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# TRANSFORMATION KINETICS OF MICROALLOYED STEELS AFTER HOT CONTROLLED ROLLING

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**ABSTRACT**

Transformation kinetics of austenite into ferrite after controlled hot rolling has been investigated in three microalloyed steels (Nb, Nb-Ti and C-Mn-V) using hot interrupted compression tests on the Gleeble 1500 within the testing temperature range of 875°C-1100°C. Holding times were varied between 0.5 and 30s, strain rates of between 9.5 and 20/s and strains up to 0.9 were employed. Peak strain varied from 0.4 to 0.45 at 20/s for both C-Mn and Nb steels at 1000°C. As a result of strain accumulation, dynamic recrystallization occurred at the beginning of the 3rd pass in both C-Mn and, in Nb, steels. Measured grain sizes after reheating were 87.2, 57.4 and 50.2microns for C-Mn-V, Nb and Nb-Ti steels respectively. After undergoing full static, dynamic and metadynamic recrystallisation, austenite grains were greatly refined down to measured 19.1, 18.0 and 17.5microns for C-Mn-V, Nb, and Nb-Ti steels. These were the final austenite grain sizes before transformation to ferrite at the transformation temperature. Predicted ferrite grain sizes after transformation were 12.0 and 9.41microns for C-Mn and Nb steels respectively. With retained strain (0.38), better grain refinement and hence predicted lower ferrite grain values of 9.42 and 7.91microns were for C-Mn-V and Nb steels respectively. Measured ferrite grain sizes after transformation were 9.2, 6.0 and 5.1microns respectively for C-Mn-V, Nb and Nb-Ti steels. The finer the ferrite grain size, the higher the predicted lower yield stress(L.Y.S) for C-Mn steel. 347 Mpa(transformed from dynamically recrystallised austenite grains) and 317Mpa(transformed from statically recystallised austenite grains). Measured L.Y.S. from tensile tests was 361Mpa.

**KEY WORDS:** Transformation kinetics, Microalloyed steels, Hot rolling, Recrystallisation

## INTRODUCTION

There are three kinds of microstructural evolution during hot rolling which affect both the rolling loads, as well as the final microstructures that are produced. The first involves grain refinement by conventional static recrystallization, and is known as recrystallization-controlled-rolling (RCR) when employed on microalloyed steels such as Ti-V grades. It is responsible for the lowest rolling loads at a given temperature, because the occurrence of complete (or nearly complete) static recrystallization leads to the lowest dislocation densities of the three types of microstructural processes. It also leads to the lowest values of Sv, the specific surface area per unit volume of austenite grain boundary, so that the ferrite grain size after transformation displays the least refinement of the three processes (Pussegoda et al.,1991). The effect of alloying elements on conventional static recrystallization is depicted in Akben et al.,(1979). The influence of 0.035% Nb in solution corresponds to a six-fold retardation of recrystallization with respect to the rate of softening displayed by the C-Mn steel (Akben et al.,1979). The non-negligible retardations produced by alloying elements in solution play important roles when there is insufficient time for precipitation to take place, during rolling, such as in rod mills and hot strip mills. When static recrystallization is incomplete, and the work hardening retained from pass to pass, the mean flow stress increases rapidly with decreasing temperature. This corresponds to conventional controlled rolling (or CCR); it leads to the highest rolling loads (for a given temperature) because of high accumulated density of dislocations. It is also responsible for a finer ferrite microstructure than RCR, because of high Sv value of the flattened austenite grains prior to transformation. In this way, ferrite grain sizes as small as 5 to 8μm are attainable by means of CCR processing (Samuel et al.,1990). The third type of microstructural evolution that takes place during hot rolling is that associated with dynamic recrystallization of the austenite (DRC). It leads to lower rolling loads (mean flow stresses) than CCR. This is because dynamic recrystallization does not remove dislocations as effectively as static recrystallization, but still reduces density well below the levels present in work hardened austenite. The present work aims to introduce the different types of controlled rolling, analyse subsequent recrystallisation, and transformation kinetics in the three microalloy steels chosen.

