Chapter IV

Results

Critical Flow Stress

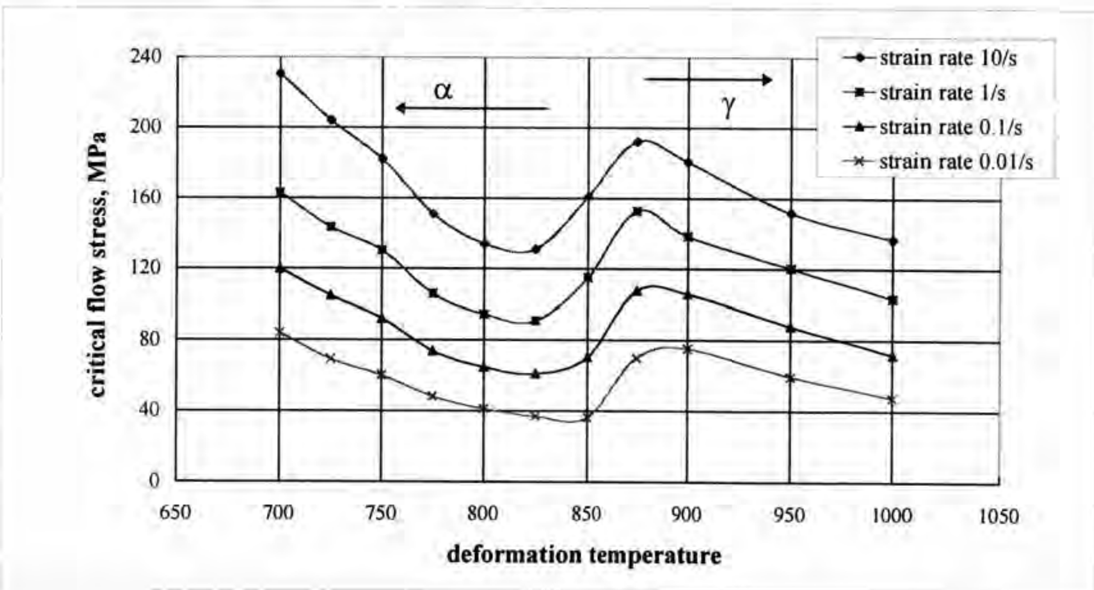


Fig. 4-1 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1000 °C for 5 minutes

Figure 4-1 shows the effect of strain rate on the critical flow stress-deformation temperature curve after austenitizing at 1000 °C for 5 minutes. The critical flow stress at a certain temperature increases with increasing strain rate for the constant austenitizing temperature. The drop of the stresses in the range 880-820 °C is attributed to the austenite-ferrite phase transformation, essentially because ferrite is softer than austenite. At a strain rate of 10/s the critical flow stress at 790 °C in the ferrite phase is similar to that at 1000 °C in austenite phase. The different phases result in the difference in the slope of the curves. The slope in the α range (700-800 °C) is negligible more than that in the γ range (900-1000 °C). A 10 times higher strain rate seems to result in a 25-70 MPa increase of the value of critical flow stress at a certain temperature. The increase of critical flow stress is nearly a linear function of log (strain rate) as shown in figure 4-2, which also shows the effect of deformation temperature on the critical stress of austenite. Same relationship is plotted for the ferritic range in figure 4-3. In both diagrams a deviation from the linear function can be found at high strain rate, which means that the increase in critical flow stress seems to be higher at high strain rate. This deviation is stronger at lower temperatures.

In figure 4-4 the influence of strain rate on critical flow stress of the ferrite and the austenite is illustrated in the same diagram for better comparison. The slope of the ferrite curves is slightly more than that of the austenite curves.

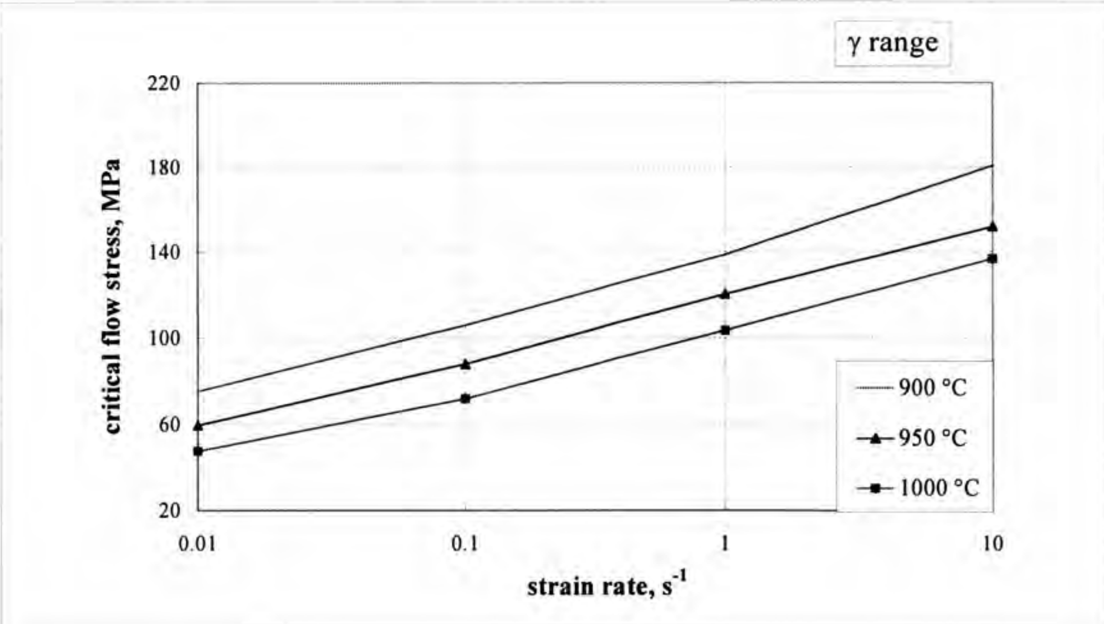


Fig. 4-2 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1000 °C for 5 minutes

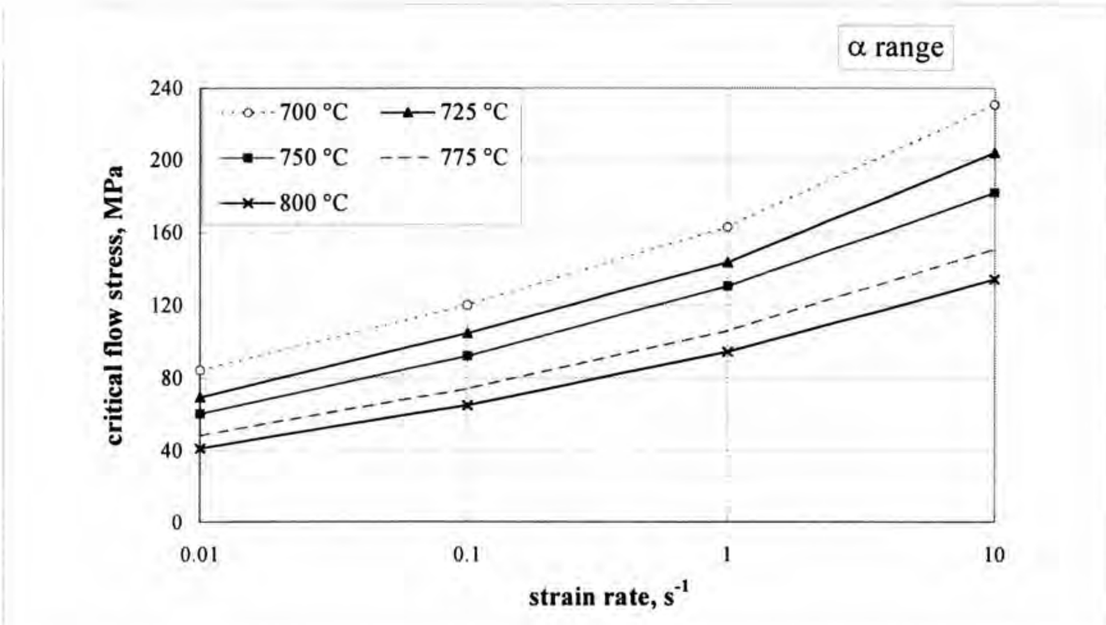


Fig. 4-3 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1000 °C for 5 minutes

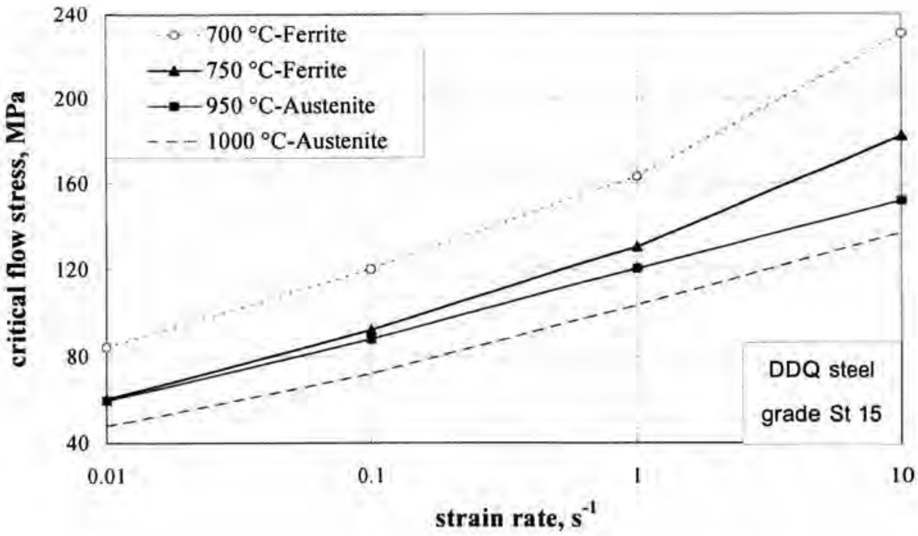


Fig. 4-4 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1000 °C for 5 minutes

The effect of deformation temperature and strain rate on critical flow stress is shown in figure 4-5 and 4-6. The austenitization of both figures was performed at 1250 °C for 10 minutes. The results obtained with a coarse initial grain size are similar to those plotted in figure 4-2 and 4-3 for a fine initial grain size. The values of the critical flow stress in the curves after austenitizing at 1250 °C for 10 minutes are higher than those after austenitizing at 1000 °C for 5 minutes, which means that coarse grain requires higher driving force than fine grain for promoting dynamic recrystallization.

