_{pl}}{2\pi\lambda}\int_{l_i=0}^{L} e^{-(X-l_i\,Sin\varphi)V/2a}\,K_o\left[\frac{V}{2a}\sqrt{(X-l_i\,Sin\varphi)^2+(Z-l_i\,Cos\varphi)^2}\right]dl_i \tag{5}$$

where dl_i is small differential segment, φ is the cylindrical polar coordinate angle, q_{pl} is the heat liberation intensity of moving plane heat source, Karpart et al. (2005) calculated the shear flow stress on the shear plane from mechanical properties of work piece material as,

$$k_{AB} = \frac{\sigma_s\,\varepsilon_{AB}{}^{n}}{\sqrt{3}} \tag{6}$$

where k_{ab} is shear flow stress on the shear plane AB, σ_s is the shear flow stress material, ε_{AB} is the plastic strain of the material or plane AB and n is the strain hardening parameter.

Johnson and Cook (as stated by Oxley, 1989) proposed an equation for the flow stress of a material that is being machined as:

$$\bar{\sigma} = \left[\sigma_i + \sigma_f(\bar{\varepsilon}_p)^n\right]\left[1 + C\,In\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\left[1-\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \tag{7}$$

$$\varepsilon_f = \left[d_1 + d_2\,e^{d_3\left(\frac{P}{\sigma_f}\right)}\right]\left[1 + d_4\,In\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\left[1 + \frac{T - T_{room}}{T_{melt} - T_{room}}\right] \tag{8}$$

where $\bar{\sigma}$ is the flow stress of materials, σ_1 is the initial yield strength of the materials at the temperature and a strain rate of 1/s, $\bar{\varepsilon}_p$ is plastic equivalent strain, n is stain hardening parameter (slope of stress/ strain curve), C is strain-rate sensitivity constant in John-Cook constitutive model, $\dot{\varepsilon}$ is strain rate, $\dot{\varepsilon}_o$ is the reference strain rate, σ_f is strain related constant in John-Cook constitutive mode (MPa), ε_f is strain at fracture, T is working temperature, T_{melt} is melting temperature, T_{room} is room temperature, P is applied load, d_1, d_2, d_3, d_4 are diameters at various necking points and m is the thermal softening parameter (slope of stress/ strain rate curve).

PREPARATION OF TEST SPECIMEN

Fifty specimens made from medium carbon steel (mcs) were machined on the lathe machine to the test specifications shown on Figure 1. The carbon content of the specimens was 0.300% and were checked by the use of a spectrometer to ensure they met specification. The specimens were prepared to fit the tensometer cavity by forging after heating to red hot. An industrial grinder was then used and an emirate paper to smoothen the samples. Chemical analysis was again done with the spectrometer to ascertain that the microstructure of the specimens had not changed.

The specimens were prepared with large ends and a narrow test length. The test length of the specimen was 22 mm and the grip ends were 15 mm. The grip end had a diameter of 10 mm and the test length a diameter of 6 mm. To harden six specimens, they were place in a furnace and heated to 850℃ for a period of 3 h to complete the microstructural transformation to austenite. The specimens were each dropped into separate containers of water where they cooled rapidly to room temperature. The batch of six samples to be tempered had their temperature raised to about 730℃ in the furnace. They were then removed and left to cool in still air which made the samples to be softer. To normalize some specimens, they were heated in the furnace at a temperature of 850℃ for a period of 15 min. This allowed a homogeneous structure of ferrite and pearlite to form after cooling in still air. The samples for annealing were heated for 3 h in the furnace at 850℃. The furnace was turned off and the samples which were then placed in a cast iron box with a mixture of cast iron borings, charcoal, lime and fine sand to arrest decarburization of the specimen, were allowed to cool in the furnace. That way the microstructure had a stress free expanded structure for easy machining. The “as received” specimens were not heat treated, as they were to serve as control samples.

