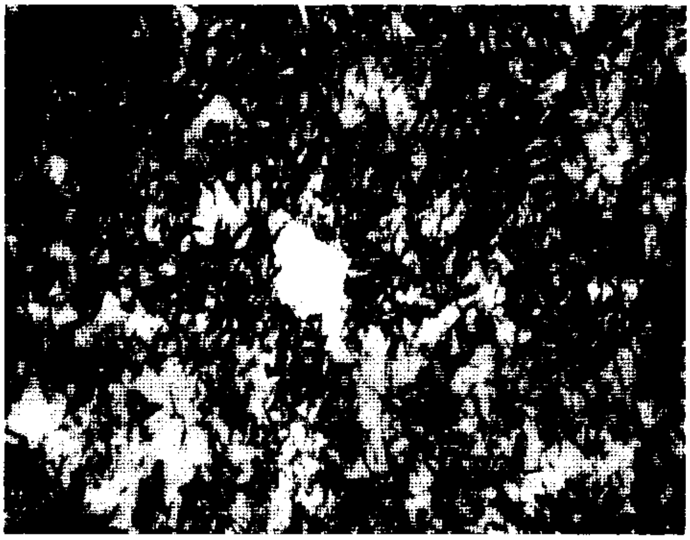

Fig (3.3) Light micrografh of as rolled structure of 34CrNiMo6 steel. Similar microsructure as fig. 3.1 and 3.2, but with higher ferrite content (etched by 2%Nital) . X 250.

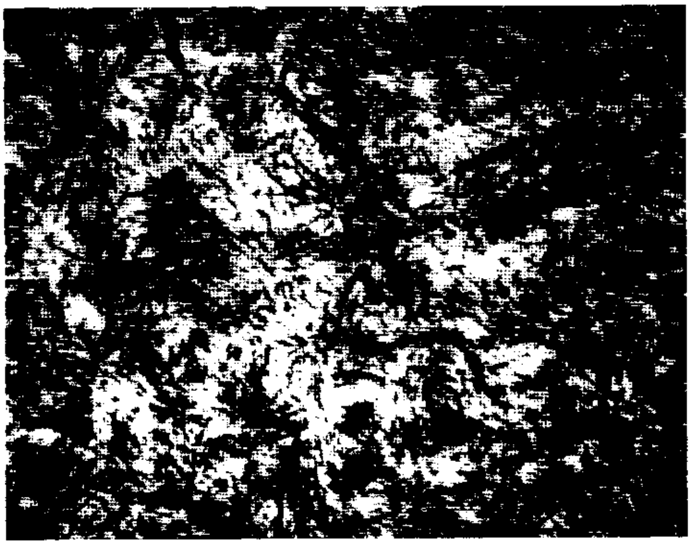

Fig (3.4) Light microgragh of the 41Cr4 steel in the as quenched condition. The microstructure contains lath martensite with some plate martensite. (etched by 2%Nital). X 250.

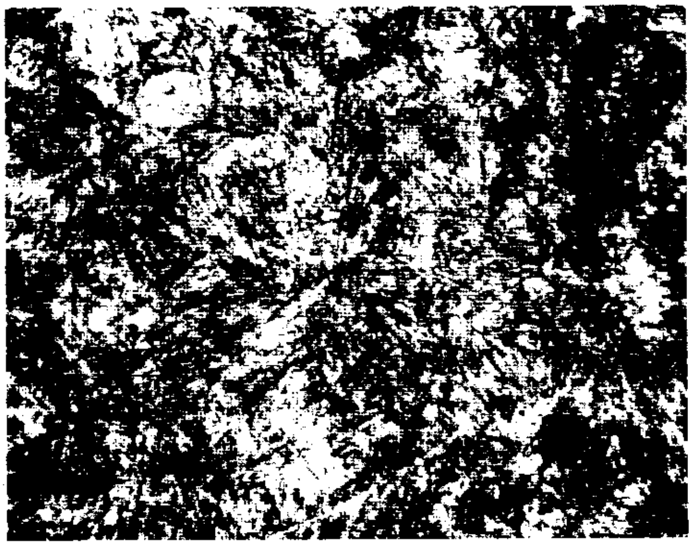

Fig (3.5) Light microgragh of the 42CrMo4 steel in the as quenched condition. It has similar microstructure as fig. (3.4). etched by 2%Nital). X 250.