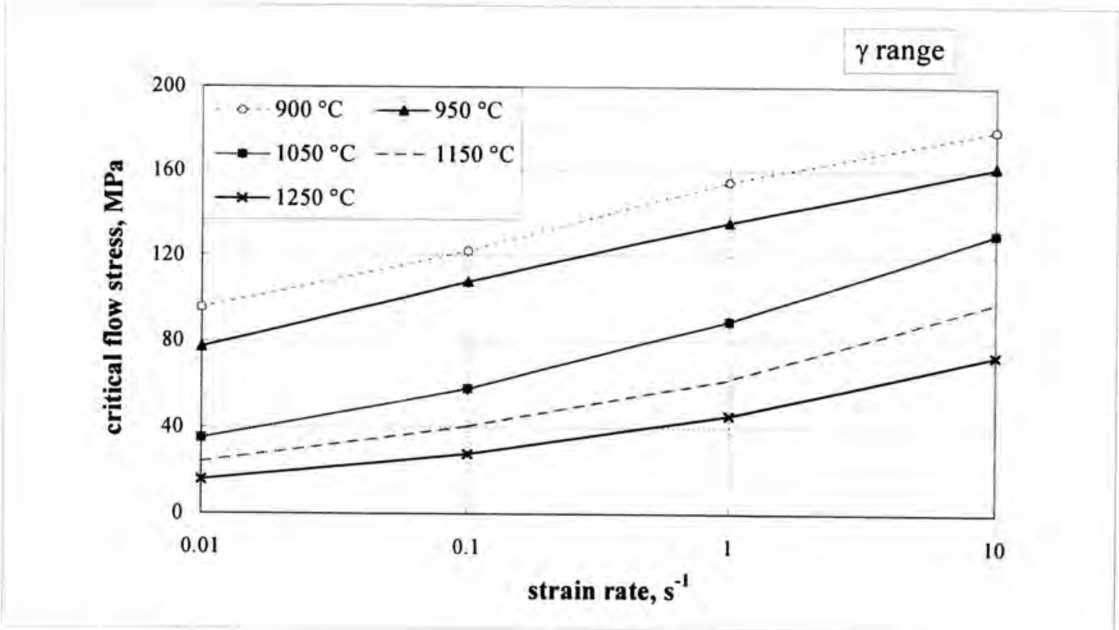


Fig. 4-5 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1250 °C for 10 minutes

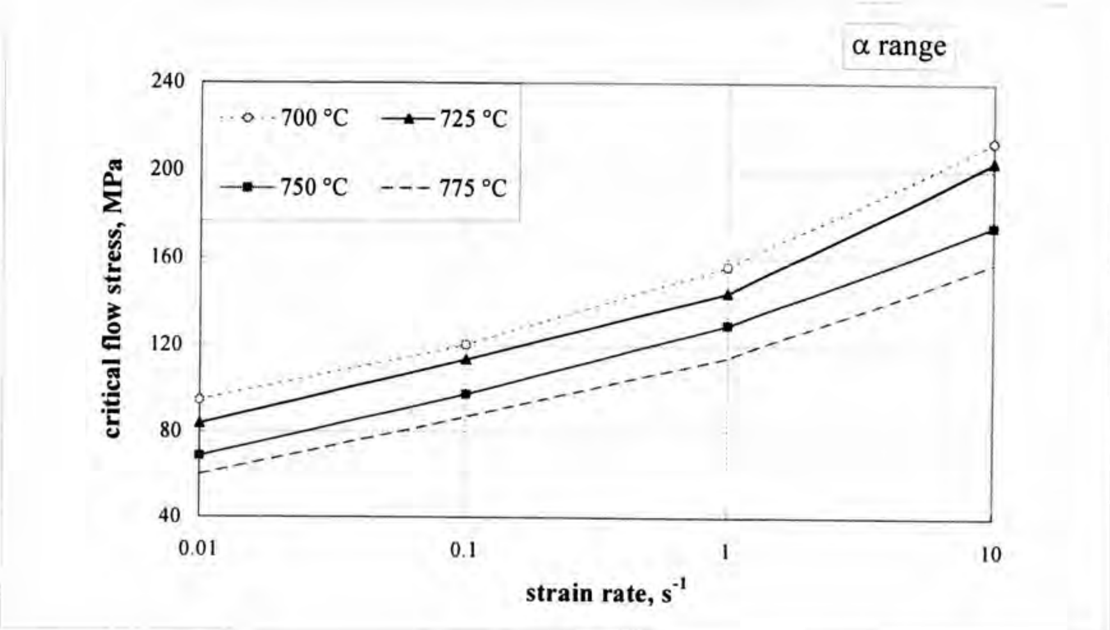


Fig. 4-6 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1250 °C for 10 minutes

The influence of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1250 °C for 10 minutes can be seen in figure 4-7. The values of the critical flow stress in these curves are higher than those after austenitizing at 1000 °C for 5 minutes. This effect can be seen very clearly in figure 4-8, where the critical flow stresses after both austenitizing treatments are compared for the same strain rate and temperature. The mentioned effect indicates that the initiation of dynamic recrystallization is retarded by a coarse austenite grain structure. In finer grain sizes the critical dislocation density to start dynamic recrystallization may be reduced.

Figure 4-8 also shows the influence of austenitizing temperature on the transformation behaviour with regard to the critical flow stress at strain rate of 1 s^{-1}. With a lower austenitizing temperature the transformation occurs at higher temperatures, the relative maximum of curve appears at about 875°C instead of 855 °C and the relative minimum of curve appears at about 825 °C instead of 790 °C. At this strain rate the temperature range between the relative maximum and relative minimum of curve in case of austenitizing at 1250 °C is about 15 K wider than that in case of austenitizing at 1000 °C. This is attributed to that the transformation range in case of austenitizing at 1250 °C is wider than that in case of austenitizing at 1000 °C. This effect can be explained by the difference in the initial grain size. After low temperature austenitization a fine grain structure with grain size of about 35 μm was obtained instead of

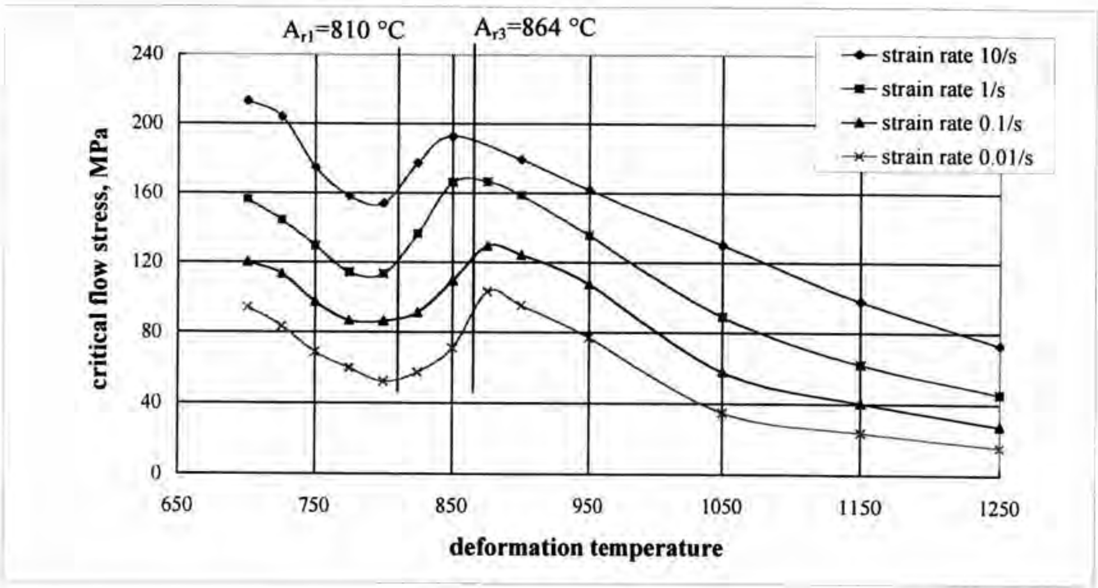


Fig. 4-7 : Effect of deformation temperature and strain rate on the critical flow stress of St.15 after austenitizing at 1250 °C for 10 minutes

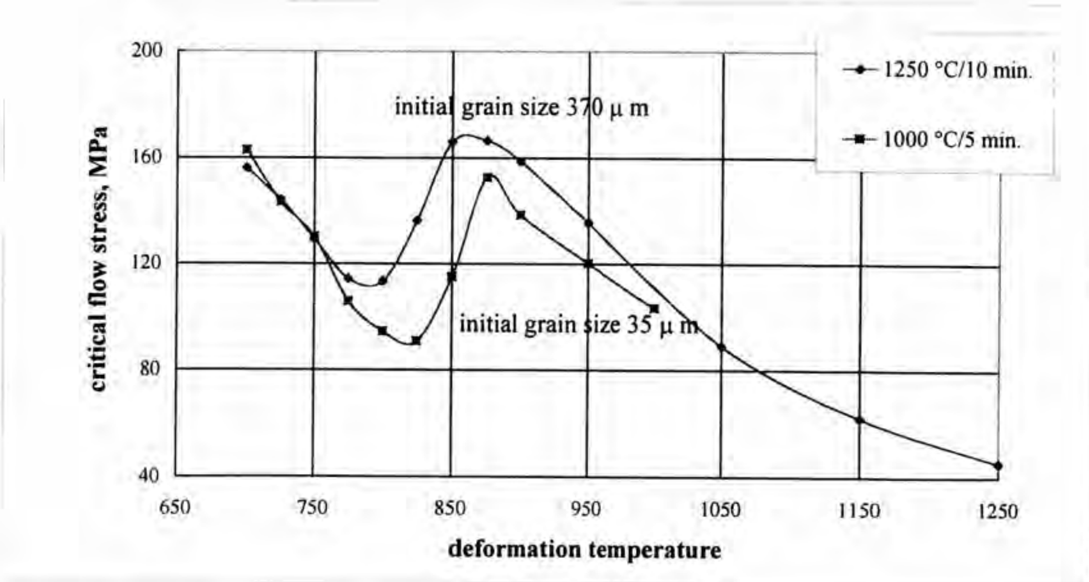


Fig. 4-8 : Effect of deformation temperature and austenitizing condition on the critical flow stress of St.15 at a constant strain rate of 1/s

370 μm, after high temperature austenitization. The finer grain size has a higher amount of grain boundaries leading to a higher number of possible nucleation site, for the subsequent transformation. Therefore a coarse grain structure needs a higher driving force for the transformation, which means a higher value for supercooling as well as lower transformation temperatures.

Flow Curves

The effect of deformation temperature on the flow stress in the austenitic and the ferritic range is shown in figure 4-9 and 4-10 respectively. In both figures, the deformation at a strain rate of 1/s was performed after austenitizing at 1000 °C for 5 minutes.

