IV. RESULTS AND DISCUSSION

4.1 Effect of reheating temperature on prior-austenite grain size

The effect of reheating temperature on average prior-austenite grain size is related to various temperature levels and holding time which governs the dissolution of second phase particle and grain growth behaviour. The prior-austenite grain size as a function of reheating temperature for 25 minutes holding time for investigated steel is shown in Fig. 4.1

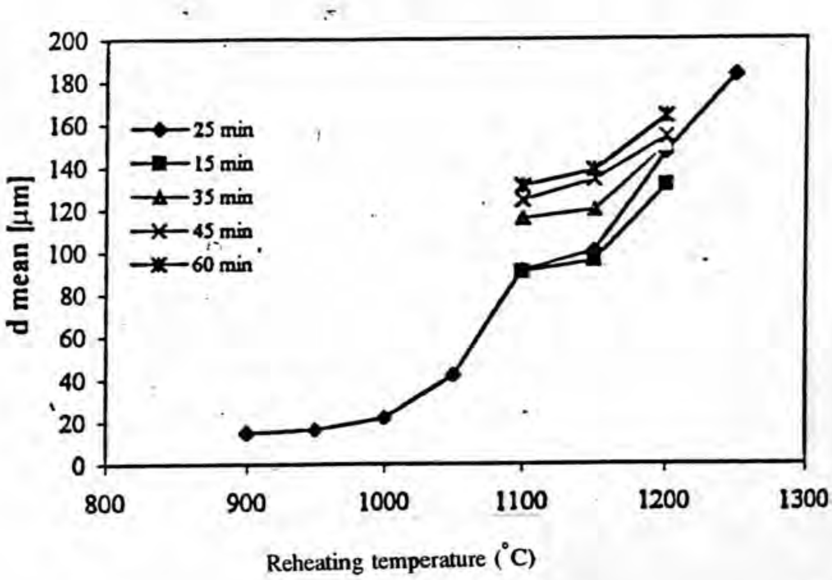


Figure 4.1 Prior-austenite grain size as a function of reheating temperature

It can be seen that in temperature between 900°C and 1000°C , the prior-austenite grain size increases slightly. The austenite grain growth become more pronounced when temperature exceeded 1100°C. Average grain size increases from 20 micron to 100 micron when temperature increases form 1000°C to 1100°C.

The prior-austenite grain sizes as function of holding time of constant reheating temperature of 1100, 1150 and 1200°C are shown in Fig. 4.2, 4.3 and 4.4 respectively. In these figures it is seen that the prior austenite grain size increases moderately with increasing holding time. The reheating temperature has greater influence on prior-austenite grain size than the holding time.

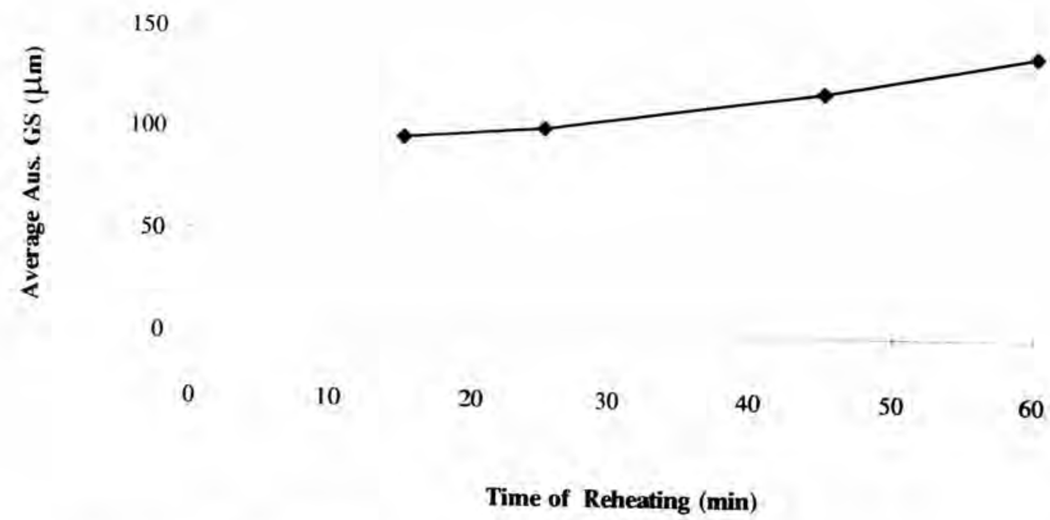


Fig. 4.2 Prior-austenite grain size as a function of holding time for 1100°C reheating temperature.

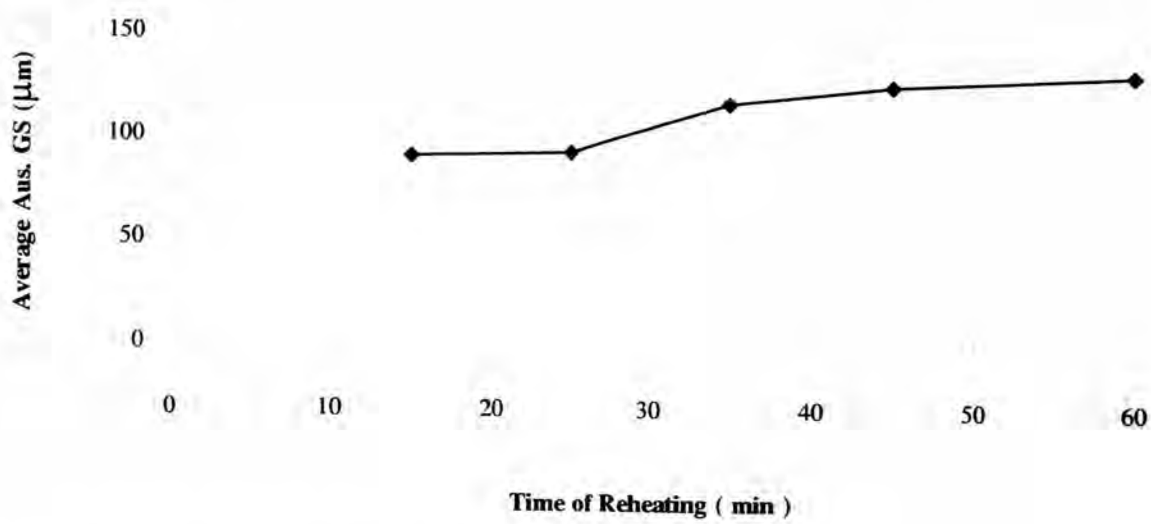


Fig. 4.3 Prior-austenite grain size as a function of holding time for 1150°C reheating temperature.