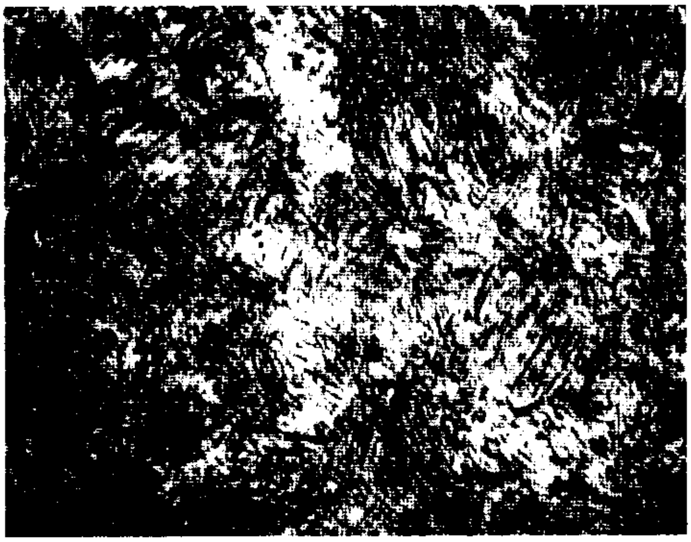

Fig (3.6) Light micrograph of the 34CrNiMo6 steel in the as quenched condition. The microstructure is also martensitic but coarser than other alloys. (etched by 2%Nital). X 250.

Fig (3.7) Light microgragh of 41Cr4 steel, oil quenched and tempered at 200 °C for 60 min., then cooled in air. The structure is tempered martensite.The carbide dispersion formed at this temperature is not observed due to the resolution limit of the light microscope. (etched by 2%Nital) X 250.

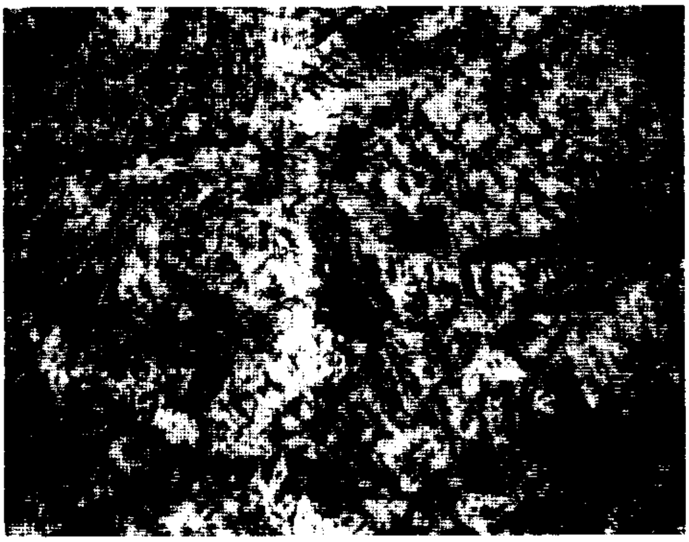

Fig (3.8) Light microgragh of 42CrMo4 steel, oil quenched and tempered at 200 °C for 60 min. then cooled in air. The structure is tempered martensite similar to fig.3.7. (etched by 2% Nital) X 250.