Decreasing temperature leads to an increase of the flow stress value. The difference in the atomic structure of ferrite and austenite has influence on softening mechanism. The austenite is prone to recrystallization, due to its low stacking fault energy. Therefore the flow curves of austenite show a relative maximum value followed by a relative minimum value and a steady state (figure 4-9). The increasing stress values with strains above 0.8 are caused by friction problems during tests and should not be considered. The ferritic range is preferably recovery as explained above. Therefore the shape of the ferrite flow curves differs from that of the austenite curves. In figure 4-10, the stress

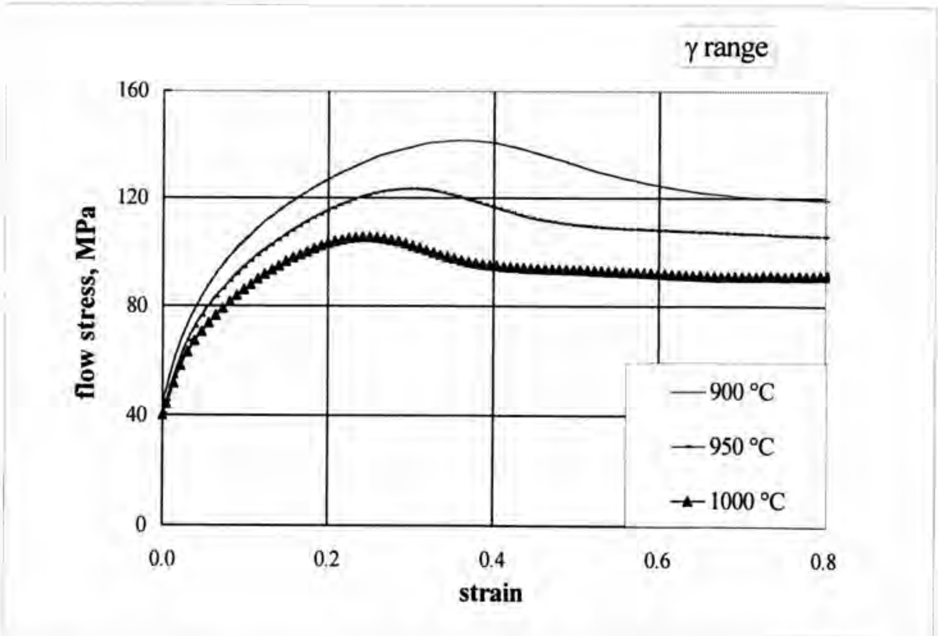


Fig. 4-9 : Effect of deformation temperature on the stress-strain curves of St.15 at a constant strain rate of 1/s (after austenitizing at 1000 °C for 5 minutes)

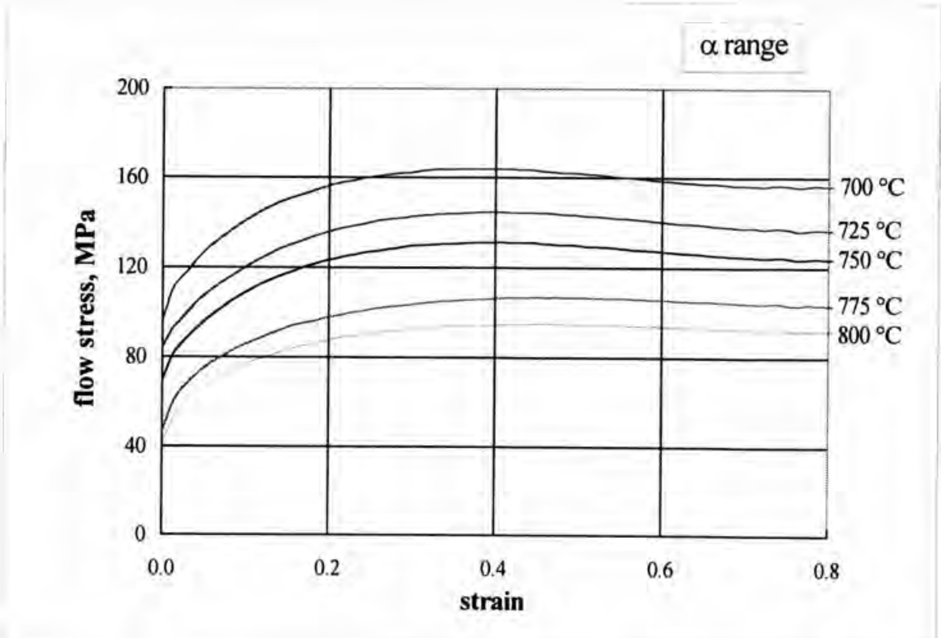


Fig. 4-10 : Effect of deformation temperature on the stress-strain curves of St.15 at a constant strain rate of 1/s (after austenitizing at 1000 °C for 5 minutes) is increasing as a monotonic function with the same strain until a steady state is reached.

In figure 4-9 the curves show a maximum stress follows by a steady stress. This was considered to be due to dynamic recrystallization, which results in the softening after the maximum stress. Decreasing deformation temperature shifts the strain at peak stress and the onset of steady state to higher strain and stress values. Besides that, the strain range between ε_p and ε_s is extended, which delays completely recrystallized microstructure. This was due to the fact that, with increasing strain rate, the processing time for softening by dynamic recrystallization is shorter. This leads to a strained microstructure, which shifts flow stress to a higher value.

The effect of deformation temperature on flow stress of austenite and ferrite at a strain rate of 1/s after austenitizing at 1250 °C for 10 minutes is illustrated in figure 4-11 and 4-12, which is similar to the one described for austenitizing at 1000 °C for 5 minutes. However, in figure 4-11 it can be seen clearly that the difference between peak stress and steady stress are lower when temperature is lower. From this, it is considered that amount of dynamic recrystallization is decreasing with temperature. In addition, from the flow curves with deformation temperature at 950 °C or lower, the dynamic

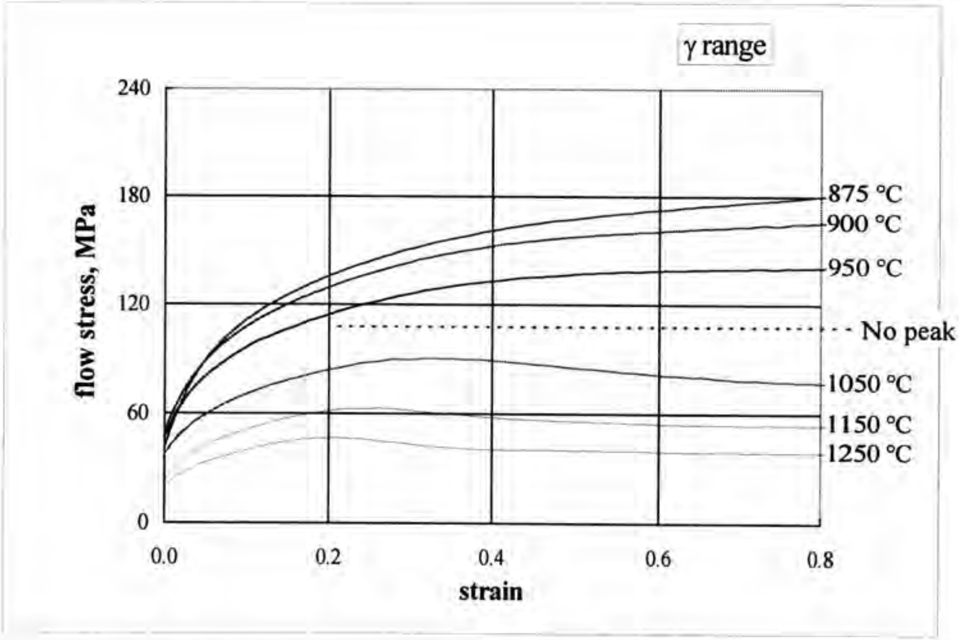


Fig. 4-11 : Effect of deformation temperature on the stress-strain curves of St.15 at a constant strain rate of 1/s (after austenitizing at 1250 °C for 10 minutes)

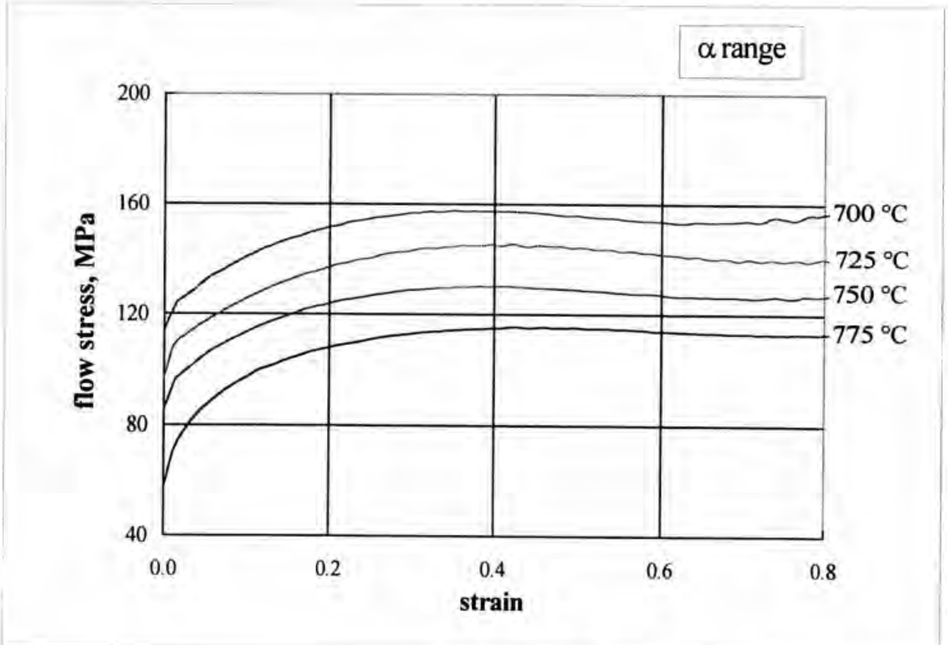


Fig. 4-12 : Effect of deformation temperature on the stress-strain curves of St.15 at a constant strain rate of 1/s (after austenitizing at 1250 °C for 10 minutes) recrystallization is completely suppressed, and the flow curves have no maximum value up to the strain range of investigation.

The effect of the strain rate on the stress-strain curves at a constant deformation temperature in the austenitic and ferritic range is plotted in figure 4-13 and 4-14 respectively for austenitizing at 1000 °C for 5 minutes. As expected, the flow stress at a constant strain increases with increasing strain rate for a constant austenitizing and deformation temperature. The shape of the stress-strain curve is influenced by the strain rate. However for austenite an increasing strain rate shifts the steady state stress to higher stress and strain values. It can also be seen that an increasing strain rate shifts the peak stress to higher strain and stress value, because it has shorter processing time so that dynamic recrystallization did not occur. This is obvious if the difference between maximum peak stress and steady state stress is considered with increasing strain rate. This value as a parameter for dynamic softening is reduced. At low strain rate the flow curve has a cyclic shape after the maximum peak. With increasing strain rate the austenite flow curve will change from multiple peaks to single peak. The stress is still increasing as a monotonic function although the value for equilibrium stress is higher and the onset of the steady state is shifted to higher values of strain. Influence of strain rate on the stress-strain curves at constant deformation temperature after austenitizing at 1250 °C for 10 minutes is shown in figure 4-15 to 4-17. This influence is similar to those for low temperature austenitization as described above.