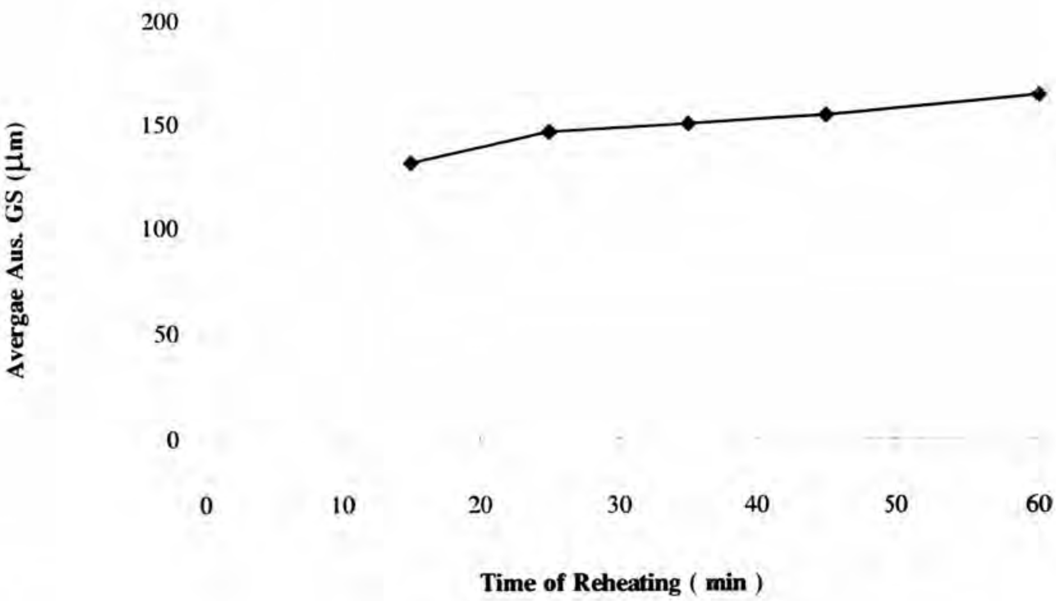


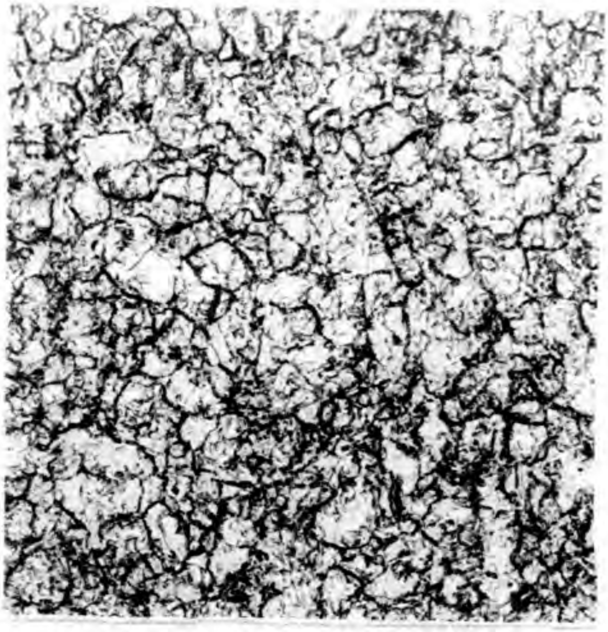
Fig. 4.4 Prior-austenite grain size as a function of holding time for 1200°C reheating temperature.

The prior-austenite microstructures of investigated steel reheated between 900-1250°C for 25 minutes are shown in Fig. 4.5. In Fig. 4.5. It is seen that in temperature of 900°C , 950 °C and 1000°C the prior austenite grain sizes are kept fine. At 1050°C the austenite grain size increase the degree of heterogenity of grain size. At the temperature over 1100°C the prior austenite grain size becomes coarser. At 1100°C the precipitate particles which pinned the austenite grain boundary dissolve into solid solution (13), and lost the function of retarding the austenite grain growth. These are in good agreement with thermodynamic calculation of dissolution temperature of Nb products shown in Table 4.1 (16-34).

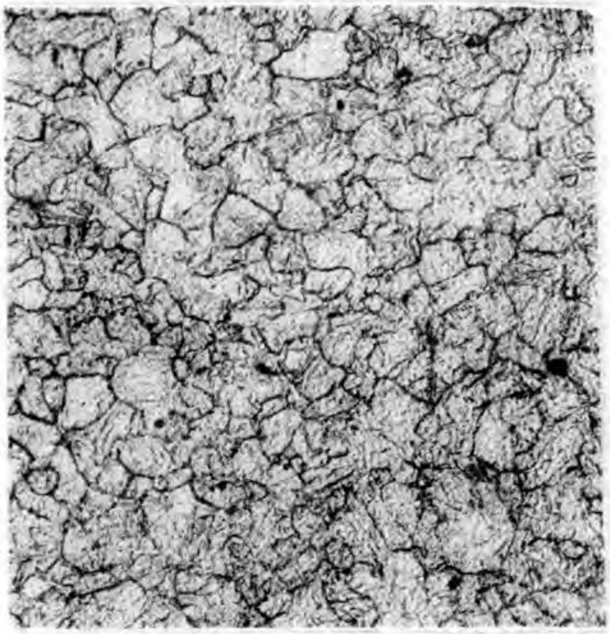
Table 4.1 Average precipitate dissolution temperature of Nb products from Table 2.1

Nb-C	Nb-N	Nb-C-N
1041°C	1068°C	1111°C

The remaining precipitate particles are complex carbonitride of Nb and Ti. Hence these particle are coarsen than those of pure Ti precipitates at the same temperature, so the effect of Ti has become diminished (36, 37, 38). When reheating temperature increased, these particle were coarsened. Thus, there is no particle pinning effect anymore. The grains start to grow. The obtained austenite grain coarsening temperature of this study are in conformity with the result in some literatures (37, 38, 44).



(a) Reheated at 900°C (200x)



(b) Reheated at 950°C (200x)

(c) Reheated at $1000^{\circ}C$ (200x)

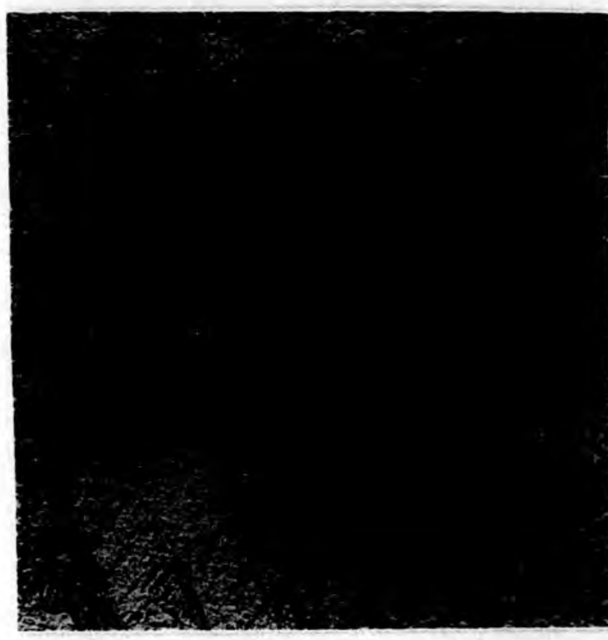


Figure 4.5 (d) Reheated at $1050^{\circ}C$ (100x)

Figure 4.5 (e) Reheated at 1100°C (100x)

Figure 4.5 (f) Reheated at 1150°C (100x)

Fig. 4.5 (g) Reheated at 1200°C (50x)

Fig. 4.5 Prior-austenite grain size after reheating to various temperature and water quenching.