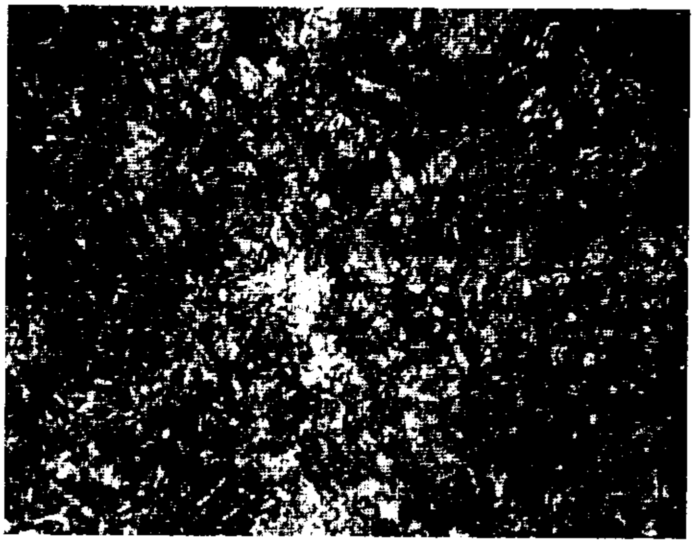

Fig (3.9) Light micrograph of 41Cr4 steel, oil quenched and tempered at 650 °C for 60 min. then cooled in air. The structure is spheroidized carbides in ferrite matrix (etched by 2%Nital) X 250.

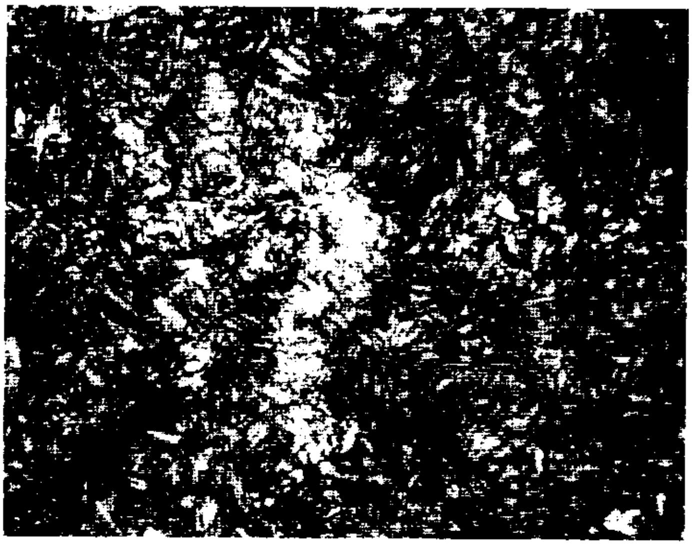

Fig (3.10) Light micrograph of 34CrNiMo6 steel, oil quenched and tempered at 650°C for 60 min. then cooled in air. The structure is spheroidized carbides in ferrite matrix (etched by 2%Nital) X 250.

3.2 Effect of Tempering Temperature on Hardness.

The hardness of the three steels used in the present study in the as quenched condition was almost identical being 56-57 HRC for grades 41Cr4 and 42CrMo4 and lower, 53 HRC for grade 34CrNiMo6.

The hardness of martensite phase, formed by rapid quenching is a result of number of hardening effects such as; the platelet nature of martensite structure formed by diffusionless shear transformation, the solid solution hardening by carbon and other alloying elements, and the increased density of imperfections formed by quenching process. For most of the low alloy steels, the hardness of martensite is dependent only on carbon (8). Therefore, the hardness value of martensite of 42CrMo4 and 41Cr4 steels was the same, due to the same carbon content. In case of 34CrNiMo6 steel, the hardness of martensite is lower because of its lower carbon content.

Martensite is very strong phase (53-57 HRC, in the present study) but it is normally very brittle, so it is necessary to modify the structure and hence improve the mechanical properties to be suitable for practical applications. This was done by tempering treatment in the range of 150-650 °C in the present study.

Generally, for all the three alloys, the hardness was found to decrease gradually with increasing tempering temperature from 150 to 650 °C, as shown in figs.3.11, 3.12, 3.13, and table 3.1. At low tempering temperature (up to 150 °C), no significant change in hardness was observed. At tempering above 150 °C, the hardness continuously decreased (from 56 HRC to 27 HRC) as the tempering temperature was increased (from 150 °C to 650 °C). This can be attributed to the microstructure changes from tempered martensite structure (fine carbides and low carbon martensite) to spheroidal carbides in ferrite matrix. As the tempering temperature increases, the carbides become coarser. Therefore, the number of carbides decreases leading to softening of the structure.