TEST PROCEDURE AND EVALUATION OF STRESS, STRAIN AND STRAIN RATE

All the heat treated and non heat treated (as received) was put to the test with the UTM which was calibrated in S. I. unit. Sample specimens were used to ascertain an adequate speed for the test. This was because of a higher speed could cause a jump of the curve away from its expected position on the graph. Strain rates of 200, 500, 1000, 1500 and 1750 mm/min were steadily maintained for all the specimens.

The specimens were each inserted one after the other into the upper and lower jaws of the tensometer. The lower jaw was fixed while the upper jaw was adjusted and was used to secure the right length of specimen to be pulled. When the specimen was correctly fastened, it was pulled by the tensometer. Necking was observed to have taken place before final fracture. The computer that was attached to the tensometer recorded all the highlighted variables for all the specimens, which were also printed out (Figures 2 and 3). The stress - strain curve obtained from the test gave the engineering stress and strain values, sample is shown on Figure 4. The engineering

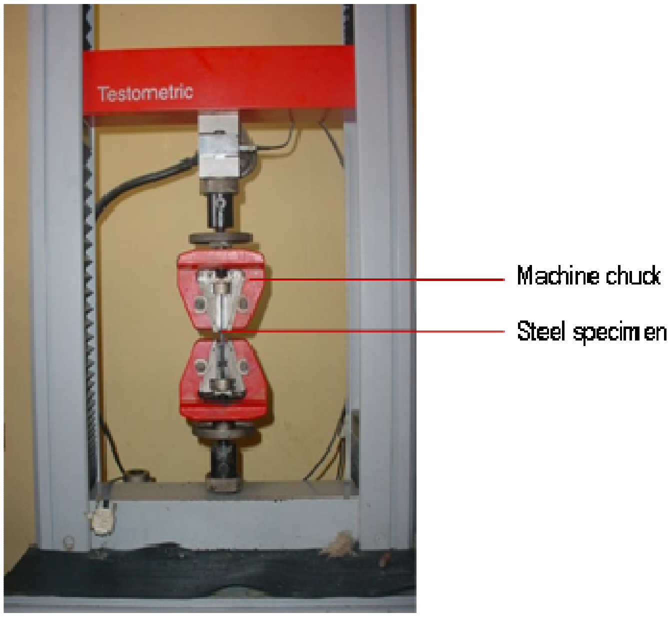

Figure 2. The arrangement of the specimen on the machine prior to the test.

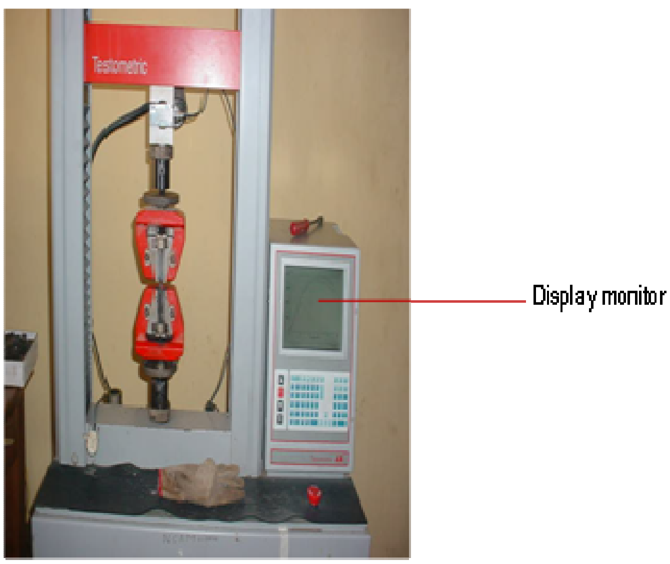

Figure 3. The specimen and the display read out on the screen after the test.

stress - strain did not give a true indication of the deformation characteristic of the specimen because it was based on the original dimension of the specimen which changed as the test proceeded. Also as the specimen was pulled and became more ductile it was unstable. The cross sectional area was observed to decrease rapidly as the applied load also decreased. The average load based on the original area likewise decreased, and it produced the fall - off in the stress - strain curve beyond the point of maximum load. The specimen continued to strain hardens all along to fracture, so that the stress required to produce further deformation also increased.

