International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:9, No:6, 2015

Effect of Alloying Elements and Hot Forging/Rolling Reduction Ratio on Hardness and Impact Toughness of Heat Treated Low Alloy Steels

Mahmoud M. Tash

Abstract**—**The present study was carried out to investigate the effect of alloying elements and thermo-mechanical treatment (TMT) i.e. hot rolling and forging with different reduction ratios on the hardness (HV) and impact toughness (J) of heat-treated low alloy steels. An understanding of the combined effect of TMT and alloying elements and by measuring hardness, impact toughness, resulting from different heat treatment following TMT of the low alloy steels, it is possible to determine which conditions yielded optimum mechanical properties and high strength to weight ratio.

Experimental Correlations between hot work reduction ratio, hardness and impact toughness for thermo-mechanically heat treated low alloy steels are analyzed quantitatively, and both regression and mathematical hardness and impact toughness models are developed.

Keywords**—**Hot Forging, hot rolling, heat treatment, hardness (hv), impact toughness (j), microstructure, low alloy steels.

I. Introduction

CONTROL of thermo-mechanical processing and subsequent heat treatment for low alloy steels are required to develop optimum structure and mechanical properties. Thermo-mechanical treatment (TMT) is a simultaneous application of heat and deformation process. Hot forging is a useful technique to produce components for aerospace applications that require high strength-to-weight ratio. Forged structure has excellent mechanical properties (improvement of alloy ductility and fracture toughness) due to fine grain structure, reduced blowholes and porosity.

Hot work provides the driving force for microstructural change and improves physical and mechanical properties. The high density of defects introduced by hot rolling or hot forging during TMT, can severely affect the phase transformation by providing nucleation sites and aiding diffusion processes. Hot forging/rolling achieves desired shape and improves physical properties and obtains excellent mechanical properties of the low alloy steels. Changes in mechanical properties occur as a result of microstructure changes during hot forging/rolling and heat treatment.

During hot forging/ rolling, plastic deformation results in the production of various crystal defects such as vacancies, dislocations, sub-grain boundaries and stacking faults which severely affect the phase transformation in metals and alloys by providing nucleation sites and aiding diffusion processes. These in turn affect the kinetics of phase transformation and morphology of the phase(s) formed. The driving force for structure modifying metallurgical phenornena, such as dynamic or static recovery and recrystallisation is the dislocation density and associated strain energy imparted by the deformation.

A heavily dislocated microstructure is created and is observed to act as nucleation sites for new grains during recrystallization [1]. Required strength levels can be provided via controlled evolution of microstructure and substructure during thermo-mechanical treatment (TMT). Further increase of toughness can be achieved by microstructural control during the thermomechanical processing [2]. Radcliffe and Kula [3] classified the various steels that undergo phase transformation according to whether deformation is introduced before, during, or after the phase transformation. Zackay et al. [4] developed a new class of high-strength metastable austenitic steels making use of strain–induced martensitic transformation. These steels are known as TRIP steels.

Improvement of low alloy steel toughness through grain refining is caused by pro-eutectoid ferrite formation [5]. Acicular ferrite microstructure is produced by a moderate cooling rate after hot forging, which in turn results in a good combination of strength and toughness [6]. Normalised steel is consisting of fine ferrite or cementite with grains of pearlite. Hardened and tempered steel is expected to have a bainitic or tempered martensitic structure. Tempering reduces brittleness imparted by hardening and produces definite physical properties within the steel. The resultant hardness and impact toughness depend on the temperature to which the steel is heated during the tempering process. Slower cooling rates produce coarser microstructures.

Chromium and Mo are carbide forming elements and form stable carbides and hence are expected to increase the alloy hardness and decrease the alloy impact toughness. Also these elements increase the stability of supersaturated iron carbide solid solution during tempering processes. On the other hand, Mn can be present in solid solutions with iron and is expected to increase the alloy impact toughness. In the present work, the effect of alloying elements and hot rolling reduction ratios on the hardness (HV) and impact toughness (J) of low alloy steels are investigated.

M. Tash is with Industrial Engineering Program, Mechanical Engineering Department, College of Engineering, Prince Sattam bin AbdulAziz University, Al Kharj, KSA, on leave from the Mining, Petroleum and Metallurgical Engineering Department, Cairo University, Giza, Egypt (e-mail: mahmoud_tash1@yahoo.com).

II. Experimental Procedures and Methodology

Low alloy steel (alloy code 1) is supplied in the form of bars (L*D=150mm*50mm). The alloy composition is listed in Table I. Hot forging is conducted at 1200ºC using mechanical presses of 500 and 800 ton capacities, respectively. Different grades of low alloy steels (alloy codes 2-5) are produced using electric arc furnaces (EAF) operations, ladel refining (LF), vacuum degassing (VD) and continuous casting machine (CCM). Billets of 160*160mm (Alloy codes 1-4) are hot rolled with different reduction ratios. Bars with different sizes are obtained. The composition of these alloys is listed in Table I. Different heat treatments procedures are given to these bars are listed in Table II. Austenitization heat treatment is carried out in the temperature range of (860°-925°C) and time of 1.7minutes/1meter. Quenching/tempering and normalizing heat treatment are performed through induction heat treatment line. Induction technology assures the maximum homogeneity of mechanical and structural properties both in the bar section and along the bar length.

Hardness and Impact toughness (J) measurements are carried out for different conditions of low alloy steels after hot forging/rolling. Samples for metallographic examination are sectioned from the broken impact samples after hot forging/rolling (corresponding to each condition), mounted, polished and etched using Nital solution. The microstructure is analyzed using an optical and SEM microscope.

