THE INFLUENCE OF Mn ON MICROSTRUCTURE EVOLUTION IN LOW C-HIGH Nb-Ti STEELS SUBJECTED TO LIMITED ROUGHING STRAIN

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Abstract

The influence of Mn content on austenite recrystallization during roughing and early finishing of low C-high Nb-Ti steels has been investigated using multi-pass rolling simulations. Stress analysis was used to study the austenite softening behaviour. The ferrite microstructure after the first finishing pass was examined. The flow stress during roughing is unaffected by the Mn content, but increases with Nb content. Sufficient strain accumulation, coupled with low Zener-Hollomon, Z, values during roughing produce extensive dynamic recrystallization, DRX, and grain refinement in low and high Mn steels. The location of an intermediate water cooling facility is important for complete softening if partial, static recrystallization dominates during roughing. It becomes less critical for conditions favouring rapidly completed dynamic and/or metadynamic recrystallization. For a finishing entry temperature of 1000 ºC, a low Mn content reduces the extent of recrystallization. Softening is completely suppressed at 900 ºC, irrespective of Mn content. Low Mn contents produce coarser ferrite grains that are relatively insensitive to roughing conditions.

Keywords: Manganese, niobium, roughing, strain, recrystallization

1. INTRODUCTION

High Nb-Ti steels containing low C and low Mn (< 0.45 %) contents developed out of a need for producing sour-resistant steels in high speed thin slab casters or aging continuous casting machines. These steels solidify though the δ-ferrite region, where solute diffusion rates are high and segregation of elements are minimized, especially at the slab centreline [1]. Toughness is excellent due to the very fine-grained microstructures developed during rolling at moderate to high temperatures. In the processing of microalloyed steels, it is important to prevent transfer bars with coarse, inhomogeneous austenite from entering the finishing mill since this can adversely affect the final microstructure and mechanical properties. Studies have been conducted on the processing of austenite during finishing of low Mn-Nb-Ti steels [2] and austenite recrystallization during roughing of high Mn-Nb-Ti steel [3]. The behaviour of low Mn-Nb-Ti steel during roughing under limited strain conditions, however, has not been investigated and will be the focus of this work. Of interest is the location of an intermediate cooling facility to optimize the austenite microstructure.

2. EXPERIMENTAL

The composition of low and high Mn grades, *LMn* and *HMn*, are given in **Table 1**. A schematic of the rolling simulations performed on a Bähr 805D deformation dilatometer using axisymmetric (5x10 mm^2) specimens is shown in **Fig. 1**. The austenitizing temperature, T_A, was varied to produce two initial grain sizes, d_0, i) soak at 1200 ºC for 5 min. and ii) soak at 1290ºC for 5min. An equalizing treatment at 1100 ºC was applied, followed by roughing according to one of the four schedules shown. The air cooling delay time before simulated water cooling, t_d, was either 20 s or 2 s. The pass strain rates, inter-pass times, total roughing strain and cooling rates were kept constant. To reveal the ferrite microstructure after deformation