When the true stress based on the actual cross - sectional area of the specimen was used, the stress - strain curve was observed to have increased continuously to fracture. If the measured strain was based on instantaneous measurements, the curve that was obtained was known as the true - stress - true - strain curve. As this was not experimentally possible, it became necessary to convert the engineering stress/ strain to the true stress/ strain values. Murarka et al. (1981) and Chapman (1972) used the equations 9 and 10 given below to convert engineering stress and strain to true stress and strain as shown;

$$\varepsilon_{true} = \ln(1 + \varepsilon_{eng}) \quad (9)$$

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}) \quad (10)$$

where ε_{true} is true strain, ε_{eng} is engineering strain, σ_{true} is the true stress and σ_{eng} is the engineering stress.

Tables 1, 2, 3, 4 and 5 show the various values of the engineering stress and strain, with the corresponding true stress and strain got from the use of equations 9 and 10 for the heat treated specimens. The strain rate was controlled by the selected strain rates which were 200, 500, 1000, 1500 and 1750 mm/min. Each of these speeds was selected and maintained constant for a particular test. The empirical relationship between true stress, true strain and true strain rate is given below, for the various heat treated specimens.

$$\sigma_n = 76.32134\varepsilon + 0.244707\dot{\varepsilon} \quad (11)$$

$$\sigma_t = 72.3241\varepsilon + 0.236757\dot{\varepsilon} \quad (12)$$

$$\sigma_a = 166.25\varepsilon - 0.126\dot{\varepsilon} \quad (13)$$

$$\sigma_h = 148.198\varepsilon - 0.13968\dot{\varepsilon} \quad (14)$$

$$\sigma_{ar} = 126\varepsilon + 0.236704\dot{\varepsilon} \quad (15)$$

where σ_n is true stress for normalized specimen, σ_t is true stress for tempered specimen, σ_a is true stress for annealed specimen, σ_h is true stress for hardened specimen, σ_{ar} is true stress for "as received" specimen, ε is strain and $\dot{\varepsilon}$ is the strain rate.

The data generated from graphs, sample shown on Figure 4, for each of the specimens were converted to true stress - strain data and were analyzed for each specimen using a non linear regression method, with the