4.2 Effect of deformation in austenite recrystallization region on austenite grain size

As previously stated that purpose of defomation in the austenite recrystallization region is to refine the austenite grain size as much as possible by repeated deformation and recrystallization. The effect of amount of defomation on the austenite grain size was studied at a chosen temperature of 1150°C. The refining process of austenite via recrystallization prior to deformation in nonrecrystallization was also investigated.

For this experimental condition, the strain rate was $8s^{-1}$ and rolling speed was 0.5 m/s. The influence of the various first deformation at 1150°C on the average grain size is shown in Fig. 4.6. It can be seen that the average recrystallized grain size decreases as the amount of deformation increase. The austenite grain size decreases from 55 micron to 36 micron and 10 micron when changing deformation degree from 30% to 40% and 50% respectively. This result is in good agreement with reference 47 and 54. The three deformation degree of 30%, 40% and 50% were carried out to simulate the various extent of austenite deformation in recrystallization region. Fig. 4.7 shows the microstructure of recrystallized austenite quenching immediately after rolling. It can be seen that, in all cases the recrystallized austenite structures are completely recrystallized consisting of equiaxed austenite grains.

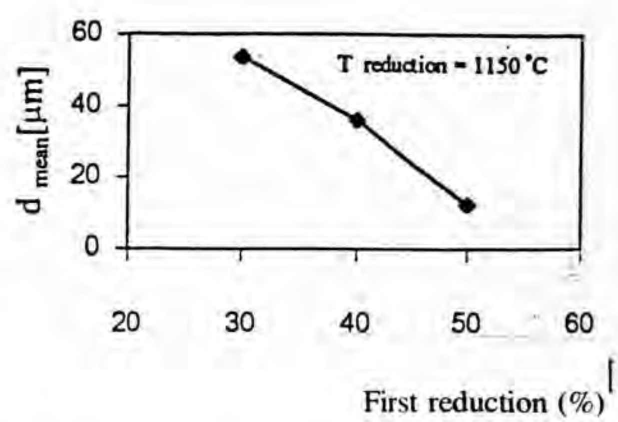
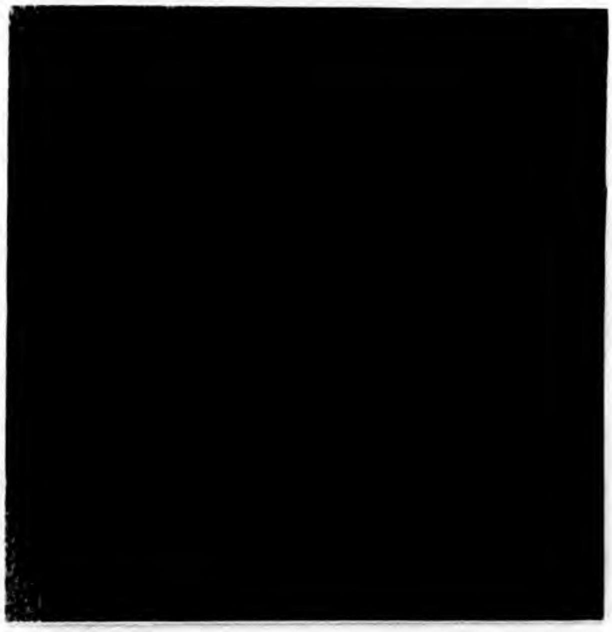


Fig. 4.6 Influence of deformation amount on recrystallized austenite grain size



(a) Rolled 30% in recrystallization (100x)

Figure 4.7 (b) Rolled 40% in recrystallization (100x)

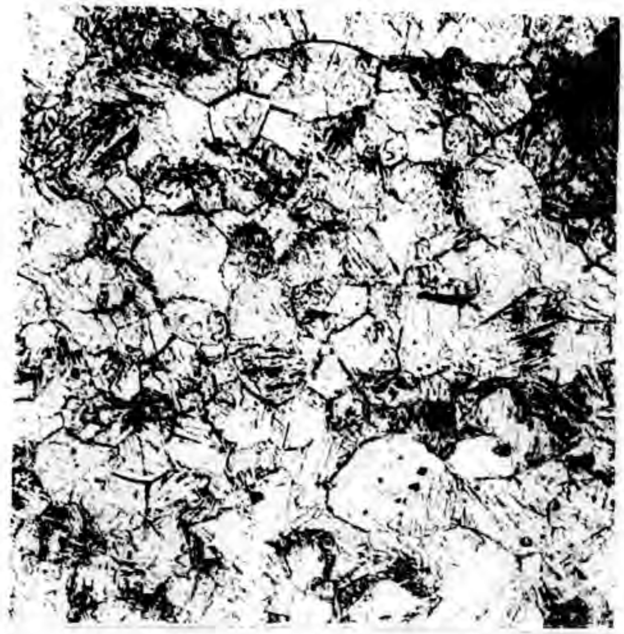


Fig. 4.7 (c) Rolled 50% in recrystallization (100x)

Fig. 4.7 Microstructure of austenite grains after deformation in recrystallization region (100 x)