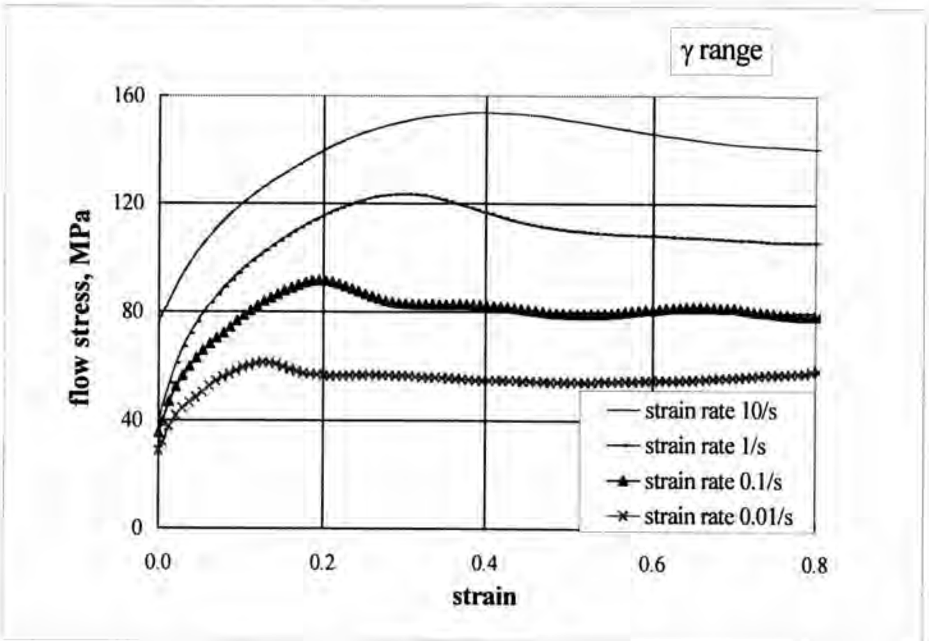


Fig. 4-13 : Effect of strain rate on the stress-strain curves of St.15 at 950 °C (after austenitizing at 1000 °C for 5 minutes)

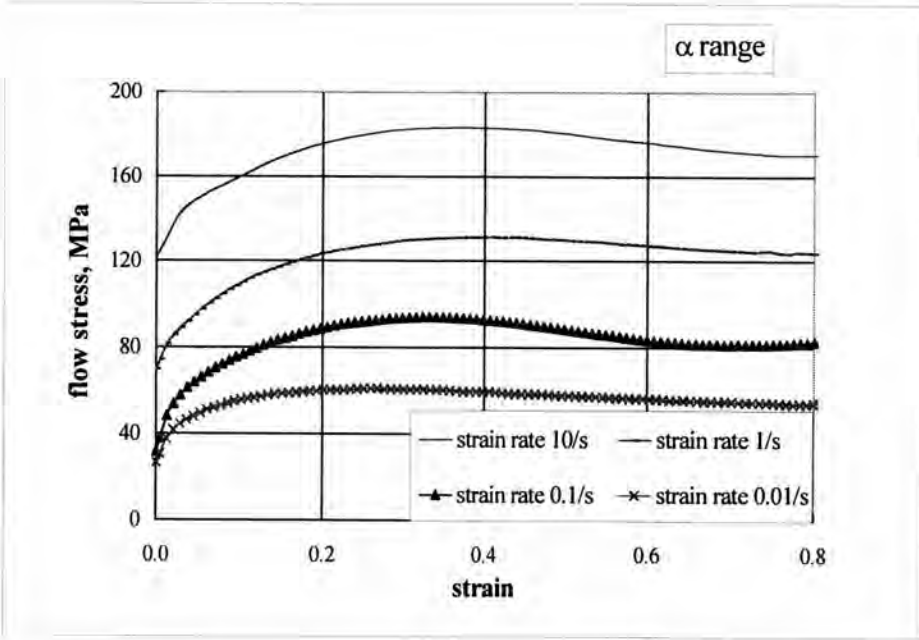


Fig. 4-14 : Effect of strain rate on the stress-strain curves of St.15 at 750 °C (after austenitizing at 1000 °C for 5 minutes)

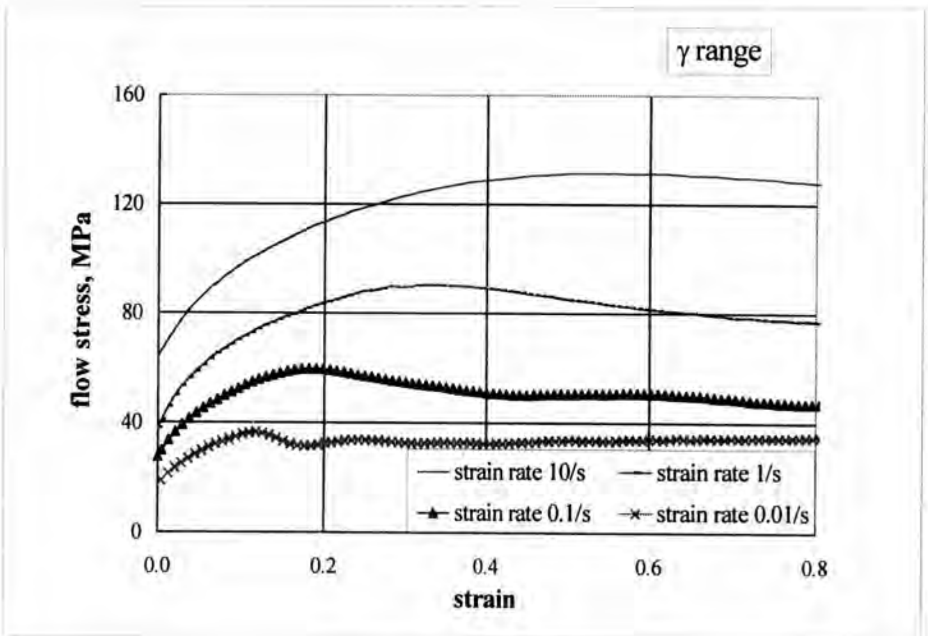


Fig. 4-15 : Effect of strain rate on the stress-strain curves of St.15 at 1050 °C (after austenitizing at 1250 °C for 10 minutes)

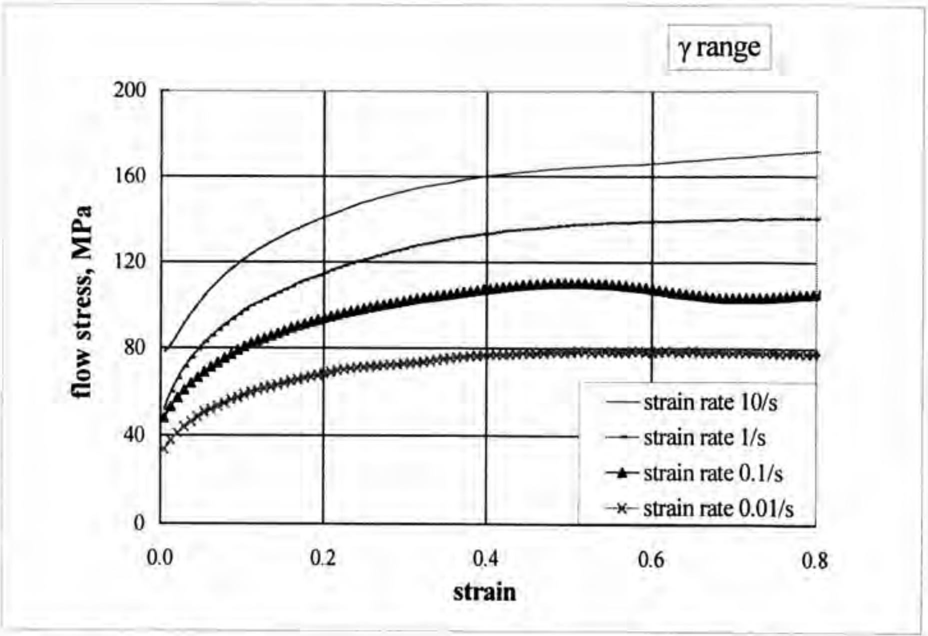


Fig. 4-16 : Effect of strain rate on the stress-strain curves of St.15 at 950 °C (after austenitizing at 1250 °C for 10 minutes)

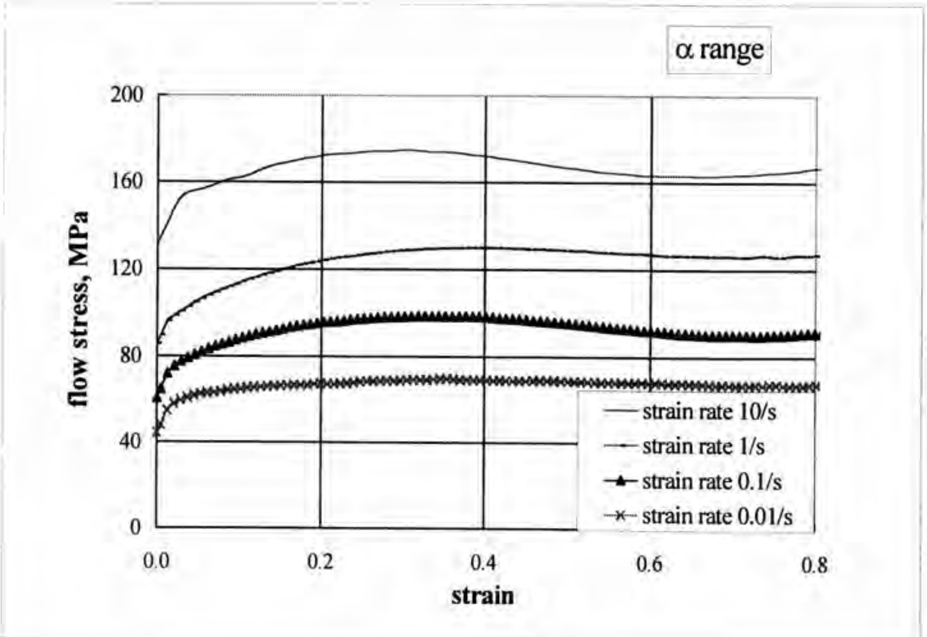


Fig. 4-17 : Effect of strain rate on the stress-strain curves of St.15 at 750 °C (after austenitizing at 1250 °C for 10 minutes)

The effect of the initial grain size on the stress-strain curve at a constant strain rate and deformation temperature in the austenitic and in the ferritic range is shown in figure 4-18 and 4-19 respectively. The different flow curves in the austenite may be caused by different softening mechanism due to different initial structures. The initial grain size of 35 μm provides a high nucleation site density for recrystallization. Therefore dynamic recrystallization is the main softening mechanism, which can be seen very easily from the shape of the flow curve with a peak. This is different in case of the initial grain size of 370 μm. Because of the monotonic shape of the flow curve recovery seem to be the main softening mechanism. The effect of the initial grain size on stress-strain curves of ferrite seems to be very small (see figure 4-19). The peak stress and the steady stress seem to be equal for same values of strain.