TABLE I
Chemical Compositions for Low Alloy Steels Grade Used in the Present Work

Alloy Code	C	Si	Mn	Ni	Cr	Mo
1	0.22	0.31	1.33	0.15	1.02	0.005
2	0.41	0.24	0.78	0.12	0.99	0.15
3	0.17	0.19	1.25	0.12	0.10	0.02
4	0.28	0.14	0.44	1.84	1.88	0.30
5	0.30	0.23	0.52	0.12	2.41	0.15

* P= 0.007-0.01% and S ranges from 0.02- 0.05%

TABLE II
Heat Treatment Conditions of Low Alloy Steels Used in the Present Work

Code	Heat Treatment**		
	Condition	Aust. Temp ºc	Temp. Temp ºc
1	Q&T	920	600
2	Q&T	860	610
3	N	925	Non
4	Q&T	895	640
5	Q&T	880	695

** Austenitization time for alloy code 1 is 30 min. and for alloy codes 2, 4 and 5 is 1.7min./1 m. and for normalized one (N) =45 min and tempering time is 2h for alloy code 1 and 2.5 min./1 m. for alloy code 2, 4 and 5.

TABLE III
Experimental Correlation between Parameters, Hardness (HV) and Impact Toughness (J) of Low Alloy Steels: Design of Experiment (DOE)- Factors and Their Uncoded Levels

No.	Parameters	Notation	Unit	Level			
				Uncoded		Coded	
				Low	high	Low	high
1	C	A	%	0.15	0.43	-1	1
2	Mn	B	%	0.44	1.31	-1	1
3	Cr	D	%	0.06	2.43	-1	1
4	Mo	E	%	0.01	0.31	-1	1
5	Rr	G	%	6	24	-1	1
6	Aust. T 0C	H	0C	860	925	-1	1

Experimental correlations of the results obtained from the hardness (HV) and impact toughness (J) measurements are analyzed through empirical models to establish the relations between responses and different factors. Once the responses, factors (6) and levels have been selected, see Table III, the next step is to design the experimental runs. After the factors and the values input into the software (MINITAB 14), a DOE model will be automatically generated with specific number of runs coupled with specific parametric settings. In this case, 38 runs were generated. The main factors are alloying elements (C, Mn, Cr and Mo) and TMT parameters (reduction ratio (Rr) and Austenitization Temperature (AT)).

III. Results and Discussions

A. Hardness (HV) and Impact Toughness (J) Results for Alloy Code (1)

Hardness (HV) and impact toughness (J) measurements are obtained from all specimens prepared from alloy code 1 after hot forging. The results are provided in Table IV. Hot working during the TMT accelerates the recrystallization and grain refinement rate and leads to a sharp rise in hardness and strength of the low alloy steel. However, it is noticed that hot working prior to austenitization treatment has a significant effect on the heat treatment and mechanical behaviour of low alloy steel. This apparently leads to recrystallization and grain refinement of the microstructure. Hot working can affect the annealing behaviour of low alloy steels. Annealing improve alloy toughness and decrease alloy strength. Normalizing refine the microstructure and improve the alloy mechanical properties.

Increasing the hot forging reduction ratio produces a remarkable increase in the hardness profile in the TMT conditions. As the hot forging reduction ratio increase from 1.11 to 1.29, the hardness increase and the toughness decrease of low alloy steel. This can be explained due to the high defect structure obtained with higher reduction ratio in the TMT. An increase in alloy hardness was observed when hot forging was carried out at 1200ºC using mechanical press with 800 ton capacity (i.e. reduction ratio=1.29). This may be explained on the basis of the combined effect of deformed structure and strain hardening. It is observed that the hardness of TMT conditions increases from 360 HV to 433 HV with increasing reduction ratio from 1.11 to 1.29, respectively. Hardness increases from 366 HV to 393 HV for the TMT plus hardening conditions with increasing reduction ratio from 1.11 to 1.29, respectively. While a decrease of impact toughness from 69J to 62J are observed.

Non-homogeneity of the structure can be expressed by the variation in hardness or impact toughness results (i.e. standard deviation results). The non-homogeneity is observed to be high with hot forged plus normalised condition (SD=15 and 13) than hot forged plus annealed one (SD= 7 and 3) when hot forging reduction is 1.11 and 1.29, respectively. Non-homogeneity are observed to be the highest with the hot forged conditions (SD= 38 and 40) at both reduction ratio 1.11 and 1.29, respectively. Also, similar results for the non-homogeneity observed from impact toughness, see Table IV.

The results presented in Fig. 1 show that for low alloy steel grade G51210 (alloy code 1) containing 1%Cr and 1.33%Mn and 0.22%C, the annealed alloy exhibit lower hardness levels compared to the TMT and normalised ones. Only in the case of highly hot deformed alloy do the annealed alloy display hardness values that equal to those obtained for the normalised alloy. In the case of heat treated alloy, both annealed and normalised show lower hardness values than the TMT alloy when 1.11 and 1.29 reduction ratio.

However, the opposite is observed for impact toughness, when hot forging is carried out at same reduction ratio. In annealed and normalised alloys, the annealed alloy exhibit higher toughness levels than do the normalised alloy at the two reduction ratio. The hardness value in the annealed alloy is lower than the normalised one at lower reduction ratio, i.e. 1.11. This may be explained on the basis of the amount of dislocation density produced and it role in recovery and recrystallization processes of such alloys.

The results for different heat treatment carried out following TMT for low alloy steel under investigation, revealed that annealing following TMT with hot forging reduction ratio of 1.29 yields optimum mechanical properties than those at all other heat treatment and percent reduction ratios. It is noticed that hot work prior to heat treatment has significant effect on the mechanical behaviour of low alloy steel. This apparently leads to recrystallization and grain refinement of the microstructure. Whereas hot work, during TMT, accelerates the recrystallization and grain refinement rate leading to a rise in hardness and strength. Also, it is noticed that the mechanical behaviour of the low alloy steel shows highest hardness in the TMT specimens. For TMT specimens, the result shows that annealing reduces the strength and increases the ductility. This could be attributed to recovery effects.