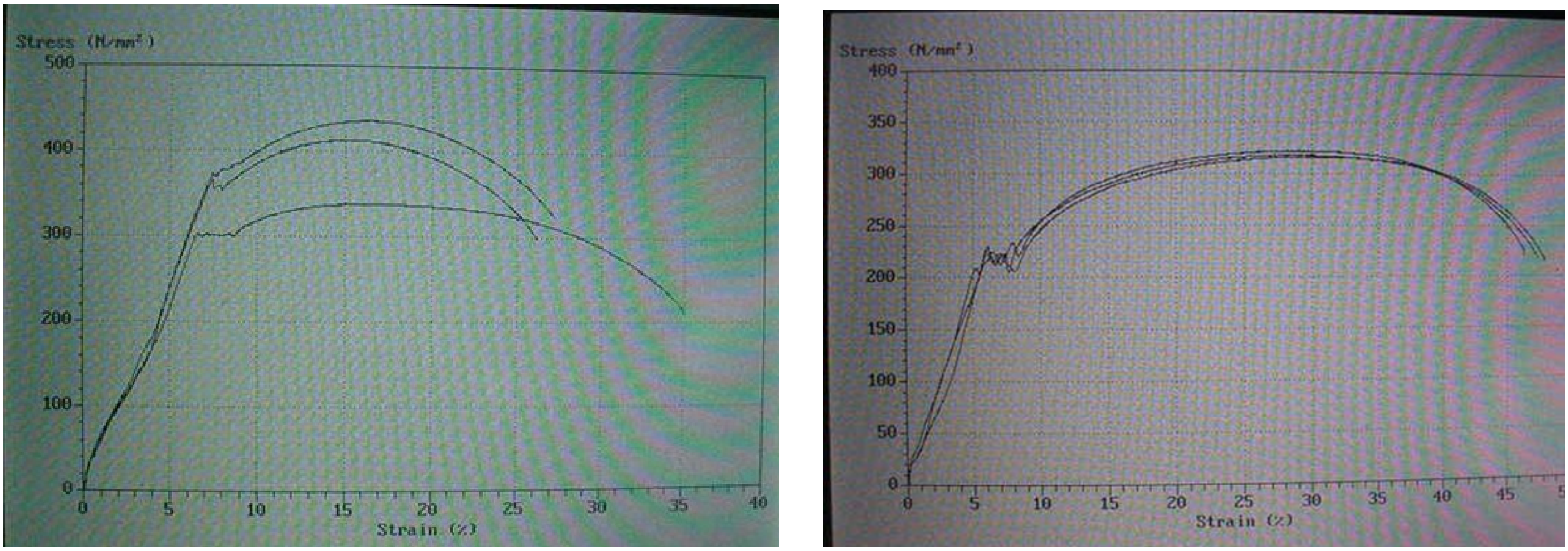

Figure 4. Stress- strain curves for the heat treated specimens.

aid of an SPSS software, to determine the materials' constitutive constants. These constants are the melting temperature T_m, the yield strength σ_y, the ultimate tensile strength, σ_u of the material at room temperature and a strain rate of 1/s, the strain - rate sensitivity constant C, the strain hardening parameter n, which is the slope of the stress strain curve, and the thermal softening parameter specimen, m which is the slope of the stress - strain rate curve for each of the specimen. Different values of the materials' constitutive constants were obtained because heat treating the specimens had altered their microstructure from the initial properties. The results obtained in the work compared with the previous work by Ozel and Zeren (2004) on Table 6.

RESULTS AND DISCUSSION

The results of engineering, true strain and stress data got from experiment are shown on Tables 1 to 5 is for normalized, tempered, annealed, hardened, and "as received" specimens respectively. When subjected to processing by the SPSS software, part of the product got were the true stress and strain empirical relationship seen in equations 11 to 15. The graphical relationship of stress against strain for the normalized and tempered specimens were a straight line before necking and had positive slopes with gradients of 76.32134 for normalized and 72.3241 for tempered specimens, (equations 11 and 12). The lines cut the vertical axis at 0.244707 and 0.236757 $\dot{\varepsilon}$ for normalized and tempered specimen respectively. The greater value of slope of normalized specimen meant that it was harder than tempered specimen. From the same equations 11 and 12, the graphs of stress against strain rate were also straight lines up to the point where necking occurred. They had positive gradients of 0.244707 and 0.236757 for normalized and tempered specimen respectively. This suggested that the thermal softening tendency for normalized specimen was slightly higher than with tempered specimen. Therefore, normalized specimen did become softer than tempered specimen as temperature increased when pulling increased, and did machine better at high temperatures.

The annealed and hardened specimen from observation of equations 13 and 14 recorded very high positive slopes when graphs of stress against strain were considered. However, the annealed specimen with a gradient of 166.25 strain hardened more than the hardened specimen which had a slope of 148.198. Therefore, working (pulling) the annealed specimen required more energy than with the hardened specimen. Also at higher temperature, the thermal softening para-meter, the gradient of 0.13968 for hardened specimen, was slightly higher than the slope of 0.126 for annealed specimen. This further explained the higher working (pulling) energy that was required to relieve stress in the annealed specimen. The "as received ", the mcs specimens that were not heat treated, showed from equation 15 that both graphs of stress against strain and stress against strain rate had positive slopes (n and m were positive). Therefore, the high and added combination of the strain hardening and thermal softening effects had caused the "as received" specimen to be ductile and suited to pulling and fabrication processes.

The graphs of stress against strain (Figure 4) were plotted and analyzed for all the specimens. The data generated from the graphs of each specimen which were converted to true stress-strain data were processed using the non regression analysis (SPSS software) to obtain

Table 1. Engineering stress/strain with the corresponding true stress/strain.