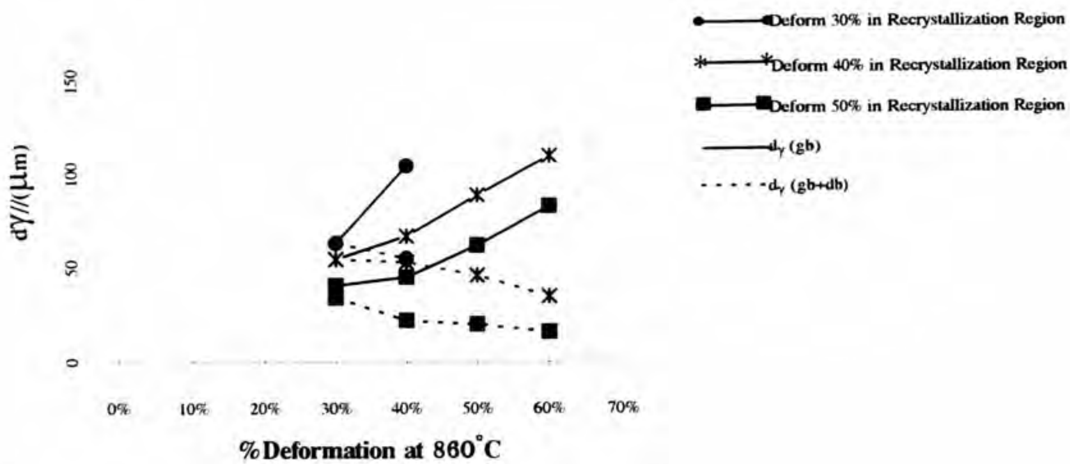
a) 30% reduction

b) 40% reduction

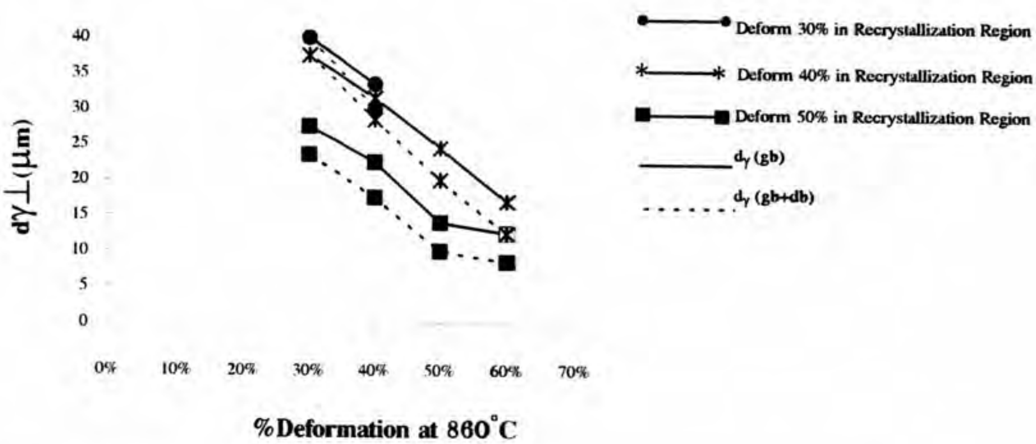
c) 50% reduction

4.3 Effect of deformation in nonrecrystallization region on austenite microstructure

The obtained results on deformed austenite grain characteristic, consisting of $d_\gamma//$ and $d_\gamma\perp$. For two different holding times 6 seconds and 360 seconds before quenching are shown in Fig 4.8 and Fig 4.9 respectively. The $d_\gamma//$ and $d_\gamma\perp$ was calculated from equation 11 and 12 respectively. It can be seen that the changes in dimension axes of deformed austenite grains are significantly effected by degree of deformation and deformation band formation. The difference between $d_\gamma//$ (gb) and $d_\gamma//$ (gb+db) become more pronounced with increasing deformation degree. Because the increase in the degree of deformation, the density of deformation bands increased also. The difference is small for the grains in perpendicular direction to the axis of rolling , because it is not influenced significantly by the density of deformation bands. It was also observed that the increasing degree of deformation had an effect on ferrite transformation temperature. This effect is called strain induced transformation (57). In Fig. 4.8 and Fig. 4.9, there are some points in which can not be calculated for the axes of austenite grain due to the changing from elogated austenite grain to equiaxed austenite grain causing from starting of transformation. Like in Fig. 4.8 these points are the points that corresponding to 70% deformation at 870°C.



a

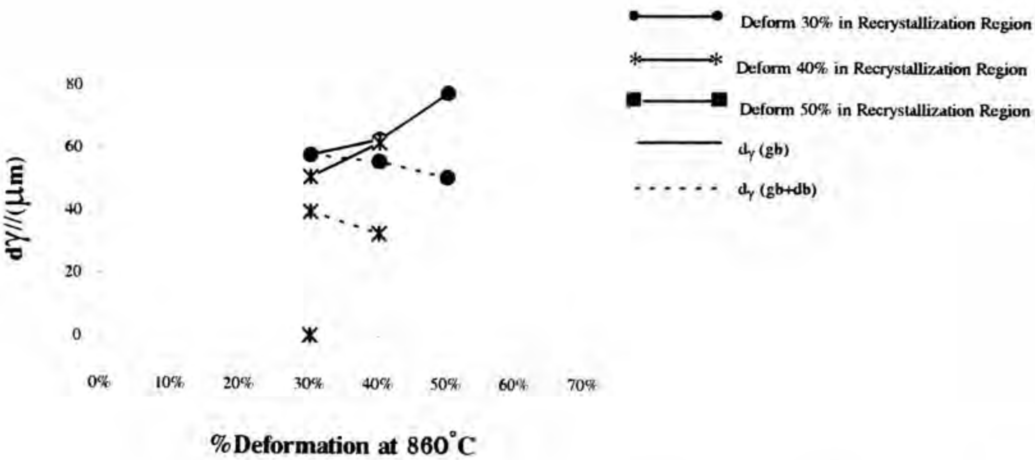


b

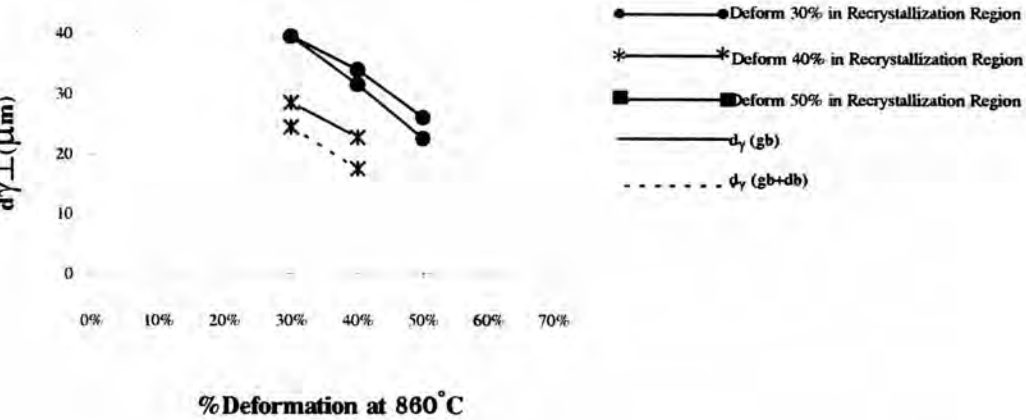
Fig. 4.8 The dependence of axes of deformed austenite grain as a function of degree of deformation holding 6 seconds before quenching

a) d_γ //

b) $d_\gamma \perp$



a



b

Fig. 4.9 The dependence of axes of deformed austenite grain as a function of degree of deformation holing 360 seconds before quenching

a) d_γ //

b) $d_\gamma \perp$

The evaluation of deformed austenite structure was done with respect to grain refinement and presence of deformation bands which are supposed to be potential ferrite nucleation sites. The site for ferrite grains nucleation are austenite grain boundary, deformation and incoherent twin boundaries (59). The density of these sites per unit volume is expressed as the total effective nucleation area per unit volume (Sv) (62). The equation for calculation of Sv is given in equation 7. The effect of degree of deformation on the Sv are shown in Fig. 4.10

and Fig. 4.11 for 6 seconds and 360 seconds holding time before quenching respectively. It can be seen that when the degree of deformation increases, the Sv value increases as well. The Sv value has been affected by degree of deformation and initial grain size resulting from degree of deformation in recrystallization. It can be seen in Fig. 4.10 and Fig. 4.11 that with the increasing degree of deformation in recrystallization region (decreasing value of innitial grain size) the Sv value increase. The considerable differences appear above that point i.e. when the formation of deformation bands has already started and their density increases. With the higher deformation in recrystallization region (smaller innitial grain size), the lower degree of deformation is required in order to obtain the same Sv value. It can be seen that not in all cases, in which Sv can be calculated. Because in some cases we found equiaxed grain characteristic that causes from start of transformation. This effect comes from strain induced transformation (57). The details of microstructure of deformed austenite are shown in Fig. 4.12 and Fig. 4.13 for 30% deformed in recrystallization region and holding 6 seconds and 360 seconds before quenching respectively. In fig. 4.12, it can be seen that the austenite grains are elongated and with the increasing degree of deformation the austenite grain become more elongated. Deformation bands are observed, in Fig. 4.12 (a) shows deformation band marked by arrow. Deformation bands exist in closely packed pairs of parallel line within a grain. In Fig. 4.12 (c) shows mixed characteristic of austenite grain consisting of elongated and exquiaxed grains. This microstructure indicates start of transformation. In Fig. 4.13 (a), ti can be seen that austenite grain starts to transform indicating by small equiaxed grain. The number of equiaxed grains increase with the increasing degree of deformation shown in Fig. 4.13(b) , Fig. 4.13 (c) , Fig. 4.13 (d) , and Fig. 4.13 (e). This implies that isothermal holding trends to promote transformation process.