For low alloy steel (alloy code 1), hot forging brings about an increase in hardness however a decrease in impact toughness is observed. It is found that hardness increases slightly with hot forging reduction ratio. However, a remarkable increase in hardness obtained for TMT samples, Fig. 1. This may be attributed to the high density of defects introduced by hot forging during TMT, which gives rise to strengthening mechanisms and severely affect the phase transformation by providing nucleation sites and aiding diffusion processes. These in turn affect the kinetics of phase transformation and morphology of the phase(s) formed. The TMT samples show higher hardness than normalized one regardless of hot forging reduction ratio. However, the reverse is true for impact toughness. Again a remarkable effect on hardness as a result of introducing hot work was observed as shown in Fig. 1; as hot work increases the hardness increases. Hardness increases by 20% as reduction ratio increases from 1.11 to 1.29. On the other hand, impact toughness reduces by 20%. Typical impact energy and hardness for low alloy steel in the TMT conditions are on the order of 8 J and 433 HV. The results demonstrate that the hardness increases as the hot forging reduction ratio increases from 1.11 to 1.29. Note that an increase in reduction ratio will also be accompanied by a reduction in impact (Charpy) toughness, Fig. 1. Hot deformation of low alloy steel provides the driving force for microstructural change. The evolution of microstructure and substructure depends on the relative proportions of dynamic and static recovery and recrystallization during TMT.

TABLE IV
VARIATION IN ALLOY HARDNESS (HV) AND IMPACT TOUGHNESS (J) AS A FUNCTION OF HOT FORGING REDUCTION RATIO AND HEAT TREATMENT CONDITIONS

Condition	Hardness (HV)		Impact Energy (J)	
	R=1.11	R=1.29	R=1.11	R=1.29
TMT*	360 ± 38	433± 40	10± 0	8± 0
TMT+A	193± 7	143± 3	182 ± 25	161 ± 1
TMT+N	230± 15	143± 13	54 ± 5	40 ± 0
TMT+H	366± 12	393± 19	69± 4	62± 3

* N.B. TMT= thermo-mechanical treatment using hot forging followed by water cooling, A=annealed, N=normalized, H= hardened and R= reduction ratio.

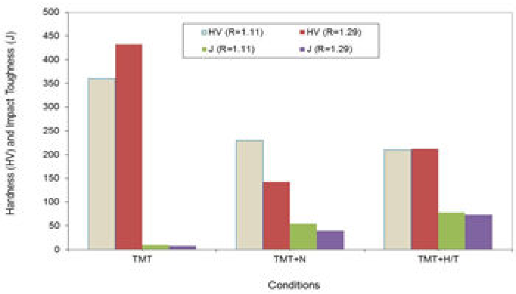
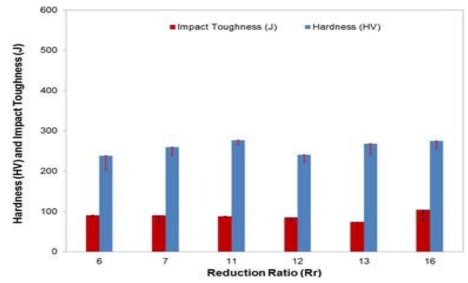


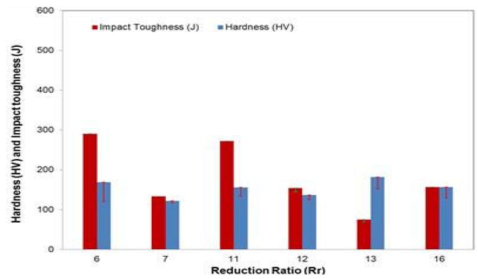
Fig. 1 Variation in alloy Hardness and Impact Toughness with Hot Forging Reduction Ratios and Heat treatment for Alloy Code (1)

B. Hardness (HV) and Impact Toughness (J) Results for Alloy Codes (2-5)

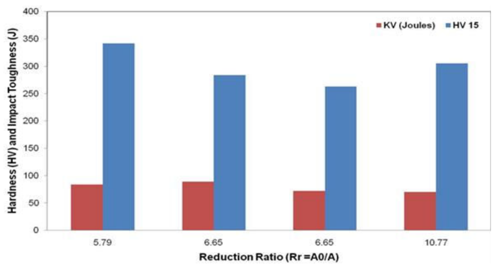
Hardness and impact toughness measurements were performed on alloy codes 2 -5 and their results after hot rolling with different reduction ratio and subsequent heat treatment are listed in Table I. Variation in alloy hardness and toughness as a function of hot rolling reduction ratios for low alloy steels are shown in Fig. 2. It is observed that the hardness increases with hot rolling reduction ratio. On the other hand, the impact toughness decreases with some fluctuation due to variations in chemical composition.



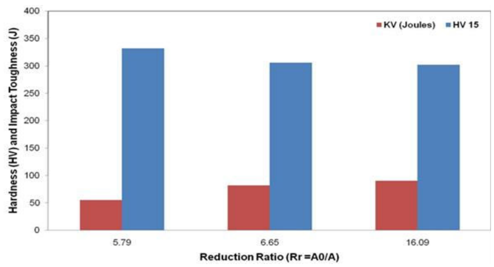
(a)



(b)



(c)



(d)

Fig. 2 Variation in Hardness and Impact Toughness with Hot Rolling Reduction Ratio; a) Alloy Code (2), b) Alloy Code (3), c) Alloy Code (4) and d) Alloy Code (5)

Hardening and tempering increase the hardness and impact toughness of low alloy steel grade (alloy code 2). The hardness and impact toughness for low alloy steel grades (alloy codes 2-5) are increased with hot rolling reduction ratios, see Fig. 2. Normalizing is carried out for low alloy steel grade (alloy code 3) at temperature of 9250C for 45 minute following air cooling. At lower hot rolling reduction ratio, it is observed that both hardness and impact toughness are increasing with high fluctuation in readings with decreasing hot rolling reduction ratios. This may be attributed to the variations in alloy chemistry. However, impact toughness decreases with increasing reduction ratio.