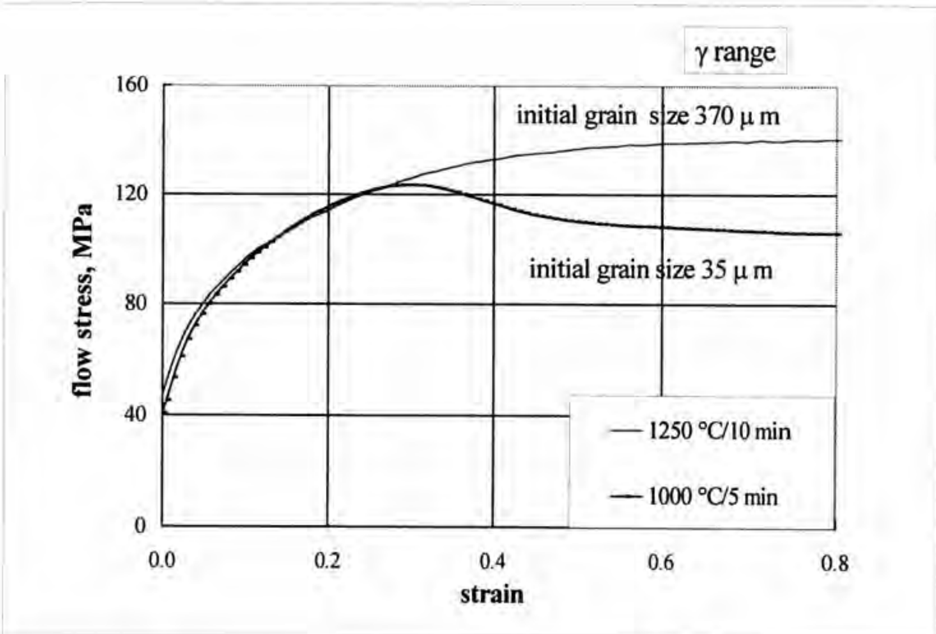


Fig. 4-18 : Effect of austenitizing condition on the stress-strain curves of St.15 at 950 °C (a constant strain rate of 1/s)

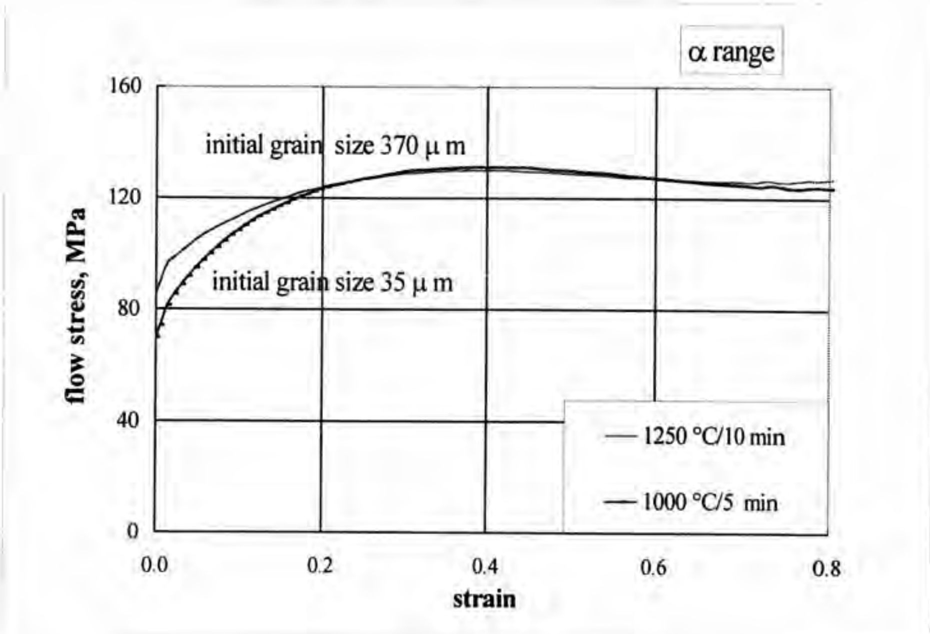


Fig. 4-19 : Effect of austenitizing condition on the stress-strain curves of St.15 at 750 °C (a constant strain rate of 1/s)

From equation (2) deformation parameters can be combined in terms of the Zener-Hollomon parameter (Z) as

$$Z = \dot{\varepsilon} \exp (Q_{def} / RT) \qquad \text{(Equation 2)}$$

At a certain temperature equation (2) can be reduced to

$$Z = c_1 \dot{\varepsilon}$$

where c_1 is a constant.

According to equation (7) the peak stress is only a function of Z as

$$\sigma_p = a_6 . Z^{a7} \qquad \text{(Equation 7)}$$

by substitution of Z in equation (7)

$$\sigma_p = a_6 .(c_1 \dot{\varepsilon})^{a7}$$

then

$$\sigma_p = c_2 . \dot{\varepsilon}^{a7} \qquad \text{(Equation 26)}$$

where $c_2 = a_6 . c_1^{a7}$

The effect of deformation temperature and strain rate on peak stress of St.15 is shown in figure 4-20 to 4-23. The peak stresses can be approximated by power function of strain rate with correlation (R squared value) more than 0.97.

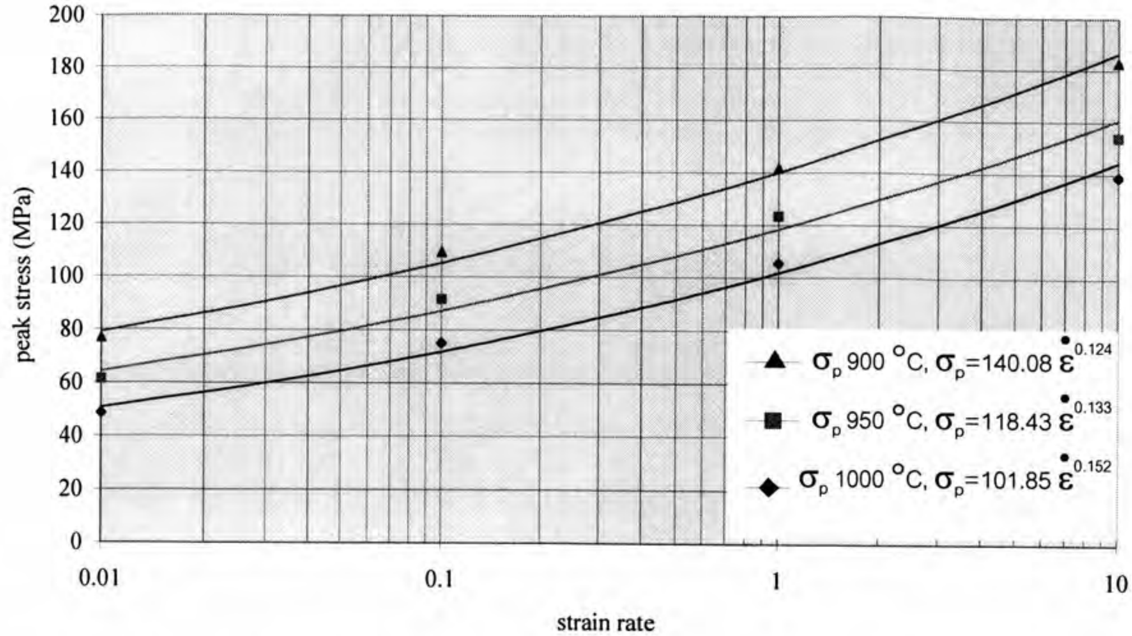


Fig. 4-20 : Effect of deformation temperature (in γ range) and strain rate on peak stress of St.15 after austenitizing at 1000 °C for 5 minutes

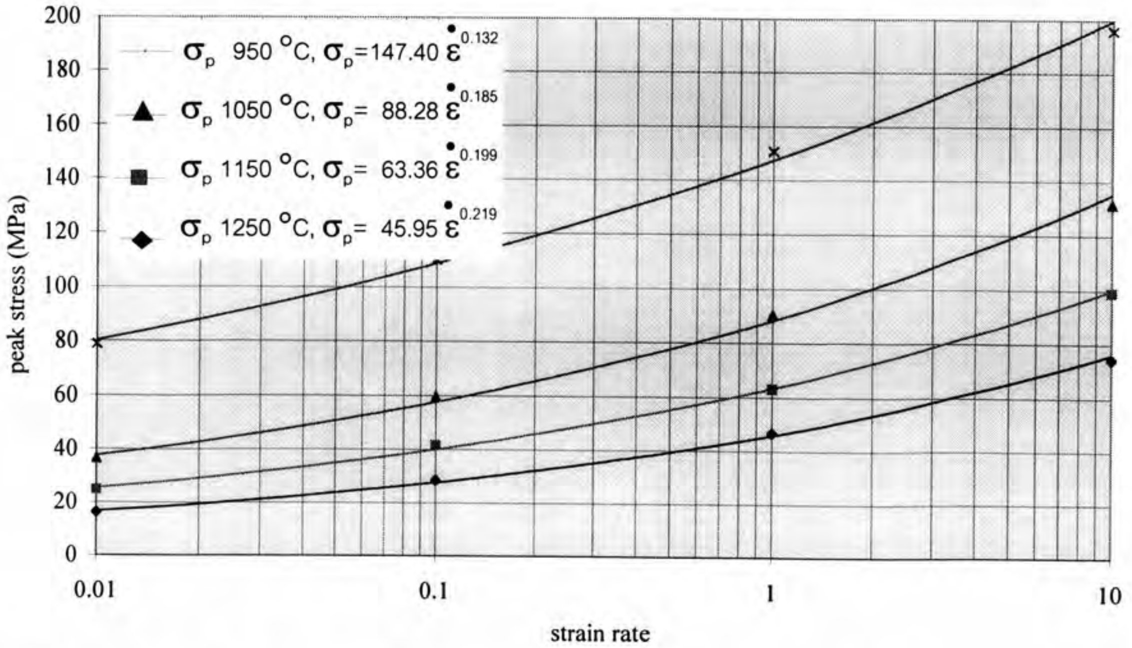


Fig. 4-21 : Effect of deformation temperature (in γ range) and strain rate on peak stress of St.15 after austenitizing at 1250 °C for 10 minutes

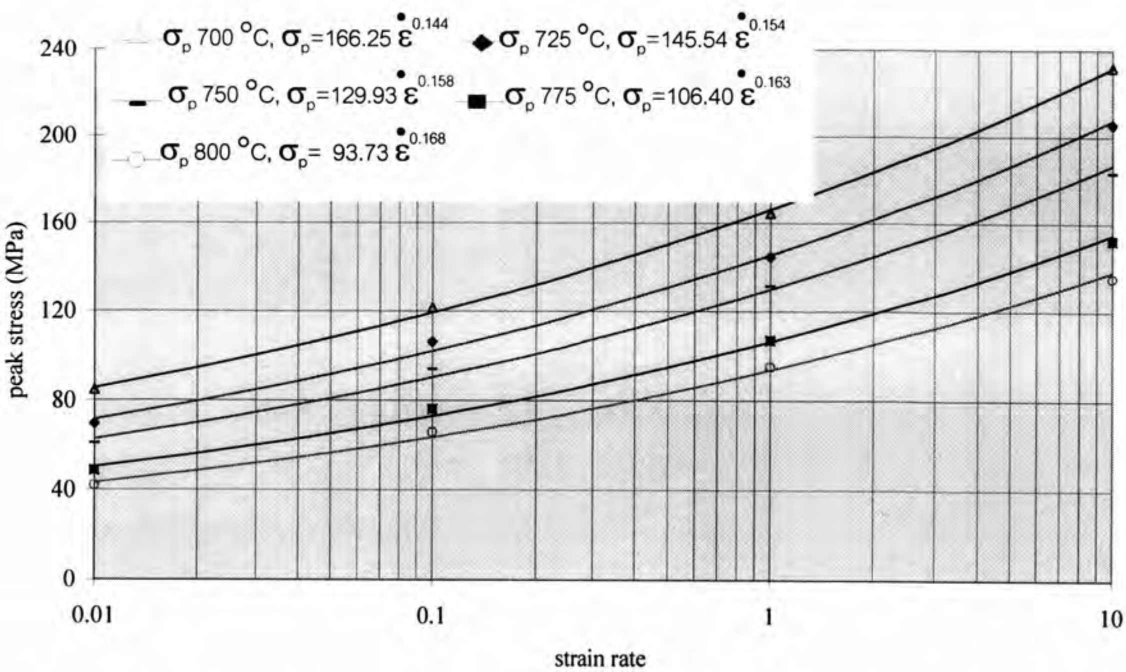


Fig. 4-22 : Effect of deformation temperature (in α range) and strain rate on peak stress of St.15 after austenitizing at 1000 °C for 5 minutes