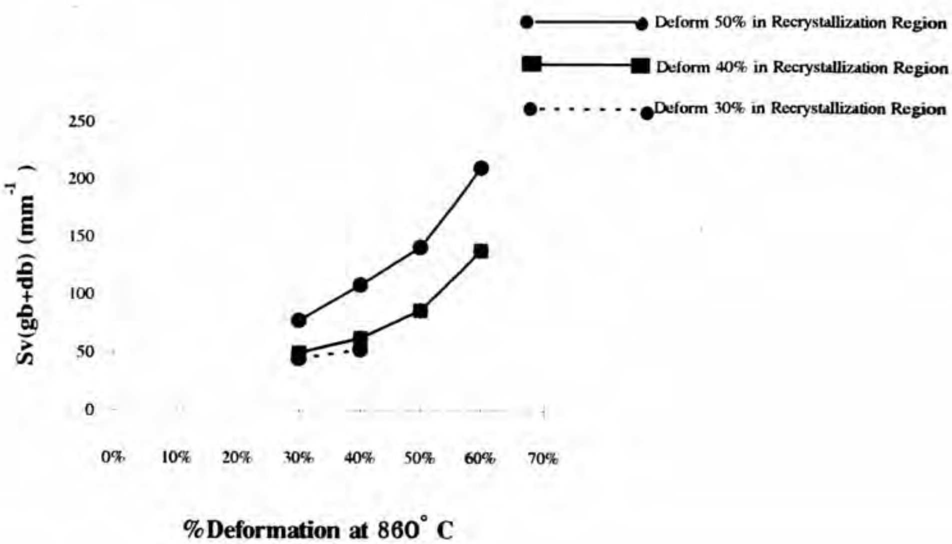


Fig. 4.10 The dependence of Sv as a function of degree of deformation holding 6 second before quenching

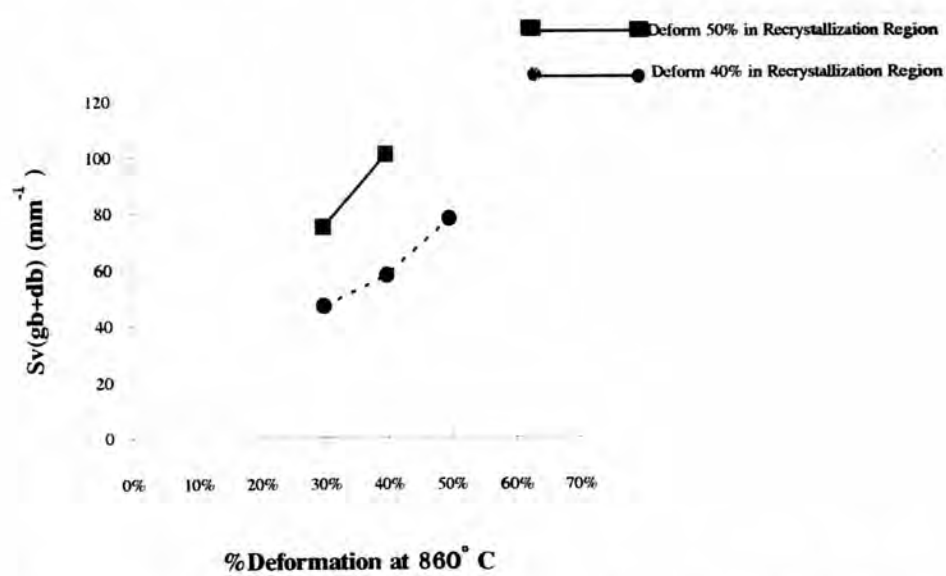
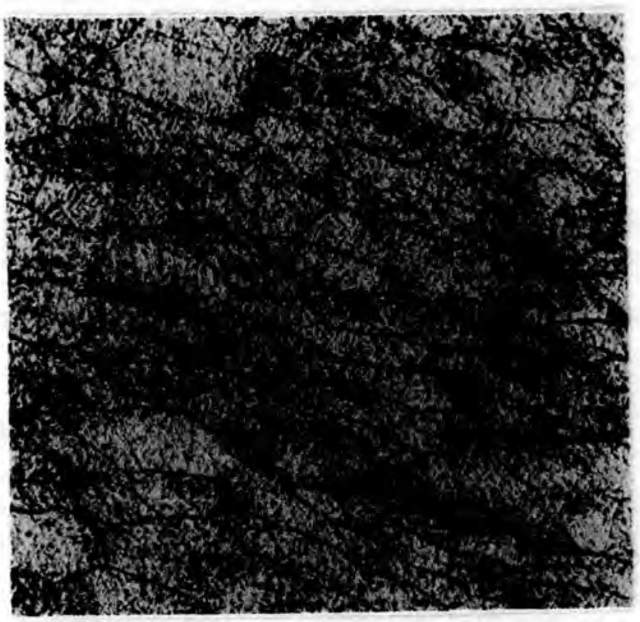
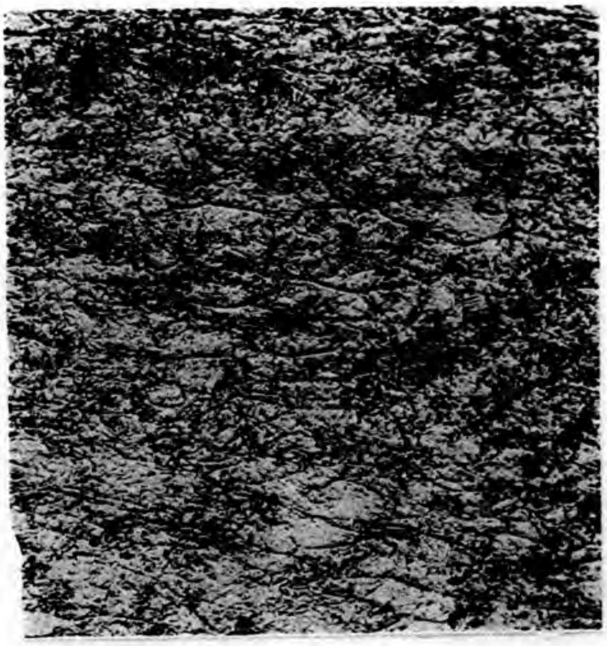


Fig. 4.11 The dependence of Sv as a function of degree of deformation holding 360 second before quenching