Normalized steel specimen							
Strain		**Engineering stress**			**Corresponding true stress**		
$\varepsilon_{engineering}$	ε_{true}	$\sigma_{engineering}$	$\sigma_{engineering}$	$\sigma_{engineering}$	σ_{true}	σ_{true}	σ_{true}
1	0.7	25	50	50	50	100	100
2	1.1	63	80	80	189	240	240
3	1.4	98	120	120	392	480	480
4	1.6	143	162	162	715	810	810
5	1.8	195	210	210	1170	1260	1260
6	1.9	230	215	215	1610	1505	1505
7	2.1	225	220	220	1800	1760	1760
8	2.2	225	205	233	2025	1845	2097
9	2.3	245	240	235	2450	2400	2350
10	2.4	250	259	259	2750	2849	2849
11	2.5	270	260	270	3240	3120	3240
12	2.6	275	270	273	3575	3510	3549
13	2.6	285	275	280	3990	3850	3920
14	2.7	290	280	285	4350	4200	4275
15	2.8	295	286	290	4720	4576	4640
16	2.8	303	294	297	5151	4998	5049
17	2.9	305	297	300	5490	5346	5400
18	2.9	309	300	305	5871	5700	5795
19	3.0	310	302	307	6200	6040	6140
20	3.0	311	305	309	6531	6405	6489
22	3.1	319	310	312	7337	7130	7176
23	3.2	320	311	315	7680	7464	7560
34	3.6	322	312	318	11270	10920	11130
25	3.3	324	313	320	8424	8138	8320
26	3.3	324	315	320	8748	8505	8640
28	3.4	325	318	320	9425	9222	9280
29	3.4	325	318	320	9750	9540	9600
30	3.4	324	320	320	10044	9920	9920
34	3.6	320	312	312	11200	10920	10920
35	3.6	319	312	312	11484	11232	11232
36	3.6	315	310	310	11655	11470	11470
37	3.6	310	310	310	11780	11780	11780
40	3.7	300	300	300	12300	12300	12300
42	3.8	285	290	285	12255	12470	12255
44	3.8	260	264	270	11700	11880	12150
45	3.8	254	259	260	11684	11914	11960

the constituted material related properties shown on Table 6. Observation from Table 6 showed that all the specimen had the same melting temperature of 1450℃ which showed that microstructural re-arrangement brought by heat treatment did not affect the melting point of mcs. The yield strength of the specimens (σ_y) was significantly different. Normalized specimen had the lowest initial yield strength of 220 MPa, followed by tempered 301 MPa, then hardened specimen 409MPa, and finally annealed specimen with 450 MPa. The atoms in the annealed specimen appeared to have adjusted to the internal stresses and residual strains had been relieved, therefore, they showed the highest σ_i. The hardened, tempered and finally normalized specimens followed in that order, according to the degree of internal stress adjustment and residual strain relieved, with the highest being annealed specimen and the lowest normalized specimen. The hardened specimen had a fcc microstructure and was γ-iron. It was ductile and this was evident when σ_u, the ultimate tensile strength of the specimen

Table 2. Engineering stress/strain with the corresponding true stress/strain.