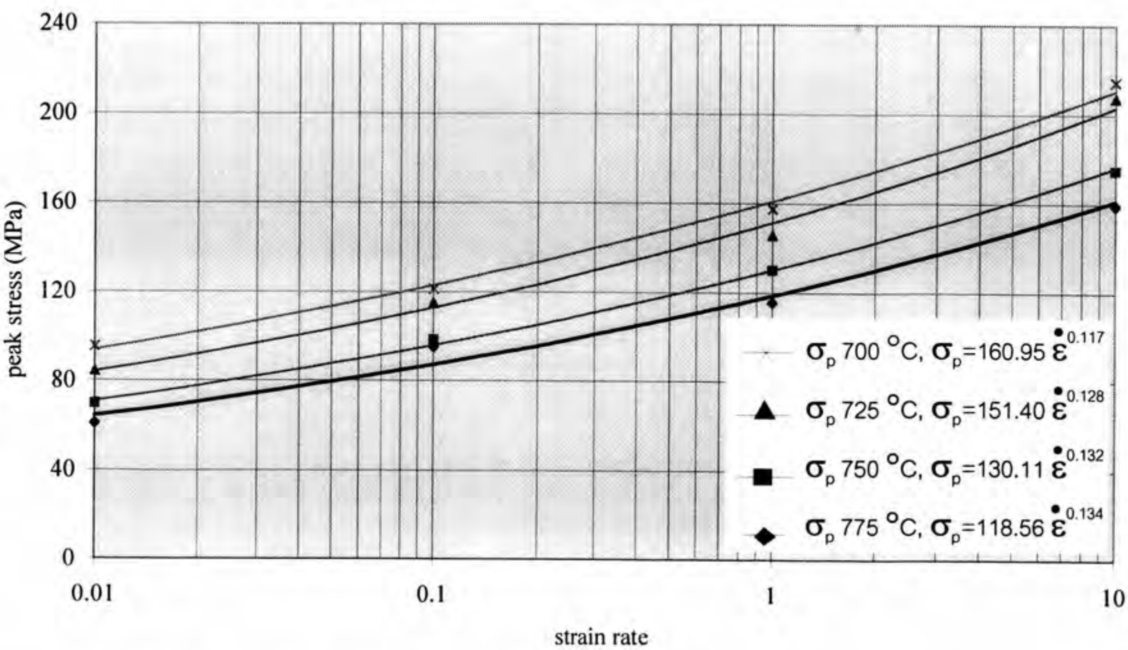


Fig. 4-23 : Effect of deformation temperature (in α range) and strain rate on peak stress of St.15 after austenitizing at 1250 °C for 10 minutes

Microstructure

Figures 4-24 and 4-25 show the microstructure after austenitizing at 1250 °C and deformation at 1250 °C at strain rates of 0.01 s^{-1} and 1.0 s^{-1}, respectively. Both micrographs show serrated grain boundaries. Increasing strain rate results in a finer grain size. The corresponding flow curves have multiple peaks (figure A19), which indicates that cyclic dynamic recrystallization is the main softening mechanism. Increasing strain rate or decreasing deformation temperature diminishes the serration of the grain boundaries.

The microstructure after austenitizing at 1000 °C and deformation at 900 °C at a strain rate of 10.0 s^{-1} is shown in figure 4-26 and 4-27. Polygonal and equiaxed grains with some small grains are formed. The grain boundary is rather straight and the microstructure is homogeneous. A difference in color is obtained between the different grains, depending on their orientation to the specimen surface. The flow curve shows a stationary range (figure A18).

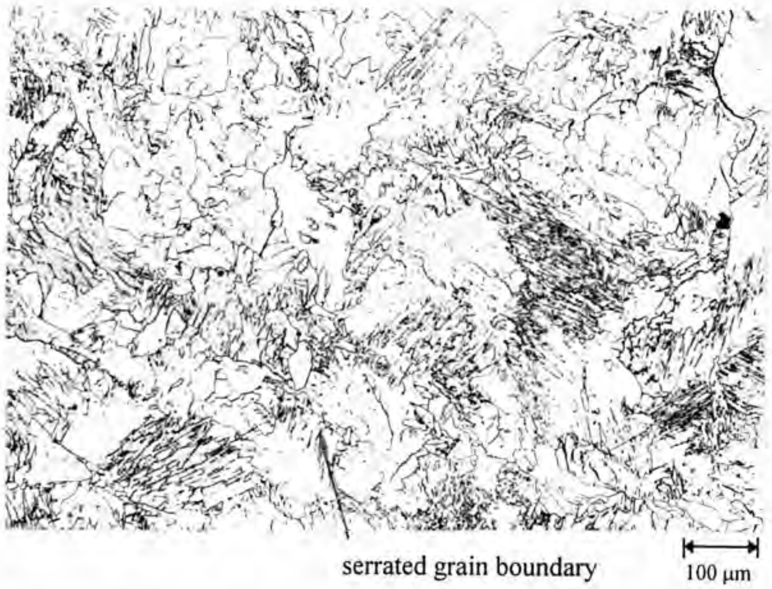


Fig. 4-24 : Microstructure after deformation at 1250 °C (in γ range), strain of 1.6 and strain rate of 0.01/s (austenitizing at 1250 °C for 10 minutes, etched with 3%HNO_3)

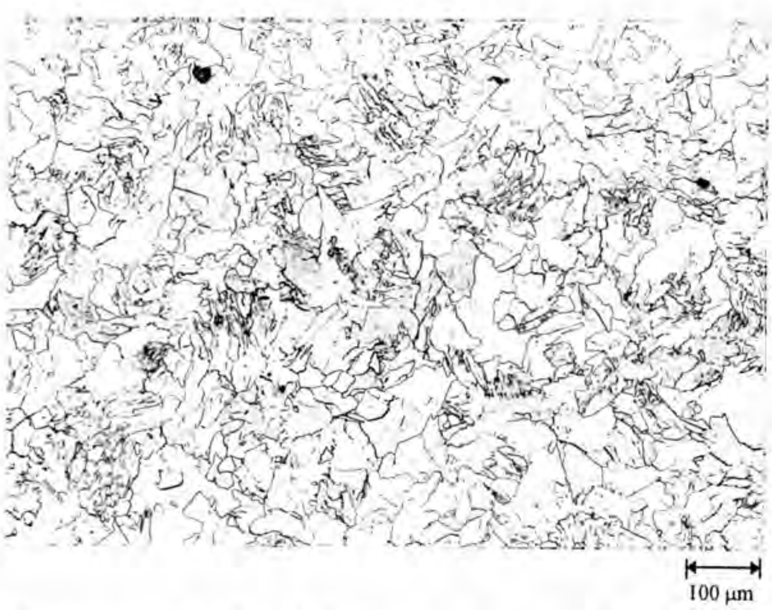


Fig. 4-25 : Microstructure after deformation at 1250 °C (in γ range), strain of 1.6 and strain rate of 1/s (austenitizing at 1250 °C for 10 minutes, etched with 3%HNO_3)

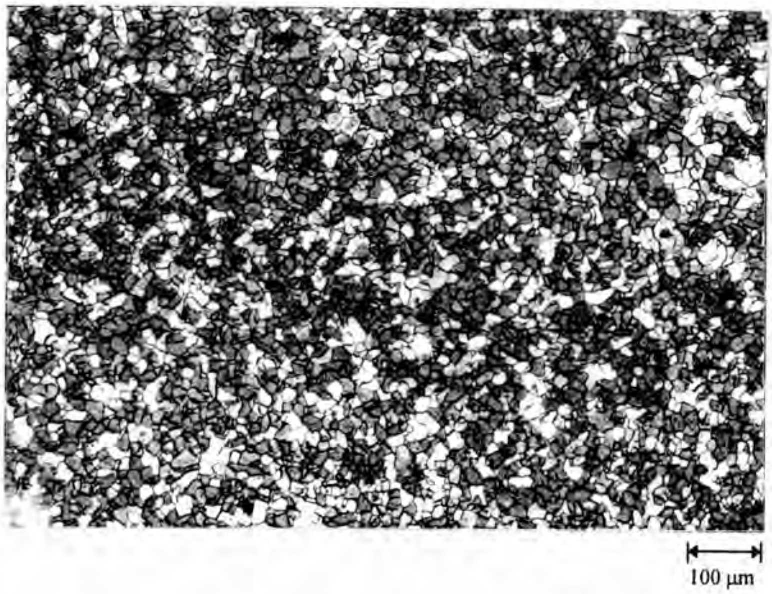


Fig. 4-26 : Microstructure after deformation at 900 °C (in γ range) , strain of 1.6 and strain rate of 10/s (austenitizing at 1000 °C for 5 minutes, etched with 3%HNO_3)

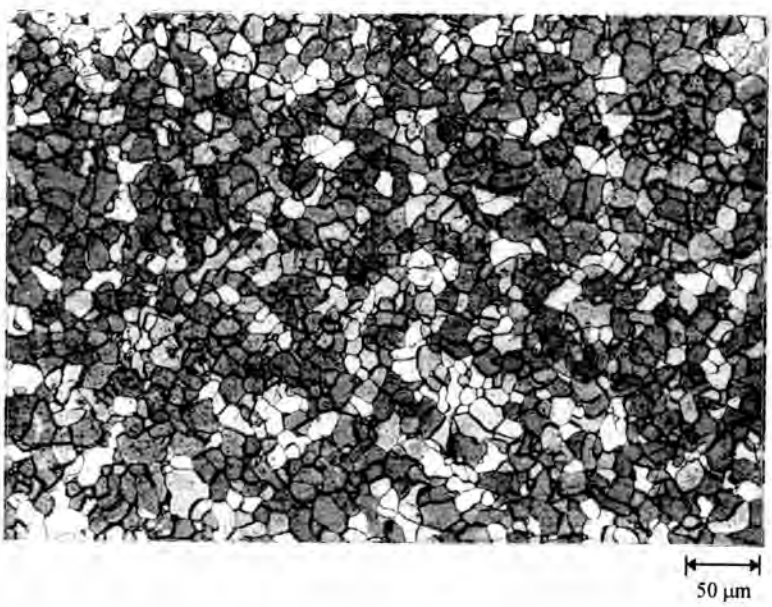


Fig. 4-27 : Microstructure after deformation at 900 °C (in γ range), strain of 1.6 and strain rate of 10/s (austenitizing at 1000 °C for 5 minutes, etched with 3%HNO_3)

Bulged grain boundaries were formed after austenitizing at 1250 °C and deformation at 1050 °C at a strain rate of 1.0 s^{-1} (figure 4-28). At the same austenitizing condition, decreasing deformation temperature (950 °C) results in not only finer grains but also the diminishing of the bulged grain boundaries (figure 4-29). The corresponding flow curves are shown in figure 4-11.