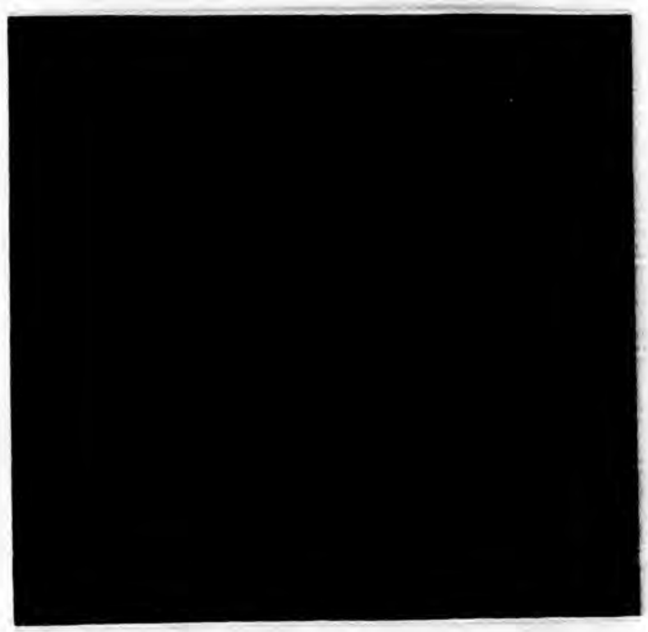
(a) Rolled 30% in nonrecrystallization region (100x)



(b) Rolled 40% in nonrecrystallization region (100x)



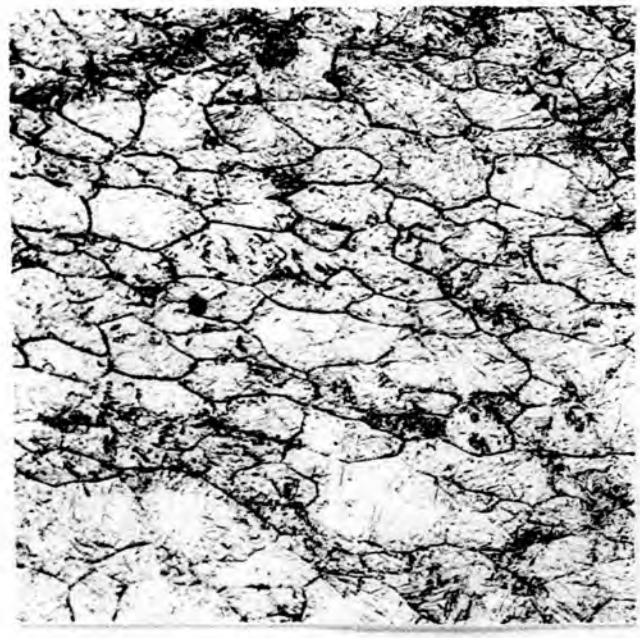
(c) Rolled 50% in nonrecrystallization region (200x)



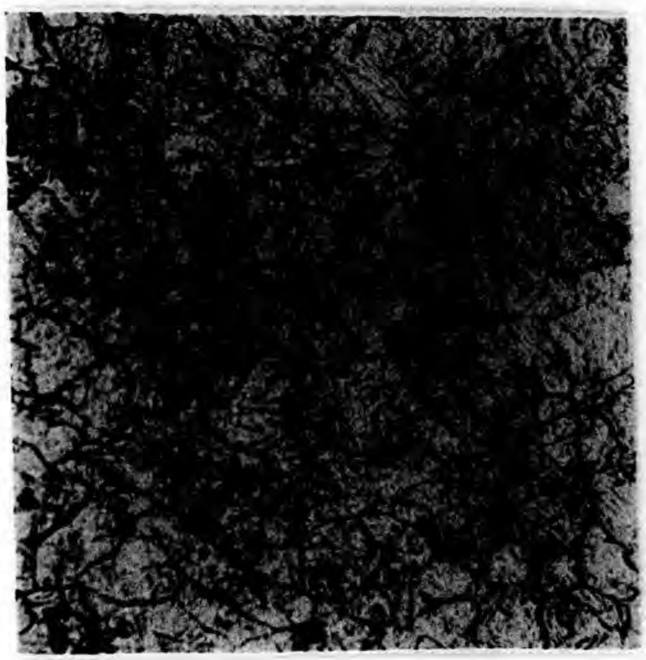
(d) Rolled 60% in nonrecrystallization region (200x)

(e) Rolled 70% in nonrecrystallization region (200x)

Fig. 4.12 Microstructure of austenite grains after 30% deformation in recrystallization region and subsequently deformed with various degree of deformation in nonrecrystallization region holding 6 seconds before quenching



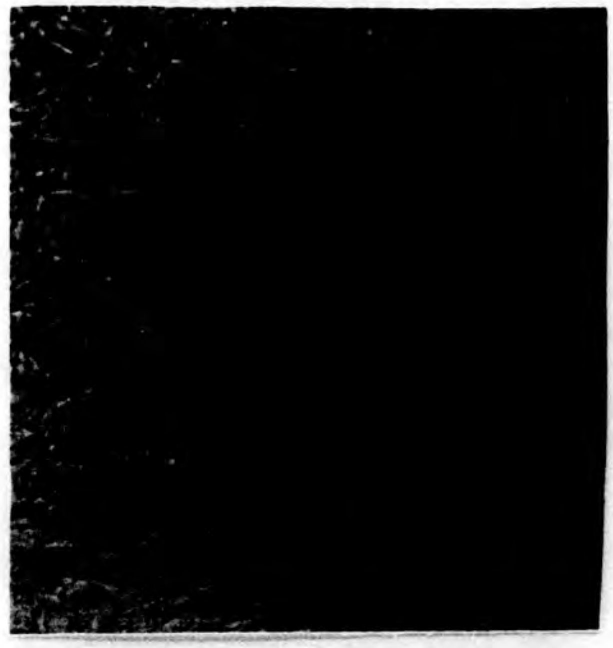
(a) Rolled 30% in nonrecrystallization (200x)



(b) Rolled 40% in nonrecrystallization (200x)

(c) Rolled 50% in nonrecrystallization (200x)

(d) Rolled 60% in nonrecrystallization (200x)



(c) Rolled 70% in nonrecrystallization region (500x)

Fig. 4.13 Microstructure of austenite grains after 30% deformation in recrystallization region and subsequently deformed with various degree of deformation in nonrecrystallization region holding 360 seconds before quenching

4.4 Effect of coiling temperature on ferrite grain size and mechanical properties.

The influence of coiling temperature on mechanical properties is through the ferrite grain size and microstructure characteristic. The ferrite average grain size as a function of coiling temperature is shown in Fig. 4.18