C. Regression Analysis, Factorial DOE and ANOVA Results for Alloy Codes (2-5)

1. Regression Analysis Results

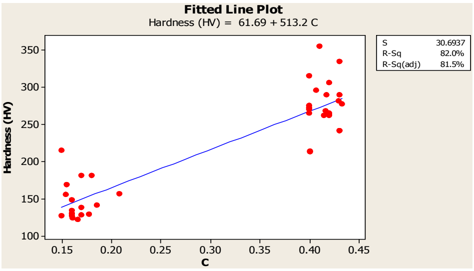
Experimental correlations of the results obtained from the hardness (HV) and impact toughness (J) results measurements are analyzed using factorial analysis method. Correlation between hot rolling reduction ratio, Hardness (HV) and impact toughness (J) of heat treated low alloy steels are investigated, to quantify the effects of hot work on the alloy Hardness (HV) and Impact toughness (J). Models that relate alloying element, hot work and heat treatment parameters to the Hardness (HV) and impact toughness (J) of such alloys are developed in the present study.

An empirical model was developed through the regression analysis to correlate the alloying additions, hot rolling reduction ratio and heat treatment parameters (i.e. austenization temperature) to the responses (Hardness (HV) and Impact Toughness (J)). The estimated regression coefficients in Hardness (HV) regression equation (1) show that Reduction ratio Rr, has noteworthy influence on the Hardness (HV). The p – value for these parameter shows that the values are below the accepted value of 0.05. For Hardness (HV) and Impact Toughness (J) regression (J) model, The R – Sq value is 89.3% and 48.5%, respectively.

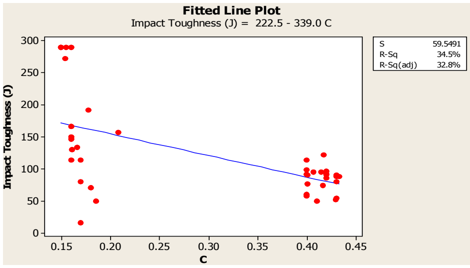
$$\text{Hardness (HV)} = -162 - 125\ C + 106\ Mn + 105\ Cr + 869\ Mo + 0.500\ \text{Reduction ratio (Rr)} + 0.18\ A.T\ ^{\circ}c \tag{1}$$

$$\text{Impact Toughness (J)} = 10890 - 1208\ C - 230\ Mn - 561\ Cr - 738\ Mo - 0.136\ \text{Reduction ratio (Rr)} - 11.0\ A.T\ ^{\circ}c \tag{2}$$

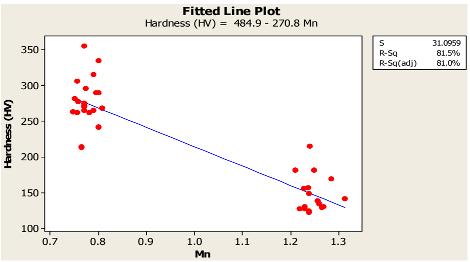
Fitted line plots for hardness and impact toughness data results in terms of different alloying elements (%C, %Mn, %Cr and %Mo), hot rolling reduction ratio (Rr) and austenitization temperature (AToC) are shown in Fig. 3. It is observed that increasing all factors levels in the present study except Mn and austenitization temperature increase alloy hardness (HV) but decrease impact toughness (J). Similar effect are observed for C, Cr and Mo. i.e. increasing C, Cr, Mo levels increase the alloy hardness (HV).On the other hand, increasing Mn and austenitization temperature decrese the alloy hardness and increases the alloy toughness.



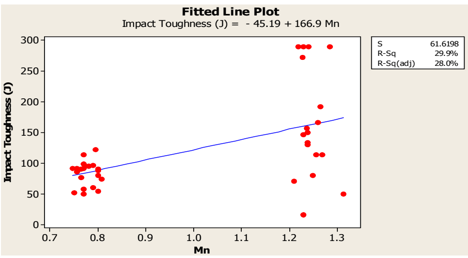
(a)



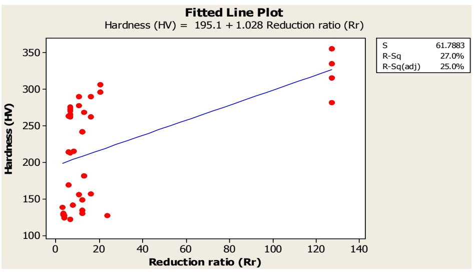
(b)



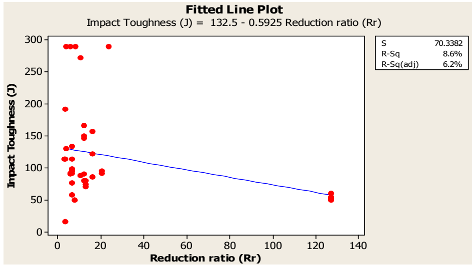
(c)



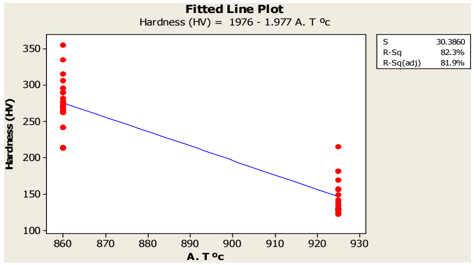
(d)



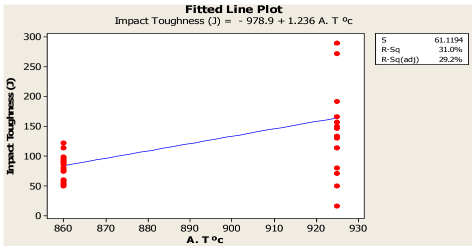
(e)



(f)



(g)



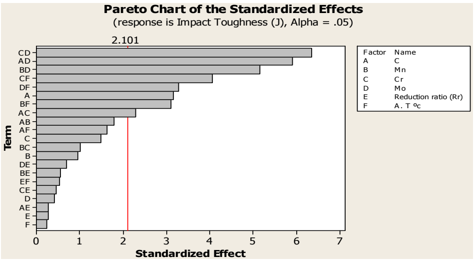
(h)