Alloying elements such as chromium and molybdenum, can restrain the coarsening of cementite in the range 400-700 °C. It causes the cementite to retain its fine structure to higher temperatures, either by entering into the cementite structure or by segregating at the carbide-ferrite interfaces. Whatever the basic cause may be, the effect is to delay significantly the softening process during tempering (1).

Hardness values of 42CrMo4 steel nearly coincide with those of 41Cr4 steel up to tempering temperature 250 °C. Above this temperature, hardness values of 42CrMo4 steel become higher than those of 41Cr4 steel as shown in table 3.1. It is due to the beneficial effect of molybdenum, which reduces the spheroidisation and coarsening rate of cementite during the tempering process (18). The hardness values of quenched and tempered 34CrNiMo6 steel are smaller than that of 42CrMo4 steel due to primarily, the lower carbon content, since nickel has a very small and constant effect on tempered hardness at all temperatures (6).

The addition of stronger carbide-forming elements to the steel, e.g. chromium, molybdenum, results in the replacement of the Fe_3C in the tempering range 500-700 °C by a very fine dispersion of alloy carbide which nucleates freshly in the ferrite as the cementite redissolves. This results in restrengthening during tempering (53). However, the secondary hardening effect due to the precipitation of alloy carbides was not observed below the tempering temperature of 650 °C in the present work. This may be attributed to the relative small amounts of chromium and molybdenum found in the selected alloys (0.9-1.6% Cr, and 0.22%Mo).

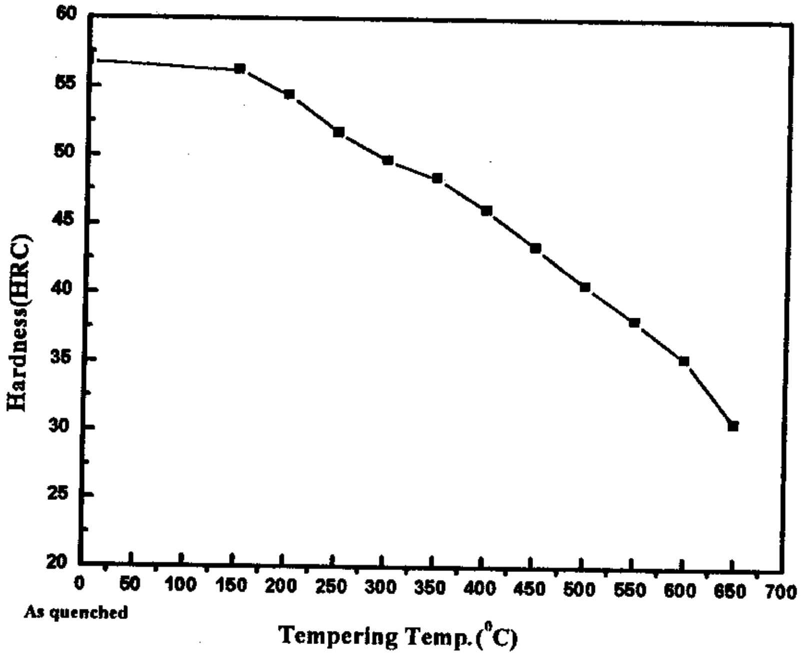

Fig (3.12) Hardness changes with tempering temperature in 42CrMo4 Steel.