Tempered steel specimen							
Strain		**Engineering stress**			**Corresponding true stress**		
$\varepsilon_{engineering}$	ε_{true}	$\sigma_{engineering}$	$\sigma_{engineering}$	$\sigma_{engineering}$	σ_{true}	σ_{true}	σ_{true}
1	0.7	30	30	50	60	60	100
2	1.1	70	70	90	210	210	270
3	1.4	100	100	107	400	400	428
4	1.6	130	130	140	650	650	700
5	1.8	170	170	190	1020	1020	1140
6	1.9	210	230	245	1470	1610	1715
7	2.1	210	235	240	1680	1880	1920
8	2.2	220	230	245	1980	2070	2205
9	2.3	235	245	250	2350	2450	2500
10	2.4	250	260	270	2750	2860	2970
11	2.5	260	270	280	3120	3240	3360
12	2.6	270	280	290	3510	3640	3770
13	2.6	275	285	300	3850	3990	4200
14	2.7	280	290	305	4200	4350	4575
15	2.8	285	300	310	4560	4800	4960
16	2.8	290	305	315	4930	5185	5355
17	2.9	291	310	320	5238	5580	5760
18	2.9	295	315	324	5605	5985	6156
19	3.0	298	318	325	5960	6360	6500
20	3.0	300	320	325	6300	6720	6825
21	3.1	300	320	326	6600	7040	7172
22	3.1	305	325	328	7015	7475	7544
23	3.2	305	325	330	7320	7800	7920
25	3.3	305	325	330	7930	8450	8580
26	3.3	305	325	330	8235	8775	8910
27	3.3	304	325	330	8512	9100	9240
28	3.4	300	325	328	8700	9425	9512
29	3.4	295	320	327	8850	9600	9810
30	3.4	296	320	325	9176	9920	10075
32	3.5	289	310	310	9537	10230	10230
33	3.5	288	308	308	9792	10472	10472
34	3.6	273	305	305	9555	10675	10675
36	3.6	265	290	290	9805	10730	10730
39	3.7	230	258	260	9200	10320	10400
40	3.7	240	230	240	9840	9430	9840

before fracture was considered. The σ_u for the hardened specimen was 608MPa, and was 501, 404 and 320 MPa for annealed, tempered and normalized specimens respectively. This arrangement had followed the degree of ductility of the specimen from least ductile normalized specimen to the most ductile, hardened specimen.

The normalized mcs specimen responded quickest of all the specimens to deformation when pulled. It recorded a strain - rate sensitivity of 0.0562. Hardened mcs specimen was list sensitive with a value of 0.0083. Tempered specimen at 0.0274 responded slower than normalized specimen, but quicker than annealed specimen at 0.0143.

The strain hardening parameter of 0.0439 for hardened specimen on Table 6 showed that it was more ductile than the annealed specimen at 0.0571 when pulled during the test. Normalized and tempered with 0.1270 and 0.1240 respectively were less ductile than the hardened and the annealed specimens. When the effect of thermal softening was considered, there was no established relationship between the specimens.

There was an attempt to compare this work with the previous work of Ozel and Zeren (2004) (Table 6). They used AISI 1045 steel, this work used medium carbon steel (0.300% carbon) heat treated. There was agree-

Table 3. Engineering stress/strain with the corresponding true stress/ strain.

Annealed steel specimen							
Strain		Engineering stress			Corresponding true stress		
$\varepsilon_{engineering}$	ε_{true}	$\sigma_{engineering}$	$\sigma_{engineering}$	$\sigma_{engineering}$	σ_{true}	σ_{true}	σ_{true}
0	0.0	0	0	0	0	0	0
0.3	0.3	20	20	20	26	26	26
0.5	0.4	26	32	32	39	48	48
1	0.7	58	60	60	116	120	120
2	1.1	100	100	100	300	300	300
3	1.4	130	130	140	520	520	560
4	1.6	180	180	210	900	900	1050
5	1.8	250	270	230	1500	1620	1380
6	1.9	315	330	250	2205	2310	1750
6.8	2.1	368	382	292	2870.4	2979.6	2277.6
7	2.1	380	385	360	3040	3080	2880
7.2	2.1	340	400	388	2788	3280	3181.6
7.4	2.1	345	414	395	2898	3477.6	3318
7.6	2.2	343	400	400	2949.8	3440	3440
8	2.2	400	400	344	3600	3600	3096
8.2	2.2	338	400	300	3109.6	3680	2760
8.5	2.3	345	400	300	3277.5	3800	2850
8.7	2.3	348	410	310	3375.6	3977	3007
9	2.3	352	413	324	3520	4130	3240
10	2.4	420	420	345	4620	4620	3795
11	2.5	468	437	340	5616	5244	4080
12	2.6	445	440	360	5785	5720	4680
13	2.6	462	458	370	6468	6412	5180
14	2.7	468	450	374	7020	6750	5610
14.5	2.7	475	455	365	7362.5	7052.5	5657.5
15	2.8	480	460	365	7680	7360	5840
16	2.8	465	458	375	7905	7786	6375
17	2.9	468	454	360	8424	8172	6480
17.6	2.9	470	450	368	8742	8370	6844.8
18	2.9	468	446	365	8892	8474	6935
19	3.0	464	438	362	9280	8760	7240
20	3.0	460	434	360	9660	9114	7560
22	3.1	450	418	340	10350	9614	7820
23	3.2	440	400	330	10560	9600	7920
25	3.3	408	330	310	10608	8580	8060