Fig. 3 Fitted Line Plots for Hardness (HV) and Impact Toughness (J) with different Alloying and TMT Parameters; a) Hardness (HV) with %C, b) Impact toughness (J) with %C, c) Hardness (HV) with % Mn, d) Impact toughness (J) with %Mn, e) Hardness (HV) with %Reduction Ratios, f) Impact toughness (J) with %Reduction Ratios, g) Hardness (HV) with Austenitizing Temperature and h) Impact toughness (J) with Austenitizing Temperature

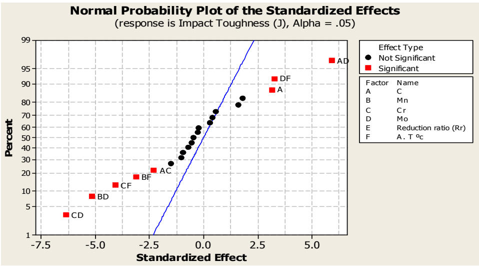
2. Factorial DOE Results

Mathematical model (Impact Toughness Model) is developed to relate the alloy Impact Toughness (J) with alloying elements, hot rolling reduction ratio and austenitization temperature to acquire an understanding of the effect of these variables and their interactions on the impact toughness (J) of heat treated low alloy steels.

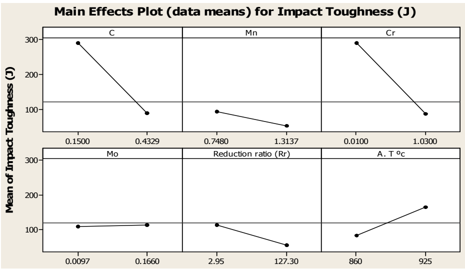
Factorial Plots (main effect plot) and Normal Probability plot of the standardized effects for the impact toughness (J) data having a confidence level of 95% are presented in Figs. 4 (a), (b). The effects plot for the mean values of impact toughness (J) and hardness (HV) data in terms of the different metallurgical parameters are shown in Figs. 4 (c)-(e).



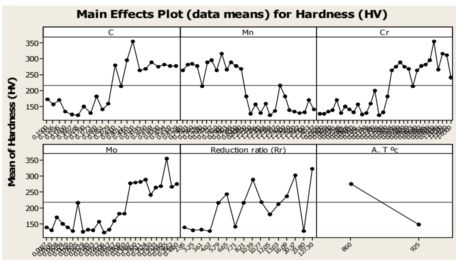
(a)



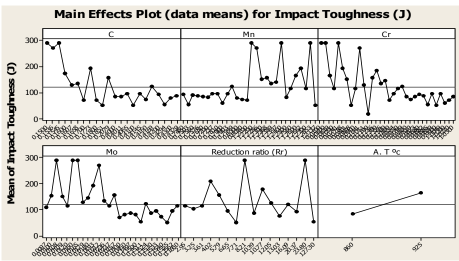
(b)



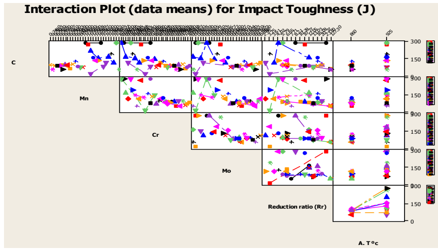
(c)



(d)



(e)



(f)

Fig. 4 Factorial and ANOVA Plots; (a) Normal Probability Plot of the standardized effects for the impact toughness (J), (b) Pareto Chart of the standardized effects for the impact toughness (J), (c) Factorial main effects plot for the mean values of Impact toughness (J), (d) ANOVA main effects plot for the mean values of Hardness (HV), (e) ANOVA main effects plot for the mean values of Impact toughness (J) and f) Interaction plot for the mean values of Impact toughness (J)

In the predicted model (Refer to (3)); within the variation range of the variables studied, the most significant effects are corresponding to the highlighted colored (main and interaction effects). The R – Sq value given is 94.08%. The p – value for the main effects (p=0.000) and 2-Way Interactions Effects (p=0.000) parameters in hardness (HV) model shows that the values are below the accepted value of 0.05.

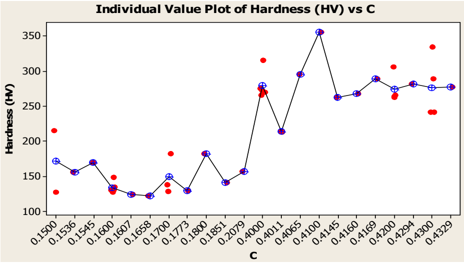
$$\text{Impact Toughness (J)} = -680052 * C - 65364.4 * C * Cr + 1070223 * C * Mo - 418978 * Mn * Mo - 856.148 * Mn * A.T\,^{o}c - 295136 * Cr * Mo - 741.437 * Cr * A.T\,^{o}c + 3092.52 * Mo * A.T\,^{o}c \quad (3)$$

3. ANOVA Results

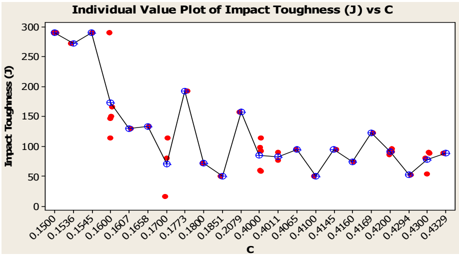
One way ANOVA for hardness and impact toughness data results having a confidence level of 95% with different alloying elements (%C and %Cr) and hot rolling reduction ratio (Rr) are shown in Fig. 5. Similar to fitted plot results, in one way ANOVA, it is observed that increasing alloying element content increase alloy hardness (HV) but decrease impact toughness (J) i.e. increasing C, Cr and Mo levels increase the alloy hardness (HV). However, Mn increases the alloy toughness. Results for Mn, Cr and Mo as well as austenitization temperature are found but not presented.