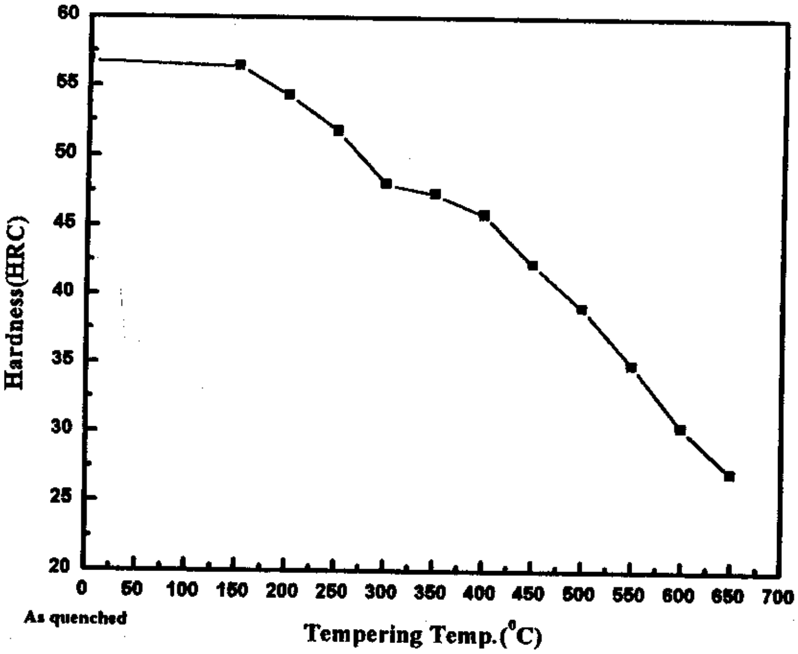

Fig (3.11) Hardness changes with tempering temperature in 41Cr4 Steel.

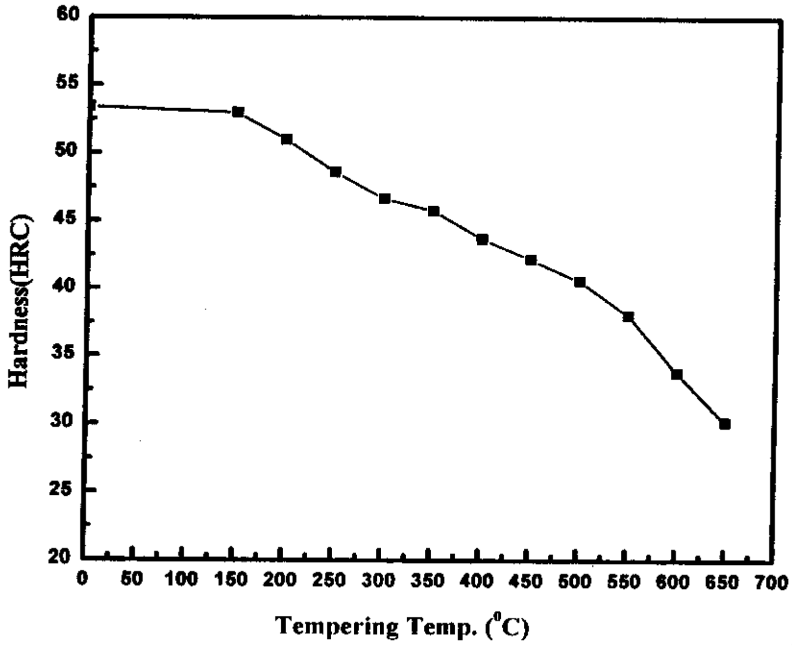

Fig (3.13) Hardness changes with tempering temperature in 34CrNiMo6 Steel.

Table 3.1 Hardness values changes with tempering temperature in 41Cr4, 42CrMo4, and 34CrNiMo6 steels.

Tempering Temp. (°C)	Rockwell Hardness (HRC)		
	41Cr4 Steel	42CrMo4 Steel	34CrNiMo6 Steel
0	56.8	56.8	53.4
150	56.4	56.23	53
200	54.3	54.36	51
250	51.73	51.66	48.6
300	48	49.66	46.66
350	47.33	48.36	45.76
400	45.83	46.06	43.70
450	42.23	43.33	42.20
500	39	40.56	40.60
550	34	38.03	38.03
600	30.33	35.30	33.76
650	27.066	30.66	30.16

3.3 Effect of Tempering Temperature on Impact Toughness.

The impact energies of 41Cr4, 42CrMo4, and 34CrNiMo6 low alloy steels, in the as quenched state are very low, due to the severe internal stresses caused during the austenite to martensite transformation, which make the steels brittle. Tempering improves impact toughness of hardened steels.