ment in the constitutive material related properties of melting temperature, T_m (1460 compare to 1450℃), the yield strength, σ_y (600.6 compare to 608 hardened mcs), the strain - rate sensitivity constant C (0.0134 compare to 0.0143 annealed mcs), and the thermal softening parameter m (1 compare to0.98495, 1.12615, 0.8442, 1.1144). The composition of the AISI 1045 steel had brought about the marked difference between areas where comparison had not been as close. They are 553.1, the yield strength σ_y and 0.234, the strain hardening parameter, n.

Conclusion

It was concluded from the empirical relationships that the high value of strain hardening parameter n of 76.32134 recorded for normalized specimen showed that it was harder than tempered specimen for pulling (drawing). Also the high value of the experimental thermal hardening parameter of 0.24407 showed that the normalized specimen was less ductile than the tempered specimen. The annealed specimen had the highest value of n of 166.25. Therefore working (pulling) the annealed

Table 4. Engineering stress/strain with the corresponding true stress/ strain.

Hardened steel specimen							
Strain		**Engineering stress**			**Corresponding True stress**		
$\varepsilon_{engineering}$	ε_{true}	$\sigma_{engineering}$	$\sigma_{engineering}$	$\sigma_{engineering}$	σ_{true}	σ_{true}	σ_{true}
0	0.0	0	0	0	0	0	0
0.3	0.3	20	20	20	26	26	26
1	0.7	20	20	45	40	40	90
2	1.1	65	50	80	195	150	240
3	1.4	80	80	125	320	320	500
4	1.6	125	125	175	625	625	875
5	1.8	165	175	230	990	1050	1380
6	1.9	210	230	292	1470	1610	2044
7	2.1	340	300	300	2720	2400	2400
8	2.2	335	340	370	3015	3060	3330
9	2.3	340	312	380	3400	3120	3800
10	2.4	380	405	390	4180	4455	4290
11	2.5	420	400	398	5040	4800	4776
12	2.6	430	420	412	5590	5460	5356
13	2.6	432	435	440	6048	6090	6160
14	2.7	440	460	435	6600	6900	6525
15	2.8	460	475	480	7360	7600	7680
16	2.8	466	500	500	7922	8500	8500
17	2.9	468	500	500	8424	9000	9000
18	2.9	470	504	506	8930	9576	9614
19	3.0	480	510	510	9600	10200	10200
20	3.0	480	510	510	10080	10710	10710
21	3.1	480	510	510	10560	11220	11220
22	3.1	480	515	510	11040	11845	11730
23	3.2	480	500	480	11520	12000	11520
24	3.2	480	480	475	12000	12000	11875
25	3.3	475	470	470	12350	12220	12220
26	3.3	464	465	465	12528	12555	12555
27	3.3	458	450	462	12824	12600	12936
28	3.4	450	420	460	13050	12180	13340
29	3.4	430	400	450	12900	12000	13500
30	3.4	410	385	441	12710	11935	13671
31	3.5	390	369	430	12480	11808	13760
32	3.5	370	358	420	12210	11814	13860
33.5	3.5	330	328	330	11385	11316	11385

specimen required more energy than was needed for all the other specimens except the "as received" specimen. The high and added combination of the strain hardening parameter n and thermal softening parameter m (126 and 0.236704) had showed the "as received" specimen (untreated) to be more ductile and required more energy to deform to fracture than was needed for all the other treated specimens.