### Experimentation

Compositions of steels used are in Table 1.Specimens were machined to length 30mm and diameter 8mm for the tests. They were then resistance heated and subjected to 2, 3 and 5-stage hot compression tests. Strain increment for the 2 stage compression was 0.3 each, 0.2 each for 3 stage and 0.12 each for the 5 stage compression. For 2, 3, 5 stage compression tests, strain rate was varied between 0.5 and 30s; and temperature between 875 and 1100°C.Tests were carried out on the Gleeble 1500, a computer controlled machine capable of performing diverse thermomechanical tests and simulations, under vacuum conditions. Gleeble computer programmes to effect 2, 3 and 5-stage compression tests were developed, filed and used to carry out the tests. 1-stage compression programme was also developed to obtain continuous stress-strain curves for comparison with the stress strain curves of the 2, 3 and 5-stage compression tests. Tests were often repeated and found to give the same results showing the accuracy of the Gleeble. During testing, force, holding times, and lengthwise strain measurements were automatically recorded and stored in the computer. These were retrieved after each test through the computer plotter system in the form of stress-strain diagrams. Specimens were allowed to cool to room temperature at the rate of 40°C/s after tests. In addition, tensile tests were performed on stamped specimens of these steels using instron universal testing machine. Metallurgical samples were polished and etched using nital solution.Optical microscope/computer evaluation of ferrite grain sizes present in micrographs was done by lineal analysis. Detailed experimental results have been reported elsewhere (Morgridge et al.,1992) Relevant results are reprinted here for convenience. Other methods of obtaining the thermomechanical properties of steels, apart from hot controlled rolling, include hot compression and hot torsion tests.

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Experimental tests in the present work, generated data for graphs and tables in the evaluation of flow stress, critical and peak strain, and ferrite grain sizes.

| Steel | Composition | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C [%] | Si [%] | Mn [%] | Nb [%] | S [%] | P [%] | V [%] | Cr [%] | N [%] | Mo [%] | Ti [%] | Cu [%] | Al [%] | Sn [%] | Ni [%] | Other |
| Nb-Ti | 0.084 | 0.23 | 1.4 | 0.031 | 0.002 | 0.013 | 0.006 | 0.018 | | 0.006 | 0.018 | | | | | |
| C-Mn | 0.18 | 0.2 | 0.8 | | 0.045 | 0.04 | 0.09 | | | | | | | | | |
| Nb | 0.081 | 0.26 | 1.43 | 0.03 | 0.003 | 0.014 | 0.009 | 0.021 | | 0.003 | 0.003 | | | | | |

Table 1 Composition of steels.

## RESULTS AND DISCUSSION

### Flow Stress

Flow stress is a measure of the amount of stress needed to deform the material during hot rolling. Flow stress is sensitive to temperature, strain and strain rate.

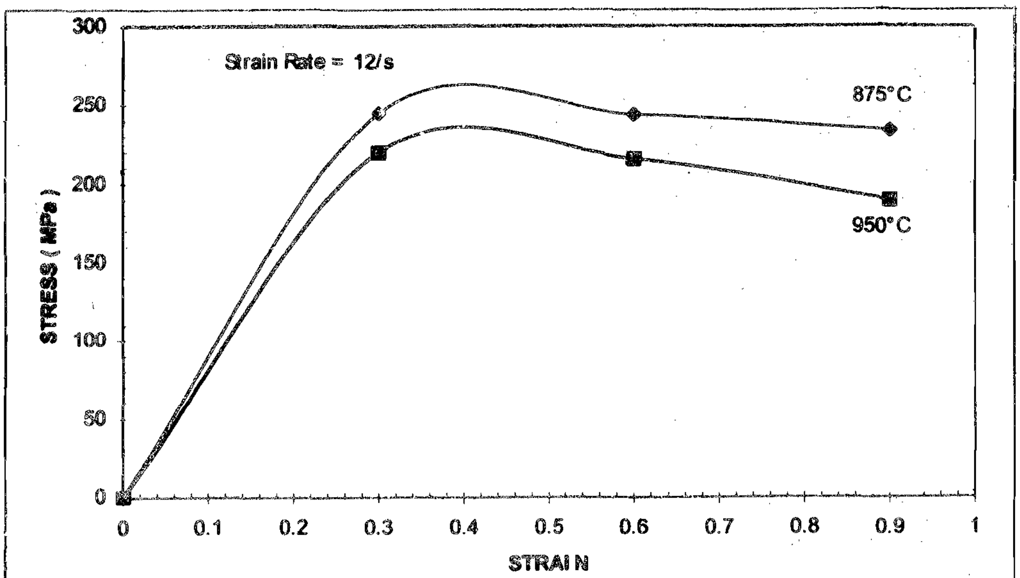


FIG.1 STRESS - STRAIN CURVES FOR Nb STEELS

Equation relating the flow stress to the Zener-Hollomon parameter is
$Z = \exp(Q/RT) = A(\sinh(\square\square))^n$ (Lenard et al.,1999)

From continuous stress – strain curve, Fig.1, static recrystallisation region recorded lowest rolling load as a result of lowest dislocation densities and lowest Sv (specific surface area per unit volume of austenite grain boundary). Dynamic recrystallisation region records higher rolling loads than static recrystallisation as dynamic recrystallisation does not remove dislocation as effectively as static recrystallisation. Conventional controlled rolling allows some of the finishing passes to be carried out at temperatures below the recrystallisation temperature, and with sufficient interpass time to allow precipitation to start thereby leading to pancaking of grains, with the highest rolling loads, but producing the best grain refinement. At low strain rates, low flow stress indicate low dislocation density and slow softening owing to low driving force. High precipitation hardening can also adversely affect flow stress levels in hot rolling. Deformation activation energy $Q_{def}$ is approximately 312 – 330 KJ/mol. Apparent activation energy for static recrystallisation is approximately 270 KJ/mol while that of metadynamic recrystallisation is approximately 50 KJ/mol. Activation energy for both static and metadynamic recrystallisation is approximately 300 KJ/mol.

Fig. 2 combines Peak stress and Peak strain with varied testing temperatures. For all steels, peak strain increased from 0.48 to 0.66 as temperature increased from 875 to 950$^0$C. The range of experimental peak strain obtained from stress – strain curves for the three steels, vary from 0.36 for Nb and Nb – Ti steels at 950$^0$C, at strain rate 9.5/s, through to 0.4 for C – Mn – V steel at 875$^0$C, at strain rate 12/s. Experimental values obtained for C – Mn - V ( 0.4 at 875$^0$C,12/s strain rate and 0.36 at 950$^0$C,12/s strain rate ) have been superimposed on theoretical values in this figure. They are lower than the theoretical ones. The initial grain sizes in these steels are lower than the 50 microns assumed for the theoretical calculations.

### Recrystallisation

#### Static Recystallisation Grain Size ($d_{rex}$)

Static recrystallisation refines austenite grains. Nb retards static recrystallisation and results in better refinement of austenite grains than C-Mn. As received grain sizes were 65microns for C-Mn-V, 40microns for Nb and 35microns for Nb-Ti steels (measured). The

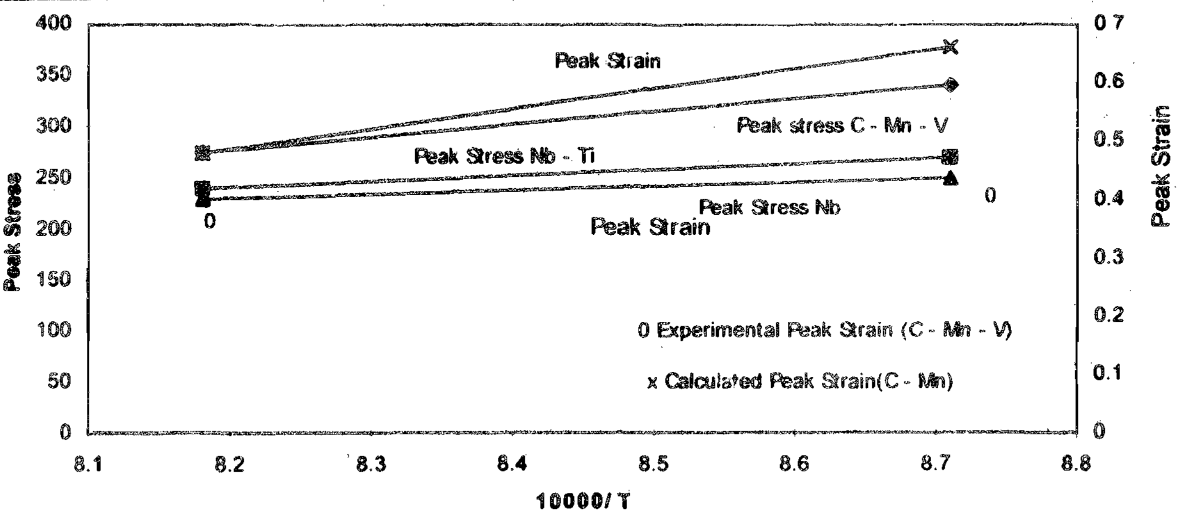


**Fig.2 Peak Stress/ Peak Strain vs 10000/ T for C - Mn - V, Nb and Nb - Ti steels,at 9.5/ s strain rate.**

reheat temperature was 1200°C and soaking was for 30mins. Measured grain sizes after reheating are 87.2microns for C-Mn-V, 57.4microns for Nb and 50.2microns for Nb-Ti. After static recrystallisation (1000°C, 9.5/s strain rate, 0.2 strain pass, time for full static recrystallisation was 8s for C-Mn-V and 20s for Nb), and using equations below for predicting grain refinement, 97.3 microns predicted for C-Mn-V was refined to 68.4microns; and 60.2 microns predicted for Nb was refined to 46.2microns. There are no modelled equations for predicting static grain refinement for Nb-Ti steel. Static recrystallisation occurs through the process of nucleation and growth. Grain refinement is limited compared with dynamic or metadynamic recrystallisation. The amount of deformation strain and initial grain size greatly affect refinement. Temperature and strain rate has little effect. Table 2 shows predicted statically recrystallized grain sizes, for 50μm initial grain size. As expected, static recrystallization refined progressively austenite grain size after 2nd and 3rd passes with greater refinement in C-Mn steel and for 50 micron start. (from 34.4 to 22.61). For Nb,refinement was from 44.46 to only 39 microns. Normally, the as-received, initial grain size of Nb steel is much smaller than the 50microns assumed above. It is usually about 20-30microns and so the final refined grain size of Nb steel will be much smaller than that of C-Mn. Regardless of initial grain size, refinement after 3rd or 4th passes produced similar grain size. Notice the levelling off after the 2nd pass for both C-Mn and Nb steel, in the table. Sellars (1979) equations for C-Mn and Nb,

$d_{rex} = 0.5 d_0^{0.67} \varepsilon^{-1}$ and $D_r = 1.1 D^{0.67} \varepsilon^{-0.67}$ respectively were used to obtain calculated values in table 2.

**TABLE 2 Summary of Statically Recystallised Grain Sizes ($d_{rex}$) for 50 microns initial grain size.**

3 passes,each pass 0.2 strain,(1st pass-1100°C; 2nd pass - 1000°C; 3rd pass- 950°C,Holding time - 30 secs

| | $d_{rex}$ (microns) | |
|---|---|---|
| | C -Mn | Nb |
| After1stpass | 34.4 | 44.46 |
| After2ndpass | 26.76 | 41.1 |
| After3rdpass | 22.61 | 39 |

**Dynamic Recrystallisation Grain Size ($d_{dyn}$)**

Dynamic recrystallisation refines austenite grains. Nb retards dynamic recrystallisation and results in better refinement of austenite grains than C-Mn. After full dynamic recrystallisation (1000°C, 9.5/s, 0.4 strain); 68.4microns for C-Mn-V was refined to 35.1microns and 46.2microns for Nb was refined to 27.4microns. Grain refinement in dynamic recrystallisation is limited, not being as good as metadynamic recrystallisation but better than static recrystallisation. Higher strain rates in dynamic recrystallisation lead to better refinement. $d_{dyn}$ decreases with decreasing temperature. Strain and initial grain size have no effect on resultant dynamically recrystallised grain sizes. Values of dynamically recrystallized grain sizes, were calculated using equation

$d_{dyn} = 1.6 \cdot 10^4 Z^{-0.23}$ (Sellars,1979), and are listed in Table3.

**TABLE 3 Summary of Dynamically Recystallised Grain Sizes($d_{dyn}$) for 50 microns intial grain size.**

Holding time 3s. Strain rate = 20/s.Temperature = 1000°C.

| | $d_{dyn}$ (microns | |
|---|---|---|
| | C - Mn | Nb |
| After 1st pass,drex | 43.4 | 44.46 |
| After 2nd pass,drex | 26.76 | 41.1 |
| After 3rd pass,ddyn | 11.82 | 20 |

As expected, greater refinement occurred in C-Mn steel with 11.82 microns and 20 microns for Nb steel after the3[rd] pass. Normally, the as-received, initial grain size of Nb steel is much smaller than the 50microns assumed above. It is usually about 20-30microns and so the final refined grain size of Nb steel will be much smaller than that of C-Mn.

**Metadynamic Recrystallisation Grain Size ($d_{meta}$)**

Metadynamic recrystallisation refines austenite grains. Nb retards metadynamic recrystallisation and results in better refinement of austenite grains than C-Mn. After full metadynamic recystallisation (0.7 strain,1000°C,9.5/s strain rate, time for full metadynamic recrystallisation is 1s for C-Mn-V and 3s for Nb steel); 35.1microns for C-Mn-V was refined to 20.7microns and 27.4 microns for Nb was refined to 18.2microns. Measured grain sizes after all recrystallisation ( Static, dynamic, and metadynamic); 19.1,18.0 and 17.5 microns for C-Mn-V, Nb, and Nb-Ti steels respectively. These are the final refined austenite grain sizes that will now transform into ferrite. Metadynamically recrystallised grain size is related to temperature and strain rate by Sellars (1979) equations (i) $d_{mrdx} = 2.6 * 10^4 Z^{-0.23}$ for C-Mn and

(ii) $d_{mrdx} = 1.37 * 10^3 \times Z^{-0.23}$ for Nb steels respectively. * means multiplication.

Metadynamic recrystallisation means recrystallisation by the growth of pre-existing nuclei without incubation time. It coarsens dynamic microstructure slightly. $d_{meta}$ is a function of strain rate and temperature only i.e. Zener-Hollomon parameter,Z. It decreases with decreasing temperature and increasing strain rate. Grain refinement in metadynamic recrystallisation is limited but final grain sizes are lower than in static or dynamic recrystallisation. Higher strain rates lead to higher grain sizes as shown in Table 4 for C –Mn and Nb steels, at strain rates of 9.5, 12 & 20/s respectively. Also, in the same table, when temperature is kept constant at 950°C, but Z increasing, similar observations were made for values of $d_{meta}$ with smallest size of 6.07 microns occurring at 9.5/s strain rate for Nb steel.

TABLE 4: Summary of $d_{meta}$ grain sizes for C-Mn and Nb steels for different values of Z;

T=1223K

| Strain rate /s | Z | $d_{meta}$(microns) | |
|---|---|---|---|
| | | C-Mn | Nb |
| 9.5 | 6.19*10^13 | 9.7 | 6.07 |
| 12 | 7.81*10^13 | 9.9 | 6.9 |
| 20 | 13*10^13 | 9.99 | 8.6 |

Similar results have been obtained by Roucoules et al (1995). They further found that the Nb steel displays a finer grain size than the Mo steel but has a similar functional dependence on Z. The Ti steel has a much stronger dependence on Z than the Mo or the Nb steel. This is due to the strain-induced precipitation of TiCN, which controls the grain size by pinning the boundaries. The Z exponents for the Mo, Nb, and Ti steels were –0.16, -0.13, and –0.42, respectively, which are in general agreement with those reported by Sellars, (1979) (-0.11) and by Hodgson et al,(1992) (-0.23) for plain carbon steel.

**Ferrite Grain Size (F.G.S)**

At transformation temperature, austenite grains from the last rolling pass transform to ferrite. The finer the austenite grains, and retained strain, the finer will be the ferrite grains. Using equations above, predicted ferrite grain sizes are 12.1microns for C-Mn-V, and 9.41microns for Nb. Measured sizes are 9.2microns for C-Mn-V, 6.0microns for Nb and 5.1microns for Nb-Ti. With retained strain (0.38), better refinement of 9.42microns for C-Mn-V, and 7.91microns for Nb was predicted for the same cooling rate.

Fig.3

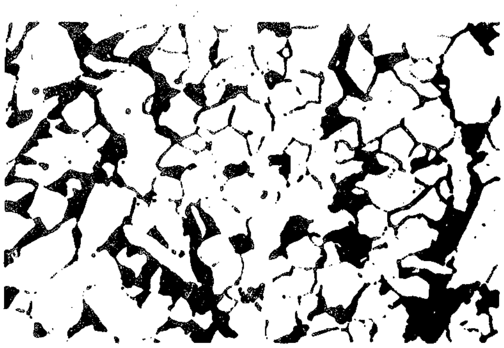

Fig.4

Fig.3 shows the as-received microstructure of C-Mn-V steel. Measured grain size was 65 microns. Magnification 650X. and Fig. 4 shows the same steel after it has been hot rolled down to 900C and air cooled to transform to ferrite. Grain size measured was 9.2microns. Magnification 650X. Factors that affect ferrite grain size are the final austenite grain size just before cooling transformation, retained strain, composition and cooling rates.The higher the cooling rate and retained strain, the finer the ferrite grain size. By contrast, the higher the finishing temperature, the coarser the ferrite grain size. The finer the ferrite grain size, the better the lower yield strength. Effect of cooling rate decreases as retained strain levels increases.

**TABLE 5 Summary of X vs t for 2 stage compression tests for C - Mn, Nb - Ti and Nb steels, T = 950°C, for all**

| | | Nb - Ti | | C - Mn | | | Nb | | |
|---|---|---|---|---|---|---|---|---|---|
| strain rate | H.T. T secs | strain = 0.3 | strain = 0.6 | strain = 0.3 | strain = 0.6 | X | strain = 0.3 | strain = 0.6 | X |
| | 0.5 | 235 | 229 | 264 | 239 | 0.56 | 225 | 215 | 0.06 |
| 9 5 | 1 | 237 | 209 | 273 | 219 | 0 98 | 222 | 199 | 0.15 |
| | 3 | 236 | 186 | 265 | 213 | 1 | 224 | 184 | 0.48 |
| | 10 | 251 | 207 | 271 | 210 | 1 | 226 | 199 | 1 |
| | 0.5 | 242 | 214 | 268 | 239 | 0.57 | 215 | 205 | 0.061 |
| 12 | 1 | 241 | 202 | 279 | 222 | 0.97 | 219 | 196 | 0.16 |
| | 3 | 239 | 187 | 268 | 210 | 1 | 214 | 184 | 0.47 |
| | 10 | 252 | 203 | 274 | 214 | 1 | 229 | 189 | 1 |
| | 30 | 246 | 204 | 271 | 210 | 1 | 228 | 189 | 1 |
| | 1 | 236 | 205 | 264 | 223 | 0.96 | 227 | 200 | 0.2 |
| 20 | 3 | 245 | 202 | 270 | 210 | 1 | 226 | 189 | 0.56 |
| | 10 | 248 | 204 | 270 | 211 | 1 | 220 | 190 | 1 |

From table 5, it can be observed that interpass time of 3 – 10s resulted in full recrystallization i.e. X=1, **while those below 1 sec resulted in strain accumulation** i.e. X<1.

Using equations by Sellars,(1979),

$$D_\alpha = \left(1 - 0.45\varepsilon_r^{1/2}\right) * \left\{1.4 + 5C_r^{-1/2} + 22\left[1 - \exp\left(-1.5 * 10^{-2} D\right)\right]\right\}$$ for C-Mn and

$$D_\alpha = \left(1 - 0.45\varepsilon_r^{1/2}\right) * \left\{1.4 + 5C_r^{-1/2} + 22\left[1 - \exp\left(-1.5 * 10^{-2} D\right)\right]\right\}$$ for Nb,

values of ferrite grain size obtained from fully statically recrystallized austenite are shown in Table 6.

**TABLE 6 Summary of Ferrite Grain Sizes (from last $d_{rex}$)**

| F.G.S.(Cooling rate = 3°C/s) | |
|---|---|
| C - Mn | Nb |
| 10.61 | 13.1 |

The calculated ferrite grain size for C-Mn was 10.61 microns and 13.1 microns for Nb. The As received, initial grain size does not significantly affect ferrite grain size because static recrystallization refines grain sizes down to similar values after 3 or 4 passes regardless of the as-received initial grain sizes as shown in table 3. In table 6, there was no retained strain and cooling rate was 3°C/s.

**TABLE 7 Summary of Ferrite Grain Sizes(from last dynamic $d_{dyn}$)**

| F.G.S.,(Cooling rate = 3°C/s) | |
|---|---|
| C - Mn | Nb |
| 7.9 | 9.42 |

Table 7 shows values of ferrite grain sizes obtained from dynamically recrystallised austenite for C – Mn and Nb steels.

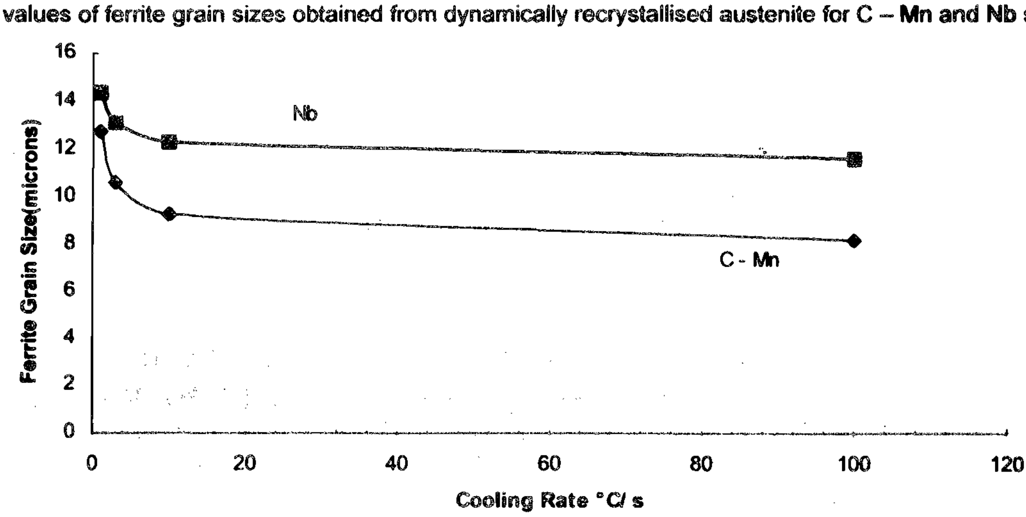


**Fig.5 Effect of Accelerated Cooling on Ferrite Grain Sizes for C - Mn and Nb steels(No Retained Strain Effect)**

In fig 5, with increase in cooling rate from 0 – 10°C/s there is rapid drop in ferrite grain size value from 14 to 9.3 microns for C-Mn but more gradual drop to 8.2 microns thereafter up to cooling rate of 100°C/s. The equations above take into account retained strain $\varepsilon_r$. For interpass times less than 1s, accumulated strain after several passes resulted in dynamic recrystallization which, as expected, resulted in slightly better grain refinement due to the effect of retained strain on ferrite grain size with increasing cooling rates. This is exemplified in Fig 6 for C – Mn and Nb steels, for retained strain of 0.38. Fig. 7 (Hodgson et al.,1992) also shows a similar trend for Nb steel, as levels of retained strain increases from 0 through to 1.2, with grain refinement from 40 down to 7 microns.

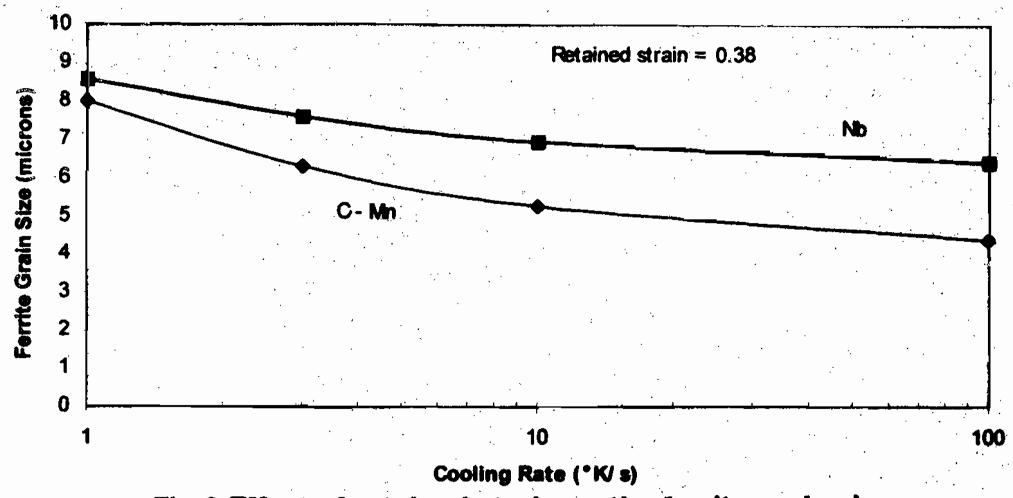


**Fig.6 Effect of retained strain on the ferrite grain size variation with cooling rate for C - Mn and Nb steels**

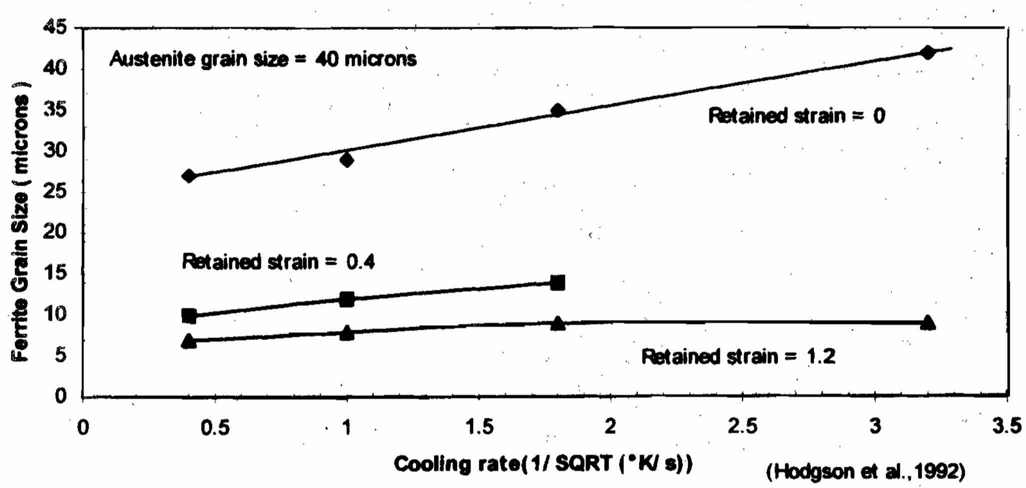


**Fig.7 Effect of retained strain on the ferrite grain size variation with cooling rate for Nb microalloyed steels.**

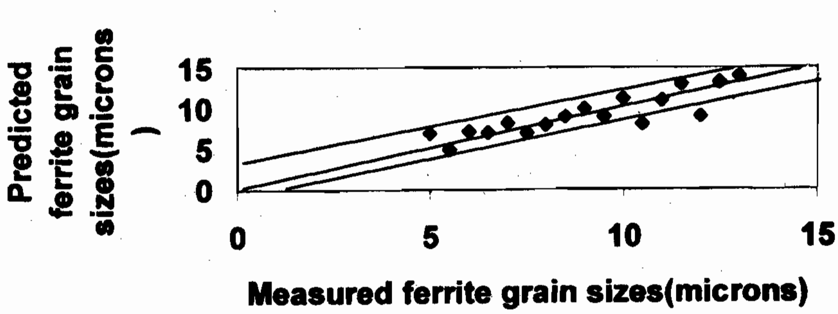


**Fig.8 Agreement between measured and predicted ferrite grain sizes (Nb nd C-Mn-V steels)**

Fig.8, from the present work, shows fairly good agreement between measured and predicted ferrite grain sizes using equations above for C-Mn-V and Nb steels, proving effective transformation.

**Lower Yield Stress (L.Y.S)**

According to Hodgson et al(1992),in bar and plate rolling, 0.1w% increase in C increases LYS by 15Mpa and 1% wt increase in Mn increases LYS by 55Mpa.

Equation by Hodgson et al (1992),

$\left(\sigma_y = 62.6 + 26.1[Mn] + 60.2[Si] + 759[P] + 212.9[Cu] + 3286[N] + 19.7(0.001D_\alpha)^{-0.5}\right)$ has been used to calculate the lower yield strength for C - Mn steel and summarised in table 8 from ferrite grain sizes obtained through transformation from statically and dynamically recystallised austenite. $D_\alpha$ values were 10.61and 7.9 microns respectively from calculations.

**TABLE 8 Summary of Lower Yield Stress Values**

| C - Mn | |
|---|---|
| From F.G.S (from static) | From F.G.S(from dynamic) |
| 317MPa | 347MPa |

Lower yield strength values of 317MPa and 347Mpa respectively were recorded. As expected, lower values of ferrite grains sizes resulted in higher lower yield stresses. Measured L.Y.S. from tensile tests was 361Mpa.

## CONCLUSIONS

1) More ferrite grain refinement was achieved by dynamic recrystallisation controlled rolling than by conventional controlled rolling.
2) Recrystallisation controlled rolling produced the lowest rolling loads, lowest dislocation densities but least grain refinement.
3) Conventional controlled rolling requires the precipitation of carbonitrides during the interpass intervals.
4) With accumulated or retained strain during transformation, better ferrite grain refinement was achieved.
5) The finer the ferrite grains, the higher will be the lower yield stress of the steel.

## REFERENCES


Akben, M. G., Weiss, I., and Jonas, J. J., 1979. Dynamic Precipitation and Solute Hardening in a V Microalloyed Steel and Two Nb Steels containing High Levels of Mn., " Acta Metallurgica, 29: 111 - 121.

Hodgson, P. D., and Gibbs, R. K., 1992. A Mathematical Model to Predict the Mechanical Properties of Hot Rolled C-Mn and Microalloyed Steels", ISIJ International, 32(12): 1329-1338.

Lenard, J. G., Pietrzyk, M., Cser, L., 1999. Mathematical and Physical Simulation of the Properties of Hot Rolled Products. Elsevier publications,Amsterdam,Holland,pp. 150.

Morgridge, A. R., Karjalainen, P.,1992. " Hot - Rolling Simulation and Modelling using Gleeble 1500 " Steel Research", 63, No. 7: 297 – 303

Pussegoda, L. N., and Jonas, J. J., 1991. Comparison of Dynamic Recrystallisation and Conventional Controlled Rolling Schedules By Laboratory Simulation", ISIJ International, Vol. 31, No. 3, pp 278 – 288.

Roucoules, C., Yue, S., and Jonas, J. J., 1995. Effect of Alloying Elements on Metadynamic Recrystallization in HSLA Steels, Metallurgical and Materials Transactions A, 26A : 181-190

Samuel, F.H., Yue, S., Jonas, J. J.,Barnes K. R., 1990. Effect of Dynamic Recrystallisation on Microstructural Evolution during Strip Rolling, ISIJ International, 30(3): 216 – 225.

Sellars, C. M., 1979. The Physical Metallurgy of Hot Working,and forming processes, ed. by Sellars, C.M., and Davies,G.J., The Metals Society, London, pp. 3-15.