EFFECT OF HOT FORGING REDUCTION RATIO AND HEAT TREATMENT ON HARDNESS, IMPACT TOUGHNESS AND MICROSTRUCTURE OF CARBON AND LOW ALLOY STEELS

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ABSTRACT

The present study was undertaken to investigate the effect of hot work reduction ratio in thermo- mechanical heat treatment (TMT) on the hardness and impact toughness of different grades of plain-carbon and low alloy steels. The effect of hot forging reduction ratios on the hardness and impact toughness properties are studied. An extensive study is carried out to investigate the combined effect of hot forging reduction ratios and heat treatment on the hardness and impact toughness of low alloy steels. An understanding of the combined effect of hot work and heat treatment on the hardness and impact toughness would help in selecting conditions required to achieve optimum mechanical properties and alloy high strength to weight ratio. It is found that hot forging can affect the mechanical behavior of plain carbon and low alloy steels. An increase in hot forging reduction ratio is produced high hardness levels and low impact toughness.

An increase in alloy hardness is observed when hot forging is carried out at 1200C using mechanical press with 800 ton capacity (i.e. reduction ratio=1.29). Annealing following TMT produced a sharp rise in impact toughness compared with the TMT conditions. Normalising following TMT optimise both hardness and impact toughness for low alloy steel. Increasing reduction ratio increases the hardness of both TMT and TMT plus hardened conditions and decrease the hardness of the TMT plus annealed and TMT plus normalized conditions. The post cooling rate following hot forging can affect the impact toughness of carbon and low alloy steels. Air cooling after hot forging improves both hardness and impact toughness of carbon steels. Normalizing refine the microstructure and improve the alloy mechanical properties. Annealing improve alloy toughness and decrease alloy strength (coarsening effect). Pro-eutectoid ferrite phase is observed in low alloy steel in the TMT conditions regardless of reduction ratio. Feathery bainite (upper) appears in the quenched and tempered conditions. Fine and coarse pearlite are observed in the normalized and annealed conditions.

Keywords: Hot Forging/Rolling, Mechanical Behavior, Microstructure, Low Alloy Steels And Thermo-Mechanical Treatment (TMT).

I. INTRODUCTION

Forging is a useful technique to produce components for aerospace applications that require high strength-to-weight ratios. Many engineering components made of carbon and low alloy steels have been, and still are being produced via forging followed by quenching and tempering. Hot forging achieve desired shape and improve physical properties and obtain excellent mechanical properties of the low alloy steel. Thermo-mechanical treatment (TMT) of steels, which entails plastic deformation with simultaneous phase transformation, yield high strength materials, improve fatigue, creep, corrosion resistance and fracture toughness coupled with good formability. High density of defects introduced by hot forging/rolling, can severely affect the phase transformation by providing nucleation sites and aiding diffusion processes. Zackay et al [2] developed in 1967 a new class of high-strength metastable austenitic steels making use of strain–induced martensitic transformation. These steels are known as TRIP steels. However, Radcliffe and Kula [1] classified the various steels that undergo phase transformation according to whether deformation is introduced before, during, or after the phase transformation.

The principle behind TMT is that plastic deformation results in the production of various crystal defects such as vacancies, dislocations, sub-grain boundaries and stacking faults. These defects can severely affecting 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. 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. A heavily dislocated microstructure is created and is observed to act as nucleation sites for new grains during recrystallization [3].

Further increase of toughness can be achieved by microstructural control during the thermomechanical processing [4]. Another influencing factor on the toughness could be the presence of grain boundary ferrite after deformation at low temperatures which improves the ductility [5]. Improvement of low alloy steel toughness through grain refining is caused by pro-eutectoid ferrite formation.[6] Acicular ferrite microstructure is produced by a moderate cooling rate after forging, which in turn results in a good combination of strength and toughness [7]. The toughness of low alloy steel can be improved by pro-eutectoid ferrite formation on the grain boundaries and grain refining [6]. Addition of vanadium and nitrogen can enhance the formation of pro-eutectoid ferrite phases along the grain boundaries in the low alloy steel that continuously cooled after heated at 1200C[8]. It is observed that the vanadium nitrides can precipitate on the manganese sulfide particles and can act as nucleation sites of pro-eutectoid ferrite plates along the grain boundaries. Complex precipitates of (MnS_V(C, N)) are currently thought one of the most superior nucleation sites of pro-eutectoid ferrite. As the size of MnS is increased, the potency of complex precipitates as the ferrite nucleation sites is increased. This result indicates that the formation of pro-eutectoid ferrite plates is promoted by increasing the number of manganese sulfide particles, resulting in an increase in the resistance to the propagation of brittle fracture.

Low alloy steel can attain acceptable properties for many applications following hot forging either via cooling freely in air, or through direct quenching. One of the most important processing factors affecting the properties of low alloy steel is the post forging cooling procedure. Forged steel is hardened when it is still in the austenitic state after hot forging. Increasing the cooling rate generally increases the strength and hardness and decrease impact toughness. Production of engineering components from low alloy steel via forging procedures designed to give fine austenite microstructure, followed by either direct quenching with a subsequent tempering or controlled cooling (ferrite/pearlite microstructure). In comparison to conventionally processed quenched-and-tempered steels, direct-cooled low alloy steels offer the potential for significant cost savings [9].

Normalised steel will consist of fine ferrite or cementite with grains of pearlite but hardened and tempered steel will be expected to have a bainitic structure or tempered martensite. Tempering reduces brittleness imparted by hardening and produces definite physical properties within the steel. The resultant strength, hardness, and ductility depend on the temperature to which the steel is heated during the tempering process. Slower cooling rates produce coarser microstructures. In the present work, an extensive study was carried out to investigate the effect of hot forging/rolling reduction ratio and different heat treatment on the hardness and impact toughness of different grades of plain carbon and low alloy steels.

II. EXPERIMENTAL PROCEDURES AND METHODOLOGY

Low alloy steel (E410) is supplied in the form of bars (L*D=150mm*50mm). However, carbon steels (A36) and (C45) are supplied in the form of bars (L*D=100mm*50mm). The alloy compositions for these alloys are listed in Table 1. Hot forging followed by water cooling is conducted for low alloy steel (E410) at 1200C using mechanical presses of 500 and 800 ton capacities. However, hot forging followed by air cooling is conducted for C-steels (C45) and (A36) at 1200C using mechanical presses of 500 ton capacity. Different reduction ratios are produced. Hardness and impact toughness measurement were performed on all specimens prepared from the various plain carbon and low alloy steels after hot forging and different heat treatment, see Table 2. Samples for metallographic examination are sectioned from the broken impact samples (corresponding to each condition), mounted, polished and etched using Nital solution. The microstructure is analyzed using an optical and SEM microscope.

Table1 Chemical compositions for low alloy steel (E410) and low and medium C-steels (A36 and C45) used in the present work.

Alloy		C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Al
1	E410	0.22	0.31	1.33	0.007	0.05	0.15	1.02	0.005	0.02	0.04
2	C45	0.46	0.21	0.64	0.02	0.028	0.07	0.08	0.01	0.21	0.02
3	A36	0.2	0.35	0.9	0.02	0.008	0.0	0.0	0.0	0.0	0.0

Table 2 Heat Treatment Conditions Used For Low Alloy Steel (E410) And For C-Steels (A36 And C45).

Alloy		Reduction Ratio (R)	Cond Ition	Heat Treatment Condition				
				A. Temp °c	Time	Q media	T. Temp °	Time
1	E410	1.11 and 1.29	TMT	1200	30 min	Water	Hot forged	
			N	920	30 min	Air	Normalized	
			A	920	30 min	Furnace	Annealed	
			H	920	30 min	Water	Hardened	
			H/T	920	30 min	Water	600	120 min.
2	C45	1.16 and 1.05-1.17	TMT	1200	30 min	Air	Hot forged	
			N	845	30 min	Air	Normalized	
			A	845	30 min	Furnace	Annealed	
			H	845	30 min	Water	Hardened	
			H/T	845	30 min	Water	620	120 min.
3	A36	1.16 and 1.05-1.17	TMT	1200	30 min	Air	Hot forged	

III. RESULTS AND DISCUSSIONS

3.1 Hardness (HV) and Impact Toughness (J) Results

The effect of hot forging reduction ratio on the hardness, impact toughness of TMT and heat treatment of low alloy steels are investigated. An understanding of these parameters would help in selecting the metallurgical conditions required to achieve the optimum mechanical properties and maximum strength to weight ratio. The hardness and impact toughness of low alloy steel depends mainly on the TMT reduction ratio and the following heat treatment conditions. Hardness (HV) and impact toughness (J) measurements are obtained from all specimens involved in this study. The results are provided in Table 3 and Table 4.

Table 3 Hardness (Hv) AND IMPACT TOUGHNESS (J) RESULTS FOR LOW ALLOY STEEL (E410) AND MEDIUM C-STEEL (C45) UNDER DIFFERENT HOT FORGING REDUCTION RATIOS AND HEAT TREATMENT CONDITION.

Condition	E410				C45	
	Hardness (HV)		Impact Energy (J)		Hardness (HV)	Impact Energy (J)
	R=1.11	R=1.29	R=1.11	R=1.29	R=1.16	
TMT*	360 ± 38	433± 40	10± 0	8± 0	170±8**	47±7**
TMT+A	143± 3	143± 13	182± 25	161 ± 1	149±2	75±7
TMT+N	193± 7	230± 15	54 ± 5	40 ± 0	165±6	94±3
TMT+H	366± 12	393± 19	69± 4	62± 3	420±9	8±3

* TMT= thermo-mechanical treatment using hot forging followed by water cooling for low alloy steel E410 and using hot forging followed by air cooling for C-steel C45. A=annealed, N=normalized, H= hardened and R= reduction ratio (A0/Ai) i.e. original cross section area (A0)/instantaneous cross section area (Ai).

Table 4 Hardness (HV) and impact toughness (J) results for C-steels (C45) and (A36) under different hot forging reduction ratio and heat treatment conditions.

TMT* /number of strokes using 500 ton capacity						C45		A36	
Dmm	Dimension L*W*H mm3	D/H	D/W	R	No. of strock	Hardness (HV)	Impact Energy (J)	Hardness (HV)	Impact Energy (J)
50	113*48*36.2	1.38	1.04	1.13	1	236±30.5	91±13	139.5±5.5	132±3
50	122*62*29.5	1.69	0.80	1.07	2	254±42.5	45.5±25	148±5.5	104±13
50	126*60*28	1.78	0.83	1.17	3	212.5±9.5	68±5.5	147.5±4.5	106±12
50	130*77*24.2	2.06	0.65	1.05	4	309±32.5	30±3	149.5±7.5	102±33.5

* TMT= thermo-mechanical treatment using hot forging followed by air cooling. R= reduction ratio (A0/Ai) i.e. original cross section area (A0)/instantaneous cross section area (Ai).

3.1.1 Low Alloy Steel (E410) and C-steel (C45): Effect of TMT Reduction Ratio (R) and Heat Treatment

For low alloy steel grade (E410), it is observed that the hardness is increased with increasing hot forging reduction ratio however, the impact toughness is decreased. As the reduction ratio is increased from 1.11 to 1.29, the hardness is increased from 360 HV to 433 HV and the toughness is decreased from 10 J to 8J, see Table 3 and Figs. 1(a, b). This can be explained due to the high defect structure obtained with the high reduction ratio.

Annealing following hot forging reduce the hardness but increase the impact toughness. For TMT (hot forged) plus annealed condition, the hardness produced is smaller than those for the TMT condition. The hardness value remains the same (i.e. 143 HV) with increasing TMT reduction ratio from 1.11 to 1.29. This can be attributed to the grain coarsening effect that takes place during annealing heat treatment with both reduction ratios. On the other hand, the TMT plus annealed condition show a remarkable increase in impact toughness as compared to those values of the TMT condition. It is found that the impact toughness is increased from 10J to 182J and from 8 to 161J when increasing reduction ratio from 1.11 to 1.29, respectively.

From the results presented in Fig. 1 (a), it is observed that the TMT plus annealed condition show the lowest hardness levels and the highest impact toughness levels as compared to the other conditions. The impact toughness is higher in the TMT plus annealed condition than the TMT plus normalized and hardened ones, due to the softening and coarsening effect. However, normalizing following TMT converts the heterogeneous structure, developed after hot forging, to a finer and more uniform one. The TMT plus normalized alloy displayed higher hardness values than the TMT plus annealed one regardless of the prior hot work, where hardening occurs by grain refining in TMT plus normalized condition compared to coarsening in the case of TMT plus annealed one. Hardness is increased from 366 HV to 393 HV for the TMT plus hardening conditions with increasing reduction ratio from 1.11 to 1.29, respectively. However, impact toughness is decreased from 69J to 62J are observed, Fig. 1(b).

3.1.2 C-Steels (C45) and (A36): Effect of TMT Reduction Ratio (R)

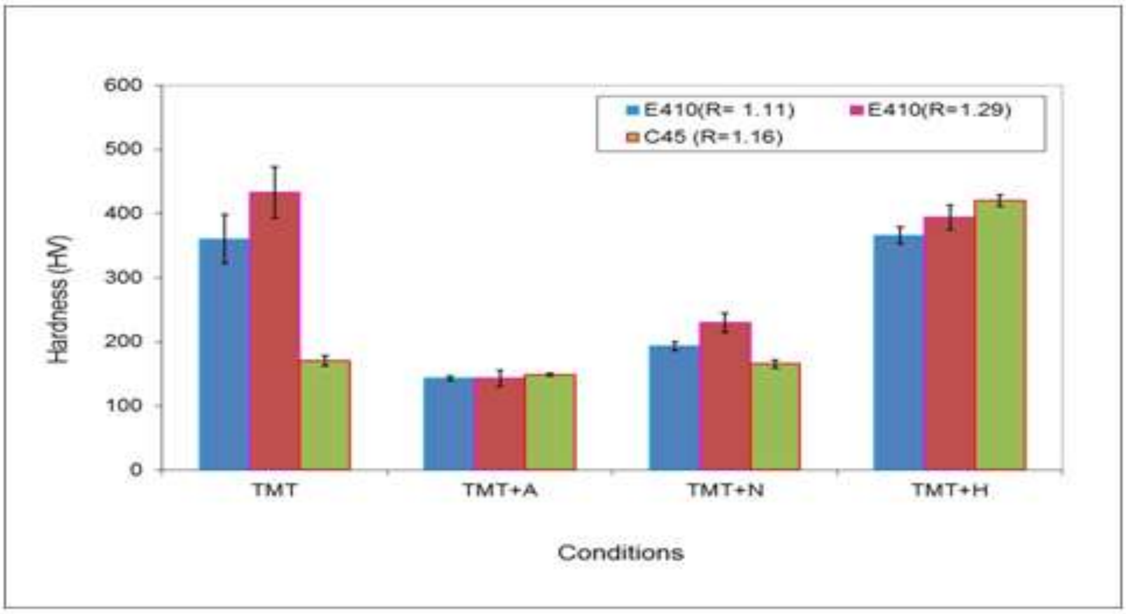
The results for different heat treatment carried out following TMT for C- steel (C45), revealed that normalizing following TMT with hot forging reduction ratio of 1.16 yields optimum mechanical properties than those at all other conditions. For C-steel (C45) in the TMT condition, it is found that the hardness and impact toughness are higher as compared to those of TMT condition for low alloy steel (E410). This can be attributed to the effect of cooling rate after hot forging. Air cooling after hot forging normalizes the microstructure of the C-steel (C45). However, water cooling enhance the carbide formation in low alloy steel (E410) due to the presence of 1% Cr.

Similar to C-steel (C45), hot forging followed by air cooling for C-steel (A36) produce high value in both hardness and impact toughness, see Fig. 1 (c, d). It is noticed that hot work prior to heat treatment has significant effect on the mechanical behavior of low alloy and plain carbon steels. 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 impact toughness.

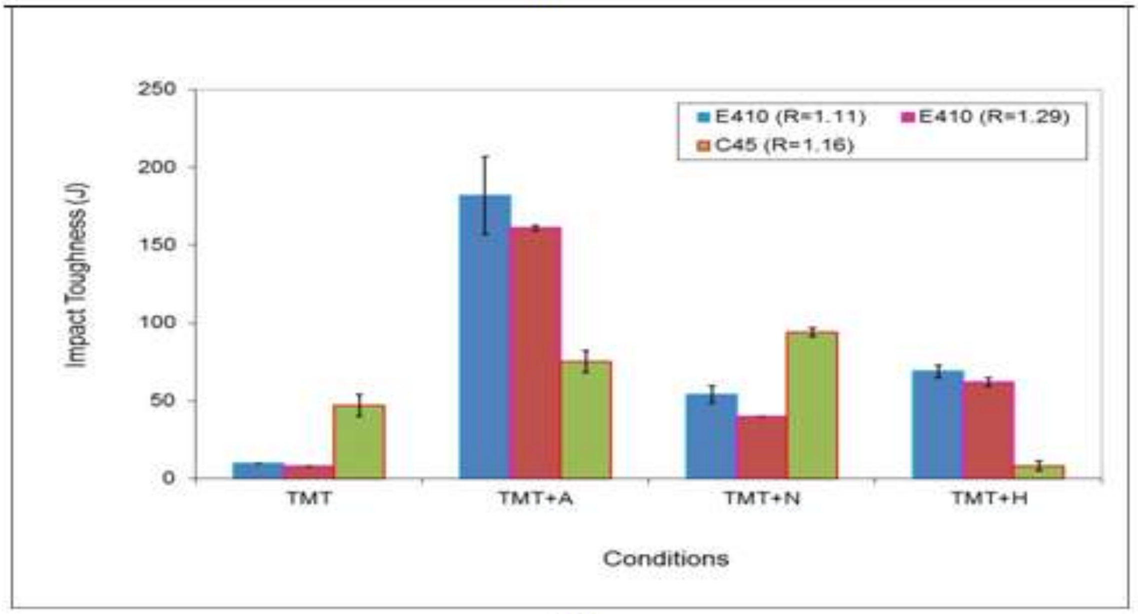
For TMT specimens, the result shows that annealing reduces the strength and increases the impact toughness. This could be attributed to recovery effects. However, the hot forged plus normalized condition for C-steel (C45) produce the optimum hardness and impact toughness properties. It is observed that, the hardness and impact toughness values are increased as compared to those of hot forged plus annealed condition. The hardness results for low alloy steels (E410) and C-steel (C45) presented in Fig. 1(a) show that, the TMT plus annealed condition exhibit lower hardness levels compared to the TMT plus normalized one. The TMT plus annealed and TMT plus normalized conditions show lower hardness values than the TMT condition regardless of reduction ratio. However, the opposite is observed for impact toughness of those alloys as shown in Figs. 1(a, b).

For low alloy steel (E410), the TMT plus annealed condition exhibit higher toughness levels than do the TMT plus normalized one regardless to the hot forging reduction ratio, see Figs. 1 (a, b). The opposite is true for C-steel (C45), see Figs. 1 (c, d). This may be explained on the basis of the cooling effect after hot forging. For low alloy steel (E410), it is found that a remarkable increase in hardness is obtained for TMT samples, Fig. 1(a).

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 the TMT plus normalized one regardless of reduction ratio. However, the reverse is true for impact toughness. Hardness is increased by 20% as the reduction ratio is increased from 1.11 to 1.29. On the other hand, impact toughness is reduced by 20%, see Figure 2. Typical impact energy and hardness for low alloy steel in the TMT conditions are on the order of 8 J and 433 HV.



(a)



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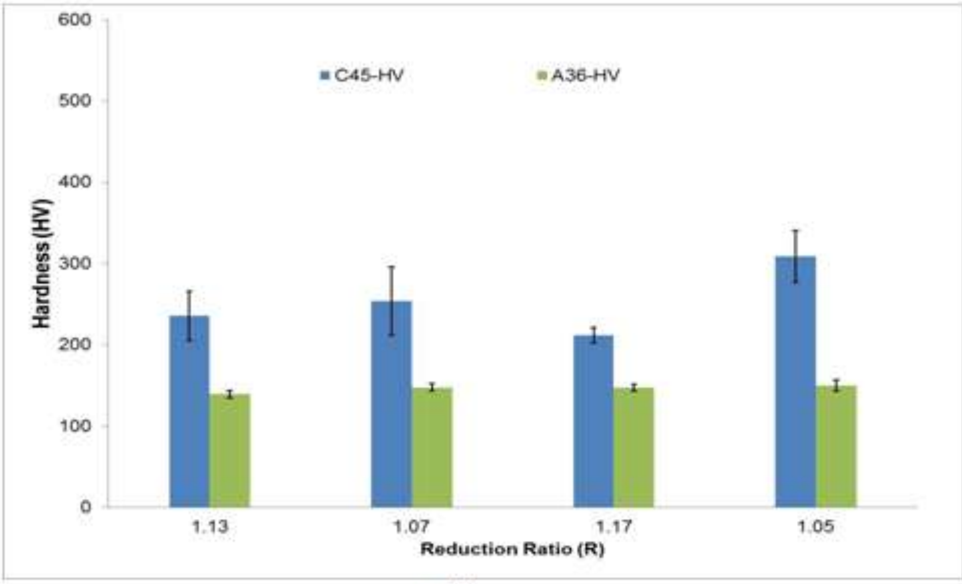
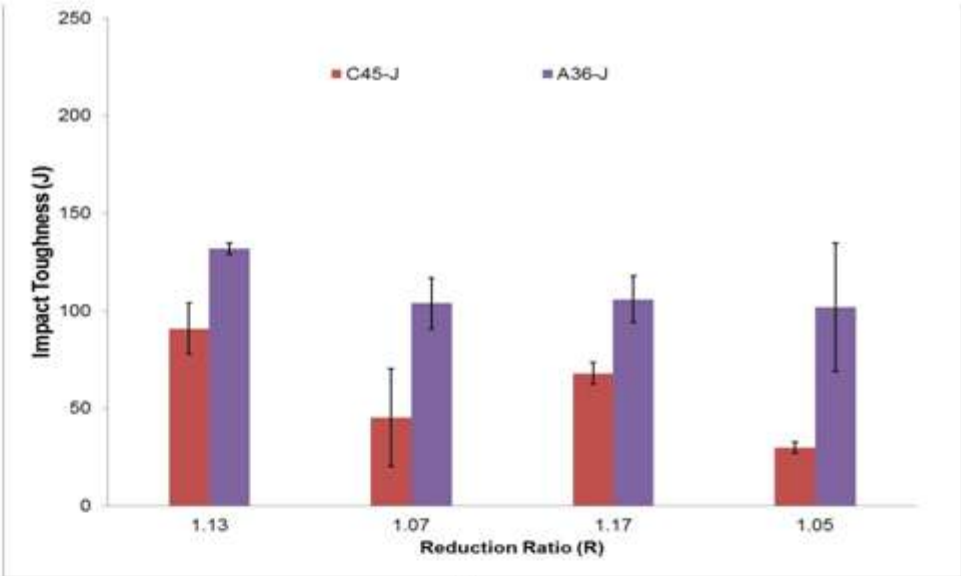


(c)



(d)

Figure 1 Hardness (HV) And Impact Toughness (J) Results; (A, B) Low Alloy Steels (E410) And C-Steel (C45): Combined Effect Of TMT Reduction Ratio And Heat Treatment, (C, D) C-Steels (C45) And (A36): Effect Of TMT Reduction Ratio.

3.2 Microstructure of TMT low Alloy Steels

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. The presence of pro-eutectoid ferrite on the grain boundaries enhances the impact toughness properties regardless of the heat treatment conditions. It is observed that impact toughness increase with increasing hot forging reduction ratio regardless to heat treatment conditions. This can be explained to the presence of pro-eutectoid ferrite with high surface fraction on the grain boundaries, see Figs. 2(a, b). The percent of pro-eutectoid ferrite is measured for the TMT samples at both reduction ratios. It is found that when the reduction ratio is increased from 1.11 to 1.29, the percent of pro-eutectoid ferrite is increased by 100 % i.e. the surface fraction of the pro-eutectoid ferrite phase is increased from 5.3%±0.2 to 10.6%± 0.8.

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, see Figs. 2 (c, d). Normalizing heat treatment has been observed to lower grain size considerably, Figs. 2 (e, f). Normalizing heat treatment after hot forging has been observed to lower grain size considerably, Table 5. 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. An equiaxed microstructure is apparent in micrographs; see Figs. 2 (e, f).

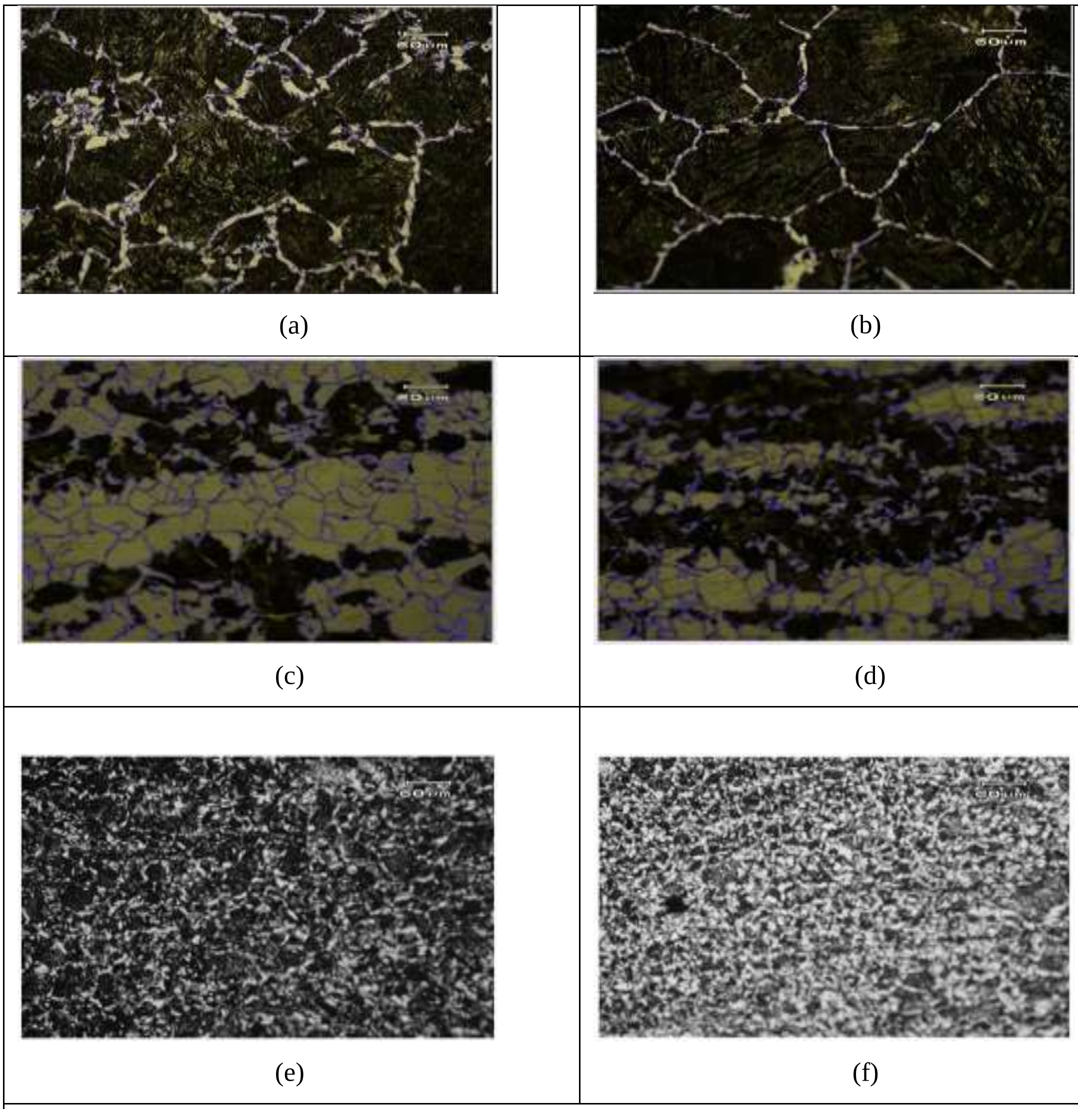


Figure 2 Optical micrographs obtained from low alloy steel (E410) samples in the (a) TMT and (b) TMT, Reduction ratio (R) in (a) R=1.11 and (b) R=1.29, and magnification in (a, b) =200X. (c, d) Optical micrographs obtained from TMT plus annealed samples (c) R=1.11 and (d) R=1.29, and magnification at 500X. (e-f) hot forging plus normalized (R= 1.11) and hot forging plus normalized (R= 1.29), and magnification at 200X.

The grain size of the TMT plus annealed samples decreases with increasing hot forging reduction ratio. The grain size of ferrite phase decreased from 12.5µm±6.7 to 10.36 µm±5.1 when increasing forging reduction ratio from 1.11 to 1.29 for the TMT plus annealed samples with magnification of 200X. The variation in ferrite grain size is reduced from SD=6.7 to SD=5.1 at magnification of 200X and from 16.5 to 11.91 at 500X when increasing the reduction ratio from 1.11 to 1.29. The percentage of ferrite phase is decreased from 56.9% ±1.3 to 42.9% ±3.9 when increasing the reduction ratio from 1.11 to 1.29 at lower magnification 200X, see Table 4. On the other hand, the TMT plus normalized samples show a reverse behavior to the TMT plus annealed samples. The ferrite grain size is increased from 5.98µm±2.32 to 9.12 µm±3.51 when increasing the reduction ratio from 1.11 to 1.29. The high defect produced at the higher reduction ratio accelerates the recrystallization processes and the grains may become coarser when the normalizing heat treatment is carried out after hot forging.

Hot forged microstructure consists of coarse primary ferrite grains which have formed on the boundaries of large austenite grains. The microstructure produced after hot forging when re-austenitized in a lower temperature range, smaller austenite grains is formed, and a fine structure is produced up on air cooling. In addition to the refinement of the prior austenite grains, there is a reduction in the size of the primary ferrite grains. This is due to the effect of the temperature of formation on the nucleation rate of these crystals. In addition, the faster cooling allows less primary ferrite to form, so that more pearlite is present. Also, since the pearlite forms in a lower temperature range, it will be finer and hence harder. All of these factors make normalised steel appreciably harder than the same steel in the annealed conditions.

Table 5 ferrite phase grain size and surface fraction as a function of hot forging reduction ratio and heat treatment conditions at different magnification

Condition	Ferrite grain size (diameter-µm)		Ferrite phase surface fraction (%)	
	R=1.11	R=1.29	R=1.11	R=1.29
TMT*+A	12.5±6.7	10.4±5.1	56.9±1.3	42.9 ±3.9
TMT*+N	6±2.3	9.1±3.5		

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

IV. CONCLUSION

1. Hot forging followed by water cooling increases the alloy hardness and decreases the toughness of low alloy steel (E410).
2. Increasing hot forging reduction ratio from 1.11 to 1.29 increase hardness and decrease toughness of low alloy steel. This can be explained due to the high defect structure obtained with higher reduction ratio.
3. Post cooling rate after hot forging affect the hardness and impact toughness properties of carbon and low alloy steels.
4. Pro-eutectoid ferrite phase formed along the grain boundaries after hot forging for low alloy steel can improve the alloy impact toughness.
5. Low alloy steel (E410) is more resistance to hot forging than carbon steels (C45 and A36). An increase of ~5 percent in reduction ratio for carbon steels than low alloy steel when using the same press capacity.
6. Prior hot work can affect the annealing behavior of carbon and low alloy steels. Annealing following hot forging improve alloy toughness and decrease alloy strength (coarsening effect)
7. Normalizing following hot forging refines the microstructure and improves the low alloy steel hardness and impact toughness.
8. Hardening following TMT of low alloy steel shows the highest hardness levels.

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