Figure 4-30 and 4-31 show the microstructure after austenitizing at 1250 °C and deformation at 800 °C at a strain rate of 10.0 s^{-1}. The deformation was performed in the temperature range of austenite+ferrite, therefore the final microstructure is heterogeneous with a large scale of different grain size because of different softening mechanisms. The progressive disappearance of the boundaries between coarse grains is observed. Fine and elongated grains are built by recovery processes of the ferrite phase. Especially in these areas a substructure due to recovery is obvious. The corresponding flow curve is plotted in figure A29.

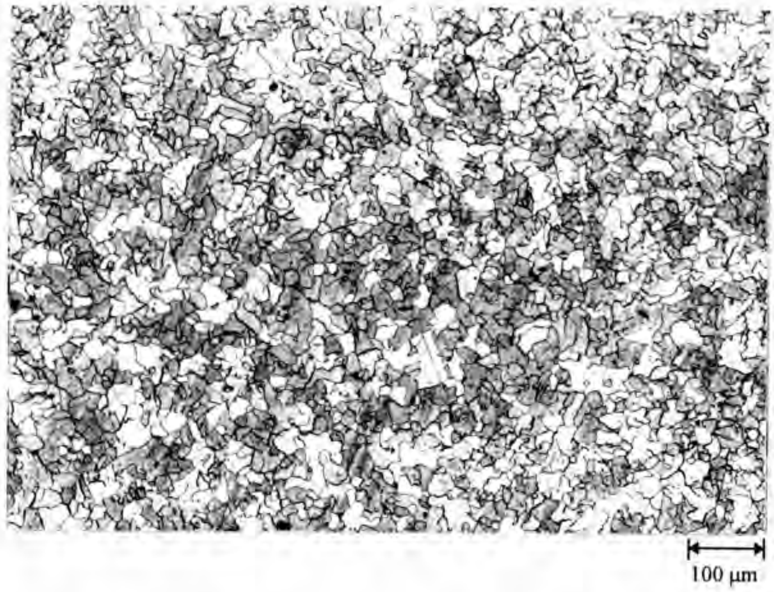


Fig. 4-28 : Microstructure after deformation at 1050 °C (in γ range), strain of 1.6 and strain rate of 1/s (austenitizing at 1250 °C for 10 minutes, etched with 3%HNO_3)

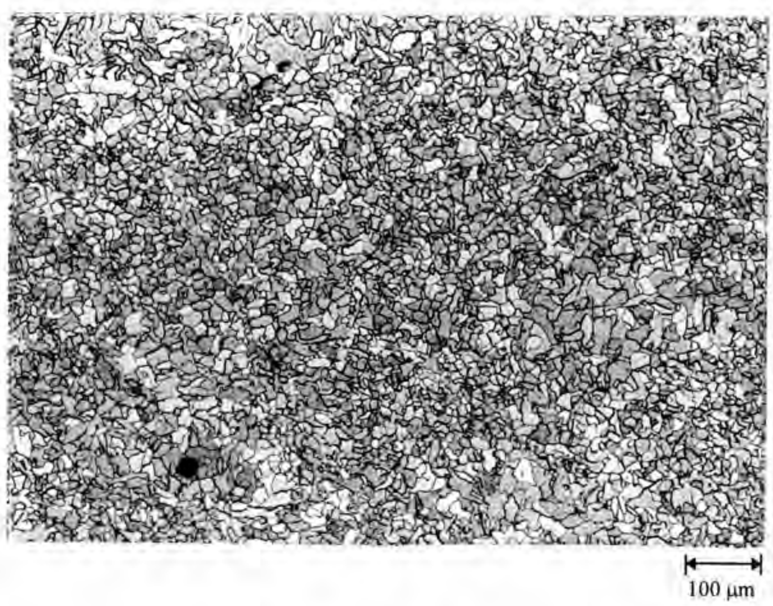


Fig. 4-29 : Microstructure after deformation at 950 °C (in γ range), strain of 1.6 and strain rate of 1/s (austenitizing at 1250 °C for 5 minutes, etched with 3%HNO_3)

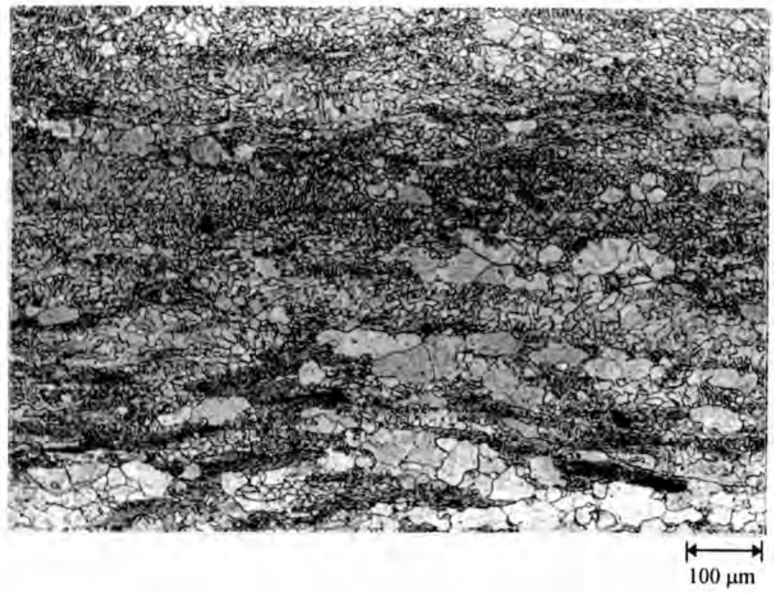


Fig. 4-30 : Microstructure after deformation at 800 °C (in $\alpha+\gamma$ range), strain of 1.6 and strain rate of 10/s (austenitizing at 1250 °C for 10 mintues, etched with 3%HNO_3)

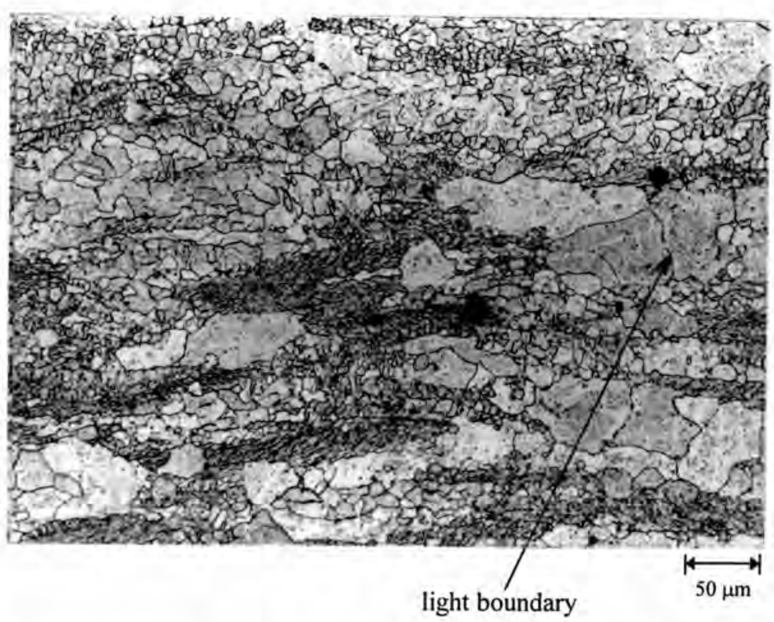


Fig. 4-31 : Microstructure after deformation at 800 °C (in $\alpha+\gamma$ range), strain of 1.6 and strain rate of 10/s (austenitizing at 1250 °C for 10 minutes, etched with 3%HNO_3)

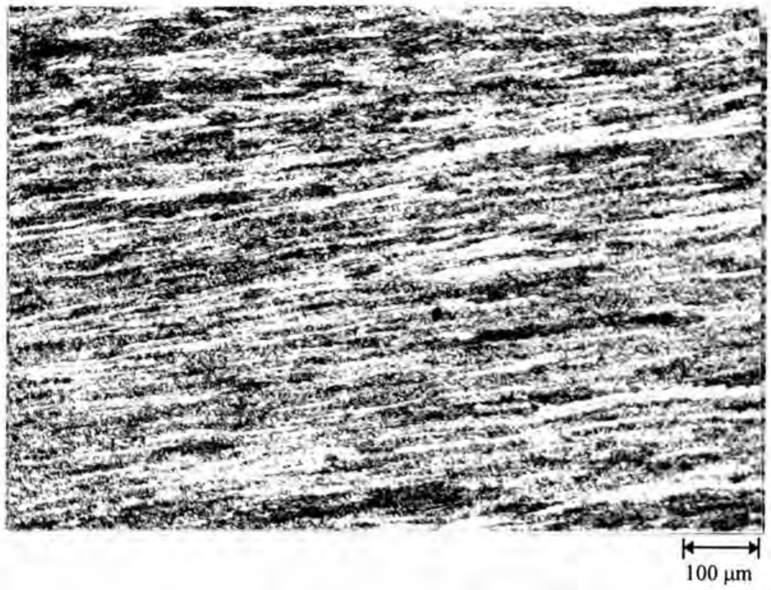


Fig. 4-32 : Microstructure after deformation at 700 °C (in α range), strain of 1.6 and strain rate of 1/s (austenitizing at 1000 °C for 5 minutes, etched with 3%HNO_3)