4. Response Surface Methodology

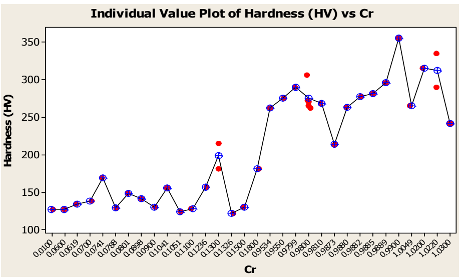
Response surface methodology is used to investigate the relationship between metallurgical parameters with the hardness (HV) and impact toughness (J) of low alloy steels. Fig. 6 shows the contour plots of impact toughness (J) and hardness (HV) at various combination values of metallurgical parameters.



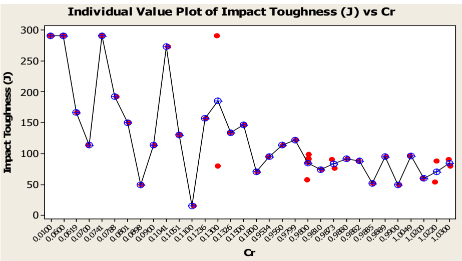
(a)



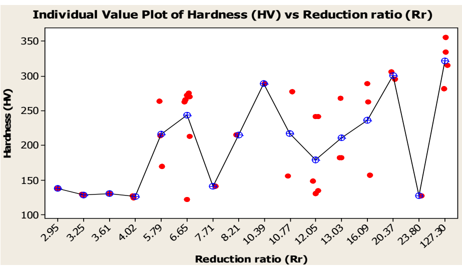
(b)



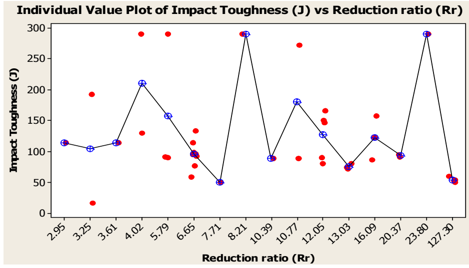
(c)



(d)

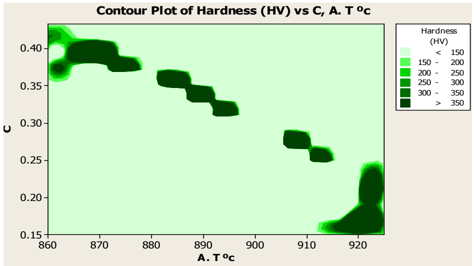


(e)

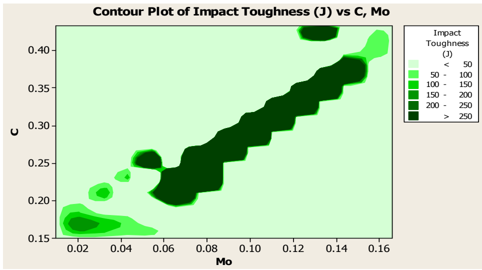


(f)

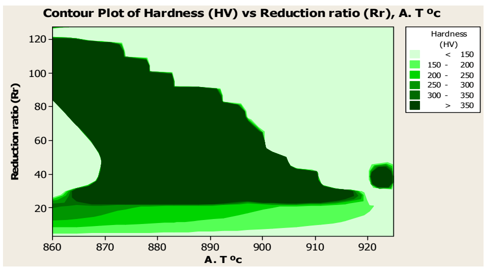
Fig. 5 One-Way ANOVA Plots for Hardness (HV) and Impact toughness (J) with different Alloying and TMT Parameters; (a) Hardness (HV) with %C, (b) Impact Toughness (J) with %C, (c) Hardness (HV) with %Cr, (d) Impact Toughness (J) with %Cr, (e) Hardness (HV) with %Reduction Ratio (Rr), and (f) Impact Toughness (J) with %Reduction Ratio (Rr)



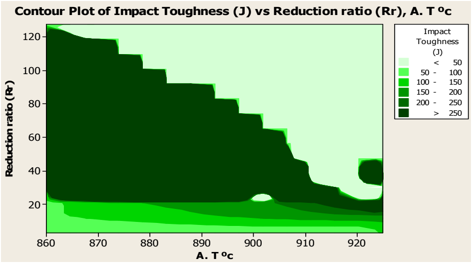
(a)



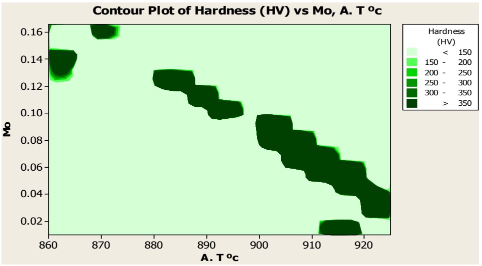
(b)



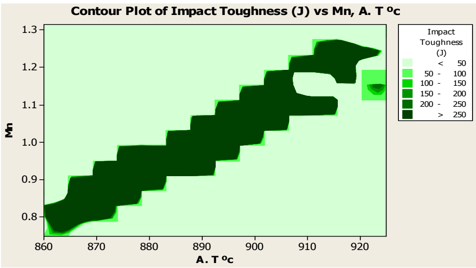
(c)



(d)



(e)



(f)

Fig. 6 Contour Plots of Impact Toughness (J) and Hardness (HV) vs. Various Combinations of Different Variables; (a) Hardness (HV) vs. %C and A. T0C, (b) Impact Toughness (J) vs. %C and %Mo, (c) Hardness (HV) vs. Reduction Ratio (Rr) and A. T0C, (d) Impact Toughness (J) vs. Reduction Ratio (Rr) and A. T0C, (e) Hardness (HV) vs. %Mn and A. T0C, and (f) Impact Toughness (J) vs. %Mn and A. T0C