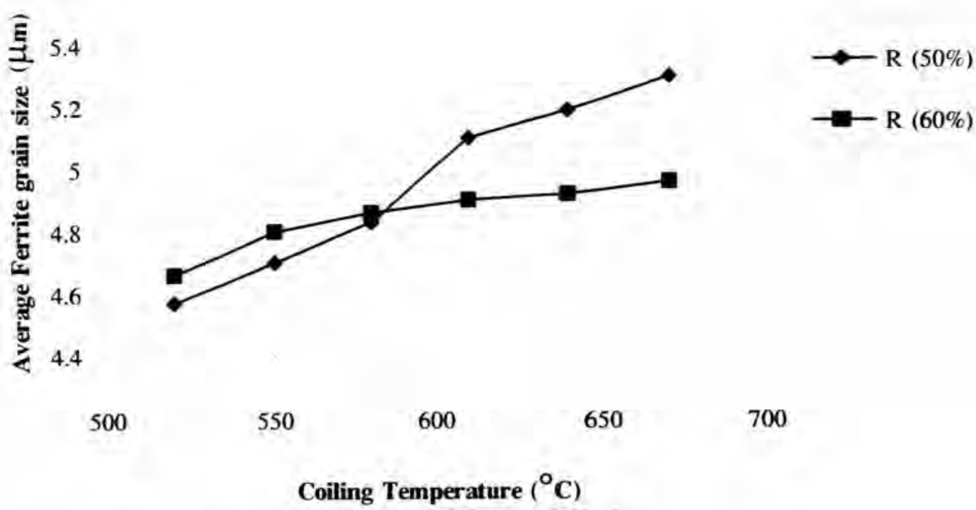
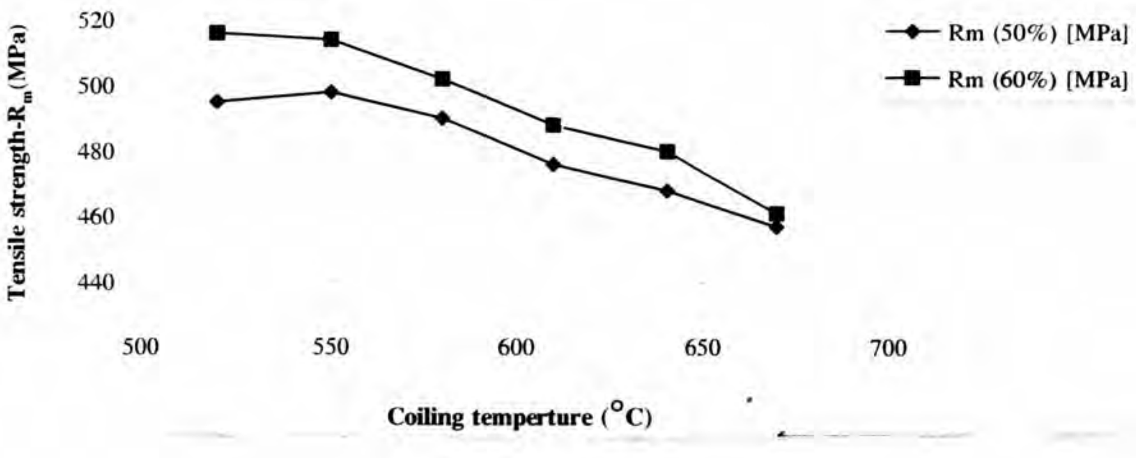


Fig. 4.18 Effect of coiling temperature and ferrite grain size

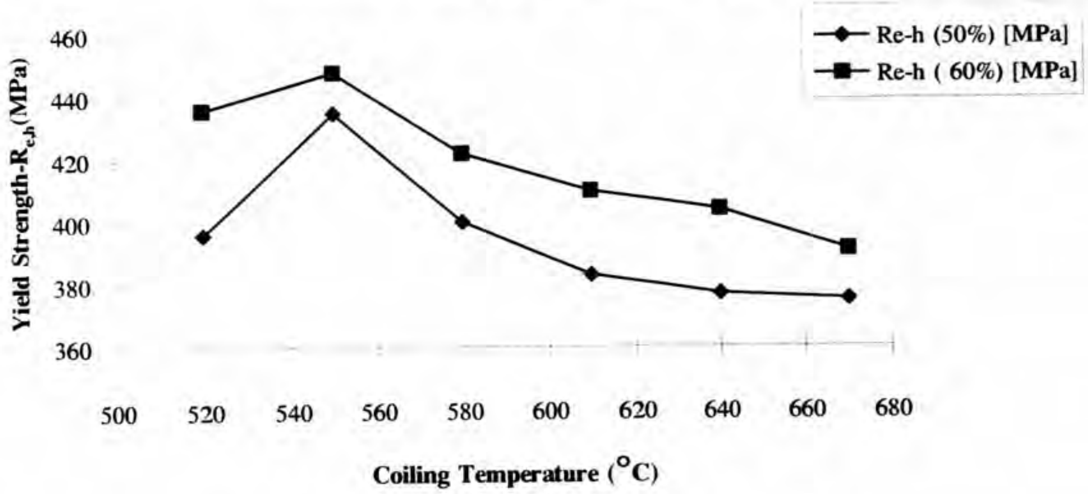
It can be seen from Fig. 4.18 that the higher amount of deformation in nonrecrystallization region has small effect in refining the ferrite grain size. It is clear that only coiling temperature governs the average ferrite grain size. In general, average ferrite grain size increases with rising of coiling temperature. Relationship between mechanical properties and coiling temperature are shown in Fig. 4.19. The tensile strength (Rm) and yield strength (Re-h) change little with rising coiling temperature in temperature range of investigation. However, there is a small peak in yield strength at 550°C. This effect should be attributed to precipitation hardening, because in the low temperature side precipitation can be suppressed. On the other hand in the high temperature side, the precipitates will be few and large, and grain size will be large also (79) Thus the optimum coiling temperature is the temperature that maximizes the strengthening effect of precipitate particles (77,79). The elongation (A5) and reduction in area (Z), increase with rising coiling temperature. Fig. 4.20 depicts the pearlite-ferrite microstructure 50% deformation in nonrecrystallization region as a result of different coiling conditions. The microstructure consists of fine equiaxed ferrite grains and pearlite, the white areas are ferrite, and the black area are pearlite.

It can be seen also in the pictures that the higher coiling temperature give a coarser ferrite grain size when compare to lower coiling temperature. For example coiling temperature of 670°C give 5.3 micron average ferrite grain size when compare to 5.2, 5.1, 4.8, 4.7 and 4.5 micron for coiling temperature of 640°C, 610°C , 580°C , 550°C , and 520°C respectively.

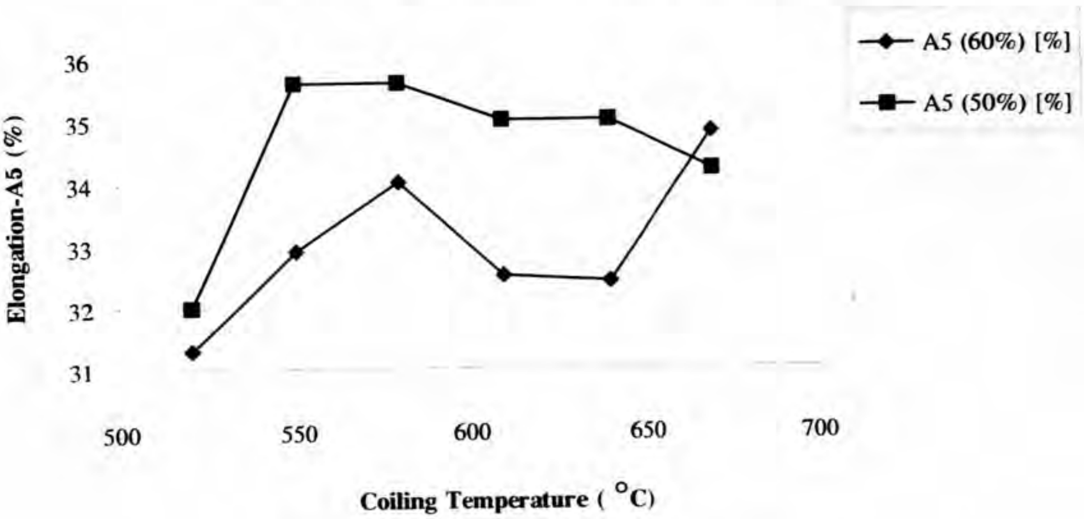
It can be seen in Fig. 4.19 that with the increasing coiling temperature and the increasing average ferrite grain size, tensile strength and yield strength decrease. In Fig. 4.19 (b) there is peak at coiling temperature of 550°C this peak should be attributed to precipitation effect. The results show that mechanical properties depend markedly on ferrite grain size with a small dependence on precipitation strengthening.