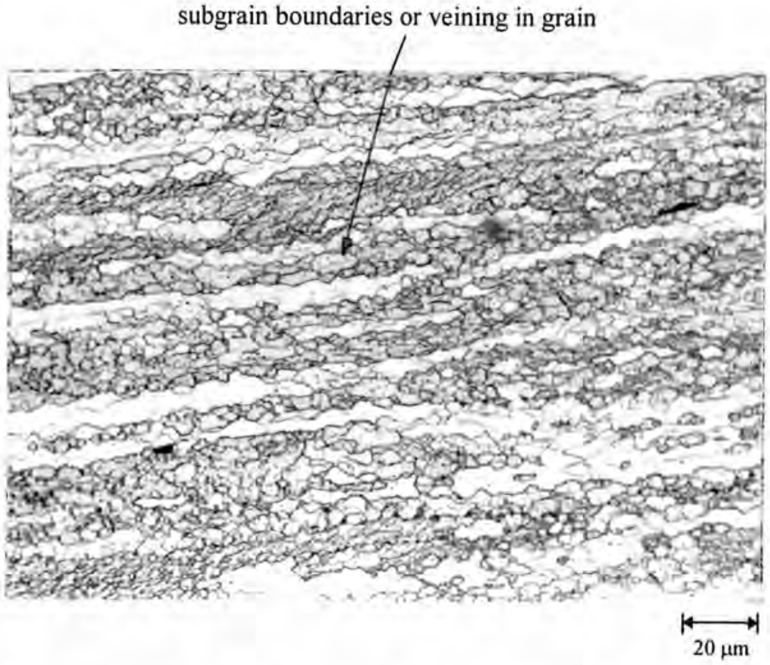
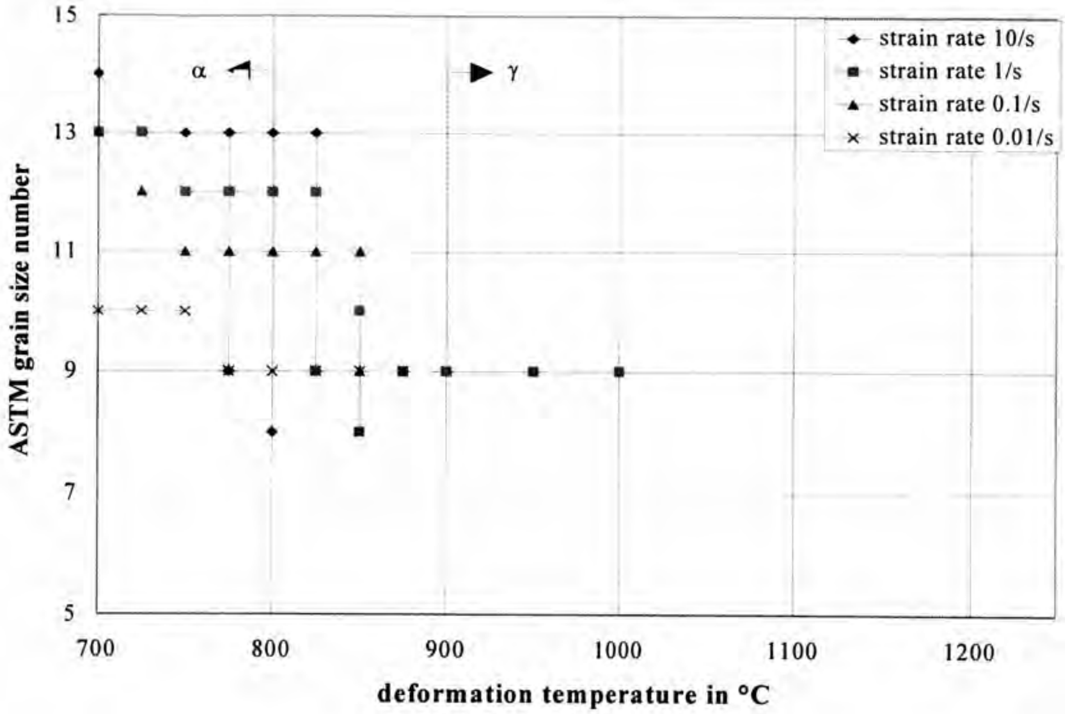


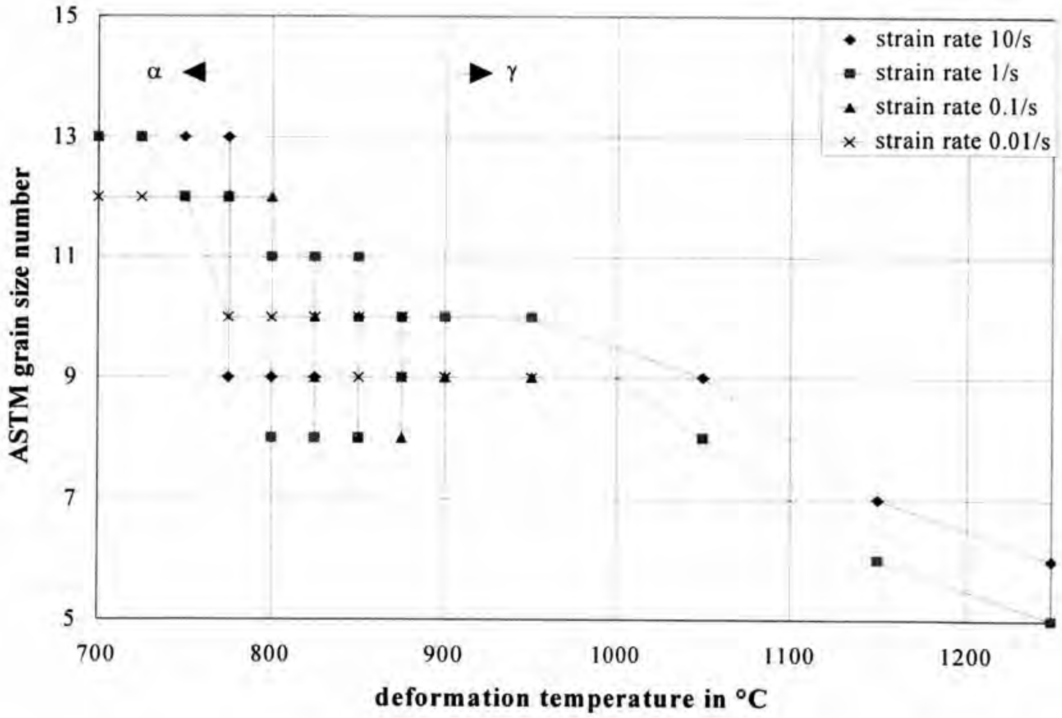
Fig. 4-33 : Microstructure after deformation at 700 °C (in α range), strain of 1.6 and strain rate of 1/s (austenitizing at 1000 °C for 5 minutes, etched with 3%HNO_3)|

Figure 4-32 and 4-33 show the microstructure after austenitizing at 1000 °C and deformation at 700 °C at a strain rate of 1.0 s^{-1}. The micrographs deformation bands and elongated grains as well as equiaxed grains can be seen. The conclusion that recovery is the main softening mechanism can be made with regard to those phases where a strong substructure has been formed. This corresponds to the flow curve shown in figure A25 (annex). The subgrain boundaries are more distinct, when the grains are more coarse. Due to the low deformation temperature, fine grain is observed.

In figure 4-34 and 4-35 the relation between the mean grain size and the deformation temperature is shown for both austenitizing conditions. In austenitic or ferritic range, the mean grain size decreases as the deformation temperature is reduced. Deformation in the dual-phase range results in an heterogeneous grain structure with small grains adjacent to coarse grains. From these diagrams it can be seen very clearly that deformation in the ferritic range leads to smaller grain size although depending on the cooling condition, a strained structure may be obtained.



(a)



(b)

<u>Fig. 4-34 :</u> Effect of deformation temperature and strain rate on ferrite grain size <ASTM No.> (a) austenitizing at 1250 °C/10 min. and (b) austenitizing at 1000 °C/5 min.

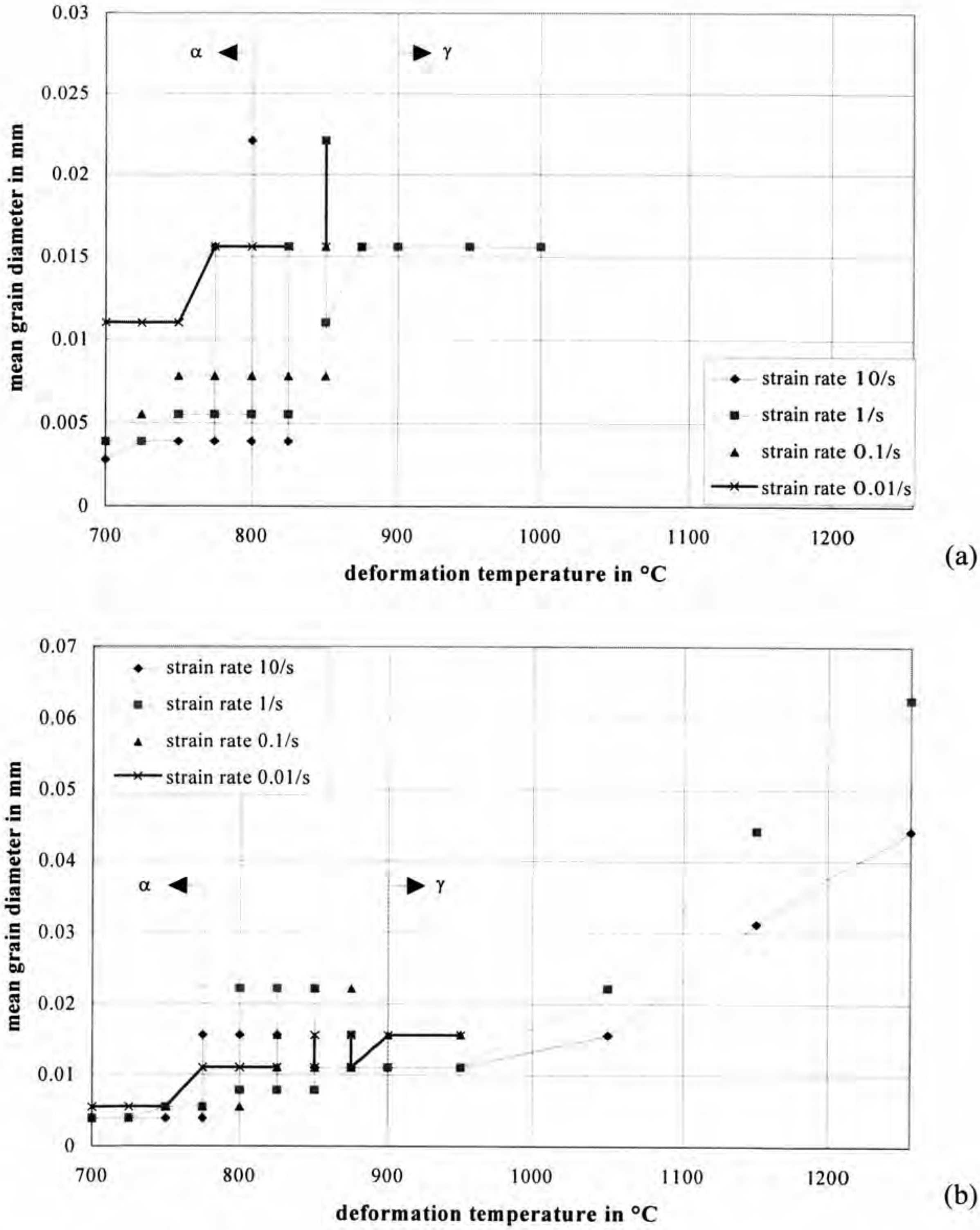


Fig. 4-35 : Effect of deformation temperature and strain rate on ferrite grain size (a) austenitizing at 1250 °C/10 min. and (b) austenitizing at 1000 °C/5 min.