3.3.1 Effect of Tempering Temperature on Impact Toughness of 41Cr4 Steel at Different Test Temperatures.

Fig.3.14 illustrates the relationship between the impact strength of quenched and tempered 41Cr4 steel and the tempering temperature. The impact strength of 41Cr4 steel when quenched and tempered at 200 °C increased over that of as quenched steel due to precipitate of fine carbides in the martensitic matrix (9) , and consequently, the carbon content of the martensite is reduced, causing partial relief of the lattice strain.

It is noticed that, the increase of tempering temperature results in a decrease of the impact strength in the tempering range 200 – 300 °C. The impact strength has a minimum value ~ 5.28 J/cm^2, when the steel is quenched and tempered at 300 °C. This minimum value is associated with the so called tempered martensite embrittlement (TME).the impact strength values increase again above this critical temperature (300 °C) and lie in the range 5 – 130 J/cm^2 through the tempering range 300 – 650 °C. This increase of charpy impact strength above 300 °C is associated with the matrix softening and coarsening of cementite particles. It is observed also, from fig.3.14 , that the tempered martensite embrittlement trough is still observed at all selected test temperatures (23, 0, -20, -40, and -70 °C), and the impact strength decreases over all the tempering temperatures as the test temperature decreases.

3.3.2 Effect of Tempering Temperature on Impact Toughness of 42CrMo4 Steel at Different Test Temperatures.

Fig.3.15 illustrates the relationship between the impact strength of quenched and tempered 42CrMo4 steel and the tempering temperature. The impact strength of 42CrMo4 steel when quenched and tempered at 200 °C increased over that of as quenched steel due to precipitate of fine carbides in the martensitic matrix (9), and consequently, the carbon content of the martensite is reduced, causing partial relief of the lattice strain.

It is noticed that, the increase of tempering temperature results in a decrease of the impact strength in the tempering range 200 – 300 °C. The impact strength has a minimum value ~ 5.37 J/cm^2, when the steel is quenched and tempered at 300 °C. This minimum value is associated with the so called tempered martensite embrittlement (TME).the impact strength values increase again above this critical temperature (300 °C) and lie in the range 5 – 101 J/cm^2 through the tempering range 300 – 650 °C. This increase of charpy impact strength above 300 °C is associated with the matrix softening and coarsening of cementite particles. It is observed also from fig 3.15, that the tempered martensite embrittlement trough is still observed at all selected test temperatures (23, 0, -20, -40, and -70 °C), and the impact strength decreases over all the tempering temperatures as the test temperature decreases. It is known that the toughness is lowered as the size of the prior austenite grain size increases (7). Although, molybdenum addition results in finer prior austenite grain size, and consequently, increases the impact strength, this is not observed in fig 3.15 as compared with fig 3.14 as illustrated in table 3.2, due to the increase of phosphorus concentration in 42CrMo4 steel (the concentration of phosphorus is 0.019% for 42CrMo4 steel against 0.009% for 41Cr4 steel). It has long been known that phosphorus produces an unfavorable effect on the impact strength of steel after a hardening and tempering treatment (9). As the amount of phosphorus in the steel increases, the room temperature fracture energy decreases after all tempering temperatures (40, 41). However, at low test temperatures (-40 and -70 °C), the impact strength of 42CrMo4 steel oil quenched and tempered at high tempering temperatures (650 °C), increases over that of 41Cr4 steel at the same condition as illustrated in table 3.3. This may be explained as follows: At this high tempering temperature, (650 °C), when the test temperature decreases, the fracture behaviour of alloys changes from mainly ductile fracture, depending on the nucleation of voids at second phase particles such as phosphides and carbides, to brittle fracture. In the brittle fracture, the effect of molybdenum as a prior austenite grain refiner predominates, so the impact strength increases.