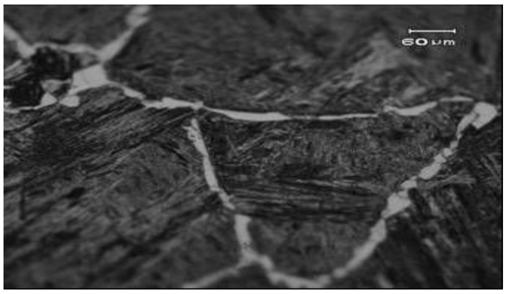
D. Microstructure of Low Alloy Steels

Hot work prior heat treatment yields an equiaxed microstructure at both reduction ratios studied, Fig. 7. Pro-eutectoid ferrite phase is observed in low alloy steels in the hot forged conditions regardless of reduction ratios. An example of proeutectoid ferrite on the grain boundaries is illustrated in Figs. 7 (a), (b) when hot forging is carried out at reduction ratios of 1.11 and 1.29, respectively. Proeutectoid ferrite becomes coarser and more numerous with increasing hot working reduction ratio, Figs. 7 (a), (b).

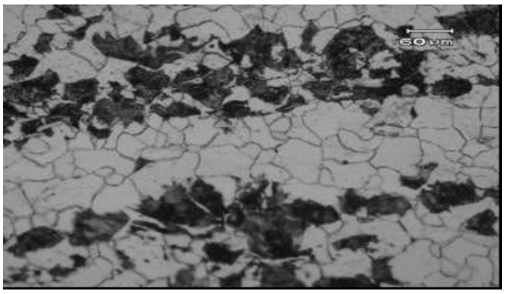
Heat treatment following TMT changes the morphology from deformed grains to recrystalized equi-axed grains, resulting in a significant change in mechanical behavior, and a corresponding increase in impact toughness. Normalizing heat treatment has been observed to lower grain size considerably, Figs. 7 (c), (d). Normalizing slightly refines the microstructure in the hot forging low alloy steels. On the other hand, annealing has a negative effect in the microstructure of the hot forged low alloy steel (coarsening effect), this effect being more pronounced in alloys with high prior hot forging reduction ratio. Normalizing heat treatment after hot forging has been observed to lower grain size considerably, (Figs. 7 (e), (f)). An equiaxed microstructure is apparent in micrographs; see Figs. 7 (e), (f). Fine and coarse pearlite are observed in the TMT plus normalized and annealed conditions. Feathery bainite (upper) appears in the hot forged plus hardened and tempered conditions.

Optical micrographs obtained from alloy codes 2 and 3 after hot rolling and different heat treatment conditions are shown in Fig. 8. Elongated and fine equi-axed structure in the heat treated and tempered conditions (Q/T) condition are shown in Fig. 8 (a). A mixture of bainite and tempered martensite structure are shown in the Q/T are shown in Fig. 8 (b). The reduction ratio in Figs. 2 (a), (b) is ~6%. Figs. 8 (c), (d) show the presence of both ferrite grains and pearlite bands in alloy code 3 in the hot rolled plus normalised conditions. The banding effect in the longitudinal direction can be clearly seen in the lower magnification micrographs, Fig. 8 (c), (d). Normalizing treatment following TMT changes the morphology from deformed grains to recrystalized equi-axed grains, resulting in a significant change in mechanical behavior, and a corresponding increase in impact toughness (J).

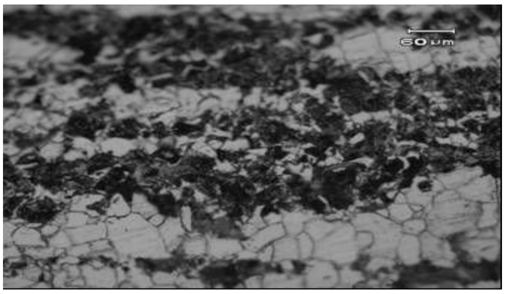
(a)



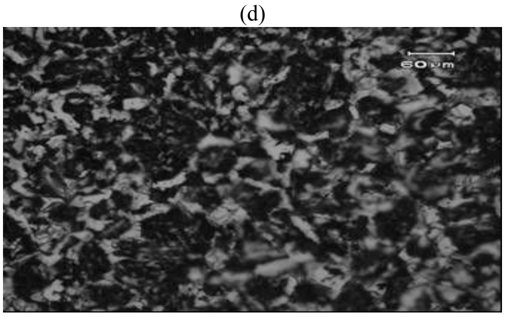
(b)



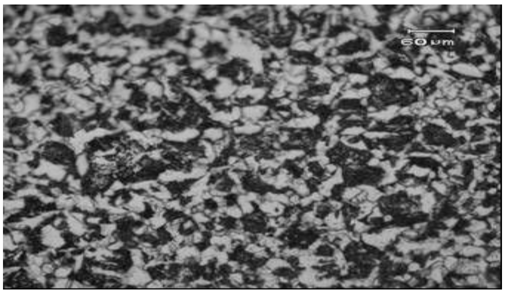
(c)



(d)

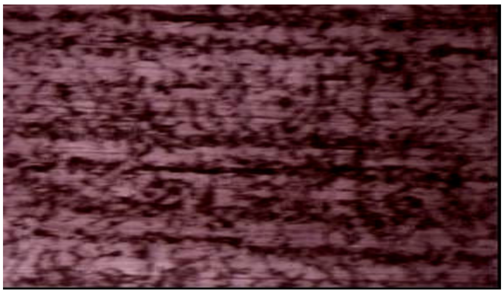


(e)

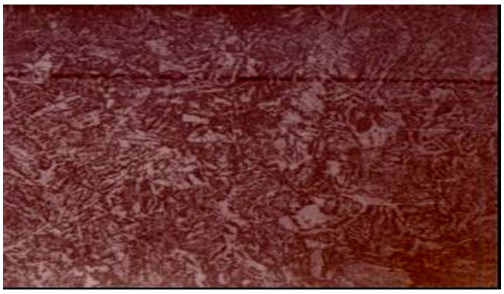


(f)