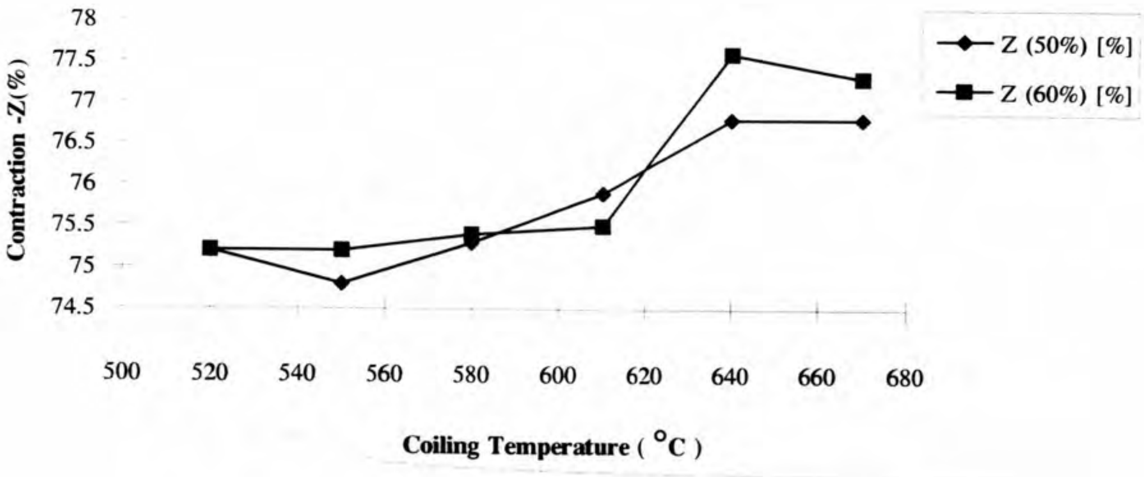
(a) Tensile strength as function of coiling temperature



(b) Yield strength as function of coiling temperature

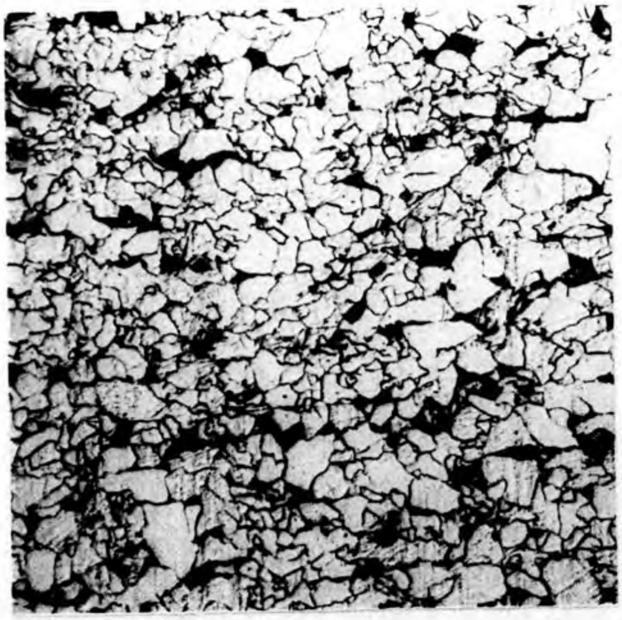


(c) Elongation as function of coiling temperature

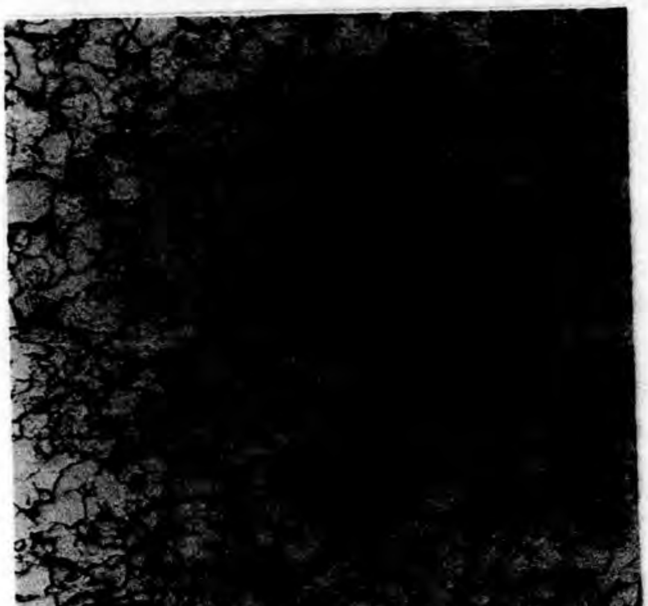


(d) Contraction as function of coiling temperature

Fig. 4.19 Mechanical properties as function of coiling temperature

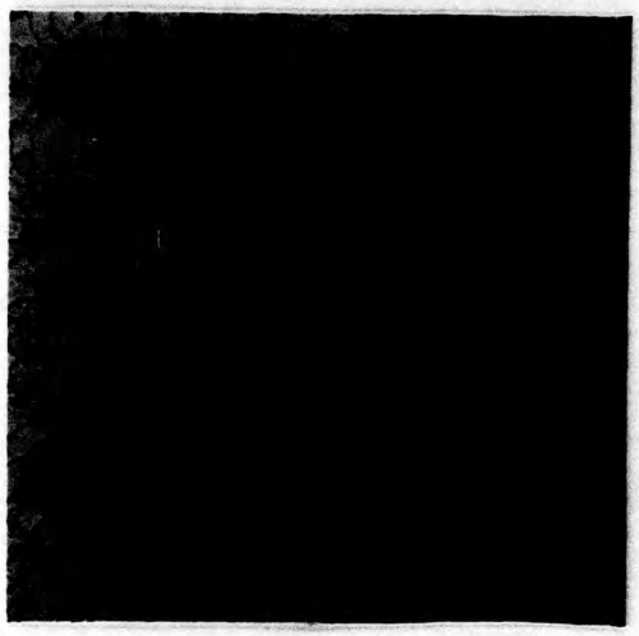


(a) Coiling at 520°C (200x)



(b) Coiling at 550°C (200x)

(c) Coiling at 580°C (200x)



(d) Coiling at 610°C (200x)

(e) Coiling at 640°C (200x)

(f) Coiling at 670°C (200x)

Fig. 4.20 Ferrite-pearlite microstructure after 40% deformation in recrystallization region, subsequently deformed 50% in nonrecrystallization region, and finally coiling to different temperature