Observation showed that using the regression method, microstructural changes brought by heat treatment did not affect the melting temperature of mcs as it remained at 1450℃. The yield strength of the specimens σ_y were significantly different, being 220, 301, 409 and 450 MPa for normalized, tempered, hardened and annealed specimens respectively. Also the ultimate tensile strength of the specimen σ_u was significantly different. The highest σ_u was recorded for hardened specimen as 608 MPa.

The lowest was 320 MPa for normalized specimen. Hardened specimen was seen to require more pulling energy to fracture while normalized specimen required the smallest in the group. The normalized specimen responded quickly, of all the other heat treated specimen,

Table 5. Engineering stress/strain with the corresponding true stress/strain.

As received steel specimen							
Strain		Engineering stress			Corresponding true stress		
$\varepsilon_{engineering}$	ε_{true}	$\sigma_{engineering}$	$\sigma_{engineering}$	$\sigma_{engineering}$	σ_{true}	σ_{true}	σ_{true}
1	0.7	60	61	62	120	122	124
2	1.1	99	100	100	297	300	300
3	1.4	140	130	130	560	520	520
4	1.6	180	162	163	900	810	815
4.3	1.7	190	190	192	1007	1007	1017.6
5	1.8	237	237	219	1422	1422	1314
6	1.9	282	282	262	1974	1974	1834
6.6	2.0	320	320	300	2432	2432	2280
6.9	2.1	340	340	295	2686	2686	2330.5
7	2.1	360	360	300	2880	2880	2400
7.2	2.1	364	362	297	2984.8	2968.4	2435.4
7.5	2.1	370	365	209	3145	3102.5	1776.5
7.6	2.2	368	350	298	3164.8	3010	2562.8
8	2.2	380	358	237	3420	3222	2133
8.1	2.2	378	350	296	3439.8	3185	2693.6
8.2	2.2	376	358	299	3459.2	3293.6	2750.8
8.7	2.3	382	364	295	3705.4	3530.8	2861.5
9	2.3	382	372	305	3820	3720	3050
9.2	2.3	382	376	310	3896.4	3835.2	3162
10	2.4	400	384	319	4400	4224	3509
11	2.5	400	390	320	4800	4680	3840
12	2.6	420	400	315	5460	5200	4095
13	2.6	425	405	320	5950	5670	4480
14	2.7	428	410	330	6420	6150	4950
15	2.8	430	420	332	6880	6720	5312
16	2.8	436	410	330	7412	6970	5610
18	2.9	420	400	325	7980	7600	6175
19	3.0	419	390	320	8380	7800	6400
20	3.0	418	388	310	8778	8148	6510
21	3.1	418	384	300	9196	8448	6600
22	3.1	400	365	290	9200	8395	6670
23	3.2	395	355	288	9480	8520	6912
24	3.2	390	340	286	9750	8500	7150
26	3.3	340	305	282	9180	8235	7614
27	3.3	345	295	280	9487.5	8112.5	7700

to deformation when pulled to fracture with a strain - rate sensitivity C of 0.0562. Hardened specimen was least sensitive with C of 0.0083. By the regression analyses method, normalized and tempered specimens with n as 0.1270 and 0.1240 respectively were less ductile in drawing (pulling) than hardened and annealed specimens.

Comparison of this work with that of Ozel and Zeren (2004) showed agreement in the constitutive material related properties of melting temperature, ultimate tensile strength, the strain - rate sensitivity constant, and the thermal softening parameter. The areas of the yield strength σ_y, and strain hardening parameter, n where comparison had not been as close, had been due to the difference in the composition of AISI 1045 steel and the heat treated 1030 steel.

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Table 6. The various material properties for different heat treated specimens.

	Operation	T_m (°C)	σ_i (MPa)	σ_f (MPa)	C	n	M
Present work	Normalized	1450	220	320	0.0562	0.1270	0.98495
	Tempered	1450	301	404	0.0274	0.1240	1.12615
	Annealed	1450	450	501	0.0143	0.0571	0.8442
	Hardened	1450	409	608	0.0083	0.0439	1.1144
Previous work	AISI 1045 steel	1460	553.1	600.8	0.0134	0.234	1

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