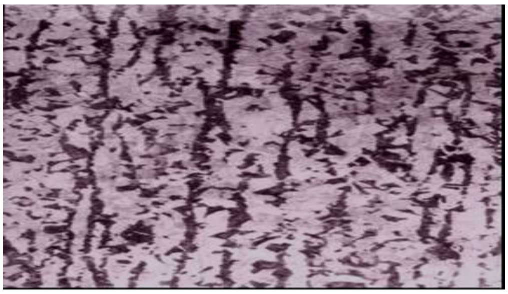
Fig. 7 Optical Micrographs for Low Alloy Steel (Alloy Code 1) at Different Conditions; (a) Hot Forged (R= 1.11) Showing the Presence of Pro-eutectoid Ferrite Phase, (b) Hot Forged (R= 1.29) Showing the Presence of Pro-eutectoid Ferrite Phase, (c) TMT plus Annealed Condition (R= 1.11) Showing the Presence of Coarse Ferrite and Pearlite Phases, (d) TMT plus Annealed Condition (R= 1.29) Showing the Presence of Coarse Ferrite and Pearlite Phases, (e) TMT plus Normalised Condition (R= 1.11) Showing the Presence of Fine Ferrite and Pearlite Phases, and f) TMT plus Normalised Condition (R= 1.29) Showing the Presence of Fine Ferrite and Pearlite Phases, All at 500X



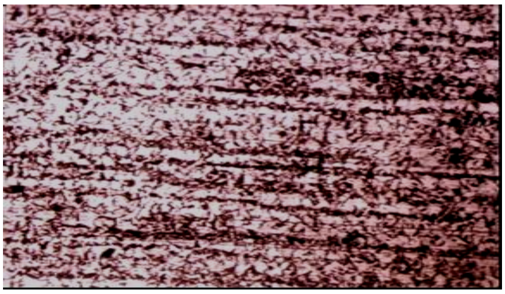
(a)



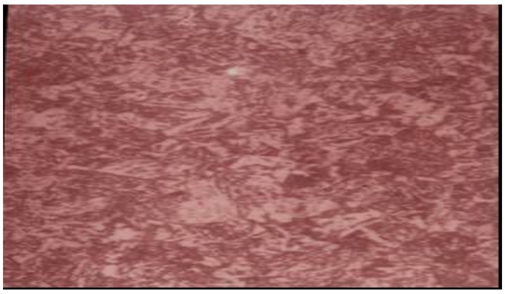
(b)



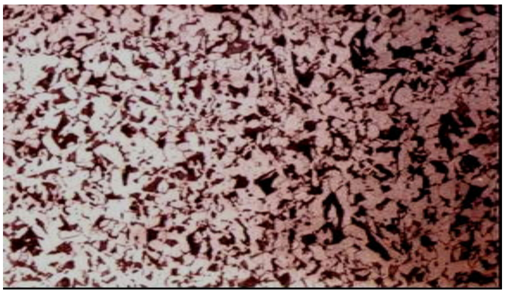
(c)



(d)



(e)



(f)

Fig. 8 Optical Micrographs obtained from Low Alloy Steels (Alloy Codes 2-5); (a) Alloy Code (2) in the Hot Rolled Condition, Rr = ~6%, (b) Alloy Code (2) in the Hot Rolled plus Heat Treated Condition (Q/T), Rr = ~6%, (c) Alloy Code (3) in the Normalized Conditions after Hot Rolling, Rr= 6%, (d) Alloy Code (3) in the Normalised Conditions after Hot Rolling, Rr= 12%, (e) Alloy Code (4) in the Normalized Conditions after Hot Rolling, Rr= 6%, and (f) Alloy Code (5) in the Normalised Conditions after Hot Rolling, Rr= 12%, All at 200X

IV. Conclusions

1. Hot forging reduction ratio can decrease alloy impact toughness in the TMT conditions.
2. Normalising following TMT show lower impact toughness than the annealing following the TMT conditions.
3. Hot rolling affects the hardness (HV) and impact toughness (J) of low alloy steels.
4. Hot rolling reduction ratio can increase the hardness (HV) and decrease the alloy toughness.
5. Equiaxed ferrirte grains and pearlite banding are revealed in the as-rolled and normalised conditions
6. Regression and mathematical models are developed for hardness and impact toughness calculation in terms of different alloying element and TMT parameters.

Acknowledgment

Financial and In-kind received support from the Deanship of Scientific Research, Vice Rectorate for Post Graduate and Scientific Research, Prince Sattam bin Abduaziz University (SAU) is gratefully acknowledged. Support from Professor El-Sayed El-Banna, Metallographic Laboratory at Mining, Petroleum and Metallurgy (MPM) Department, Faculty of Engineering at Cairo University is gratefully acknowledged.

References

[1] P. L. Orsettirossi and C. M. Sellars; mat. Sci. and tech., vol.15, February. 1999, p.185
[2] Show, B.K.; Veerababu, R.; Balamuralikrishnan, R.; Malakondiah, G. Effect of vanadium and titanium modification on the microstructure and mechanical properties of microalloyed HSLA steel. Material Science and Engineering A 2010, 527, 1595–1604.
[3] S. V. Radcliffe, E.B. Kula 1964 Deformation, Transformation, Strength. Fundamentals of Deformation Processing. Syracuse University Press, New York, PP. 321-63
[4] V. F. Zackay, E. R. Parker, D. Fahr, R. Busch 1967 The enhancement of Ductility in high strength steels. ASM Trans.Q.60: 252-59
[5] T Ochi, T Takahashi, H Takada, "Improvement of the Toughness of Hot Forged Products Through Intragranular Ferrite Formation", 30th Mechanical Working and Steel Processing Conference, Dearborn, Michigan, USA, Vol. XXVI,1988. pp. 65-72.
[6] Gunduz, S.; Cochrane, R.C. Influence of cooling rate and tempering on precipitation and hardness of vanadium micro- alloyed steel. Materials and Design 2005, 26 (6), 486–492.