Tempered martensite embrittlement is observed in both 41Cr4 and 42CrMo4 steels, and this means that molybdenum is unable to eliminate tempered martensite embrittlement.

3.3.3 Effect of Tempering Temperature on Impact Toughness of 34CrNiMo6 Steel at Different Test Temperatures.

Fig.3.16 illustrates the relationship between the impact strength of quenched and tempered 34CrNiMo6 steel and the tempering temperature. The impact strength of 34CrNiMo6 steel when quenched and tempered at 250 °C increased over that of as quenched steel due to precipitate of fine carbides, in the martensitic matrix (9), and consequently, the carbon content of the martensite is reduced, causing partial relief of the lattice strain.

It is noticed that, the increase of tempering temperature results in a decrease of the impact strength in the tempering range 250 – 350 °C. The impact strength has a minimum value ~ 7 J/cm^2, when the steel is quenched and tempered at 350 °C. This minimum value is associated with the so called tempered martensite embrittlement (TME). The displacement of TME to higher temperatures in 34CrNiMo6 steel is due to the nickel addition. This element enhances the stability of ε-carbide, and retards the formation and growth of cementite (24). The impact strength values increase again above this critical temperature (350 °C) and lie in the range 7 – 121 J/cm^2 through the tempering range 350 – 650 °C.

When the steel is quenched and tempered at 550 °C, the impact strength value becomes much lower than that for the other two alloys, as shown in table 1. To know the reason, scanning electron microscope was used to examine the fracture surface of 34CrNiMo6 charpy impact tested sample quenched and tempered at 550 °C. We observed that the fracture is intergranular fracture as shown in fig.3.17, on contrary, when we examined the fracture surface of 41Cr4 and 42CrMo4 charpy impact tested samples quenched and tempered at 550 °C, we observed that the fracture is mainly ductile rupture as shown in fig.3.18. This may be explained as follows: Nickel stimulates the impurity element, primarily phosphorus to segregate to the prior austenite grain boundaries, so, phosphorus plays a greater role in embrittlement because it interacts with nickel. These interactions lead to cosegregation of alloying element and impurity element at the grain boundary leading to resultant lowering of cohesion by the impurity content(54). R. Honeycombe and H. K. D. H. Bhadeshia (1) stated that the Analysis of Auger Electron Spectroscopy (AES) has confirmed strong interactions between Ni-P. The above result can be related to the two-step temper embrittlement, but the embrittlement has no obvious trough as shown in fig.3.16, due to the effect of molybdenum, which minimizes temper embrittlement (TE) (55). Dumoulin et al (56) found that in steel containing ≤0.02% P, molybdenum in solid solution prevents the segregation of phosphorus atoms to the grain boundaries by binding them as Mo-phosphides. In steel containing >0.03% P, the molybdenum located at the grain boundaries will reduce the embrittling effect of the phosphorus atoms.

Although the amount of phosphorus in 34CrNiMo6 steel is relatively high (0.036%P), and consequently, the impact strength is reduced, An acceptable increase in impact strength value when the steel is quenched and tempered at 650 °C as compared with that of 42CrMo4 steel is observed, due to the lower carbon content, and also, the effect of nickel which increases the toughness of ferrite in low alloy steels by simple substitutional solid solution (57). We can conclude from the large increase in impact strength at 650 °C tempering of 34CrNiMo6 steel, that the phosphorus has not sufficient time to segregate to the prior austenite grain boundaries during air cooling after tempering at 650 °C .It is observed also from fig 3.16, that the tempered martensite embrittlement trough still observed at all selected test temperatures (23, 0, -20, -40, and -70 °C), and the impact strength decreases over all the tempering temperatures as the test temperature decreases. C. L. Briant and S. K. Banerji (41)stated that the observation of tempered martensite embrittlement(TME)depends on the test temperature .It must be below the ductile to brittle transition temperature (DBTT)for samples tempered near 350 °C or else the trough will not be observed. Since TME trough is observed at all selected test temperatures as shown in figures, we can conclude that the DBTTs for samples tempered near 350 °C for all the present alloys used in this work are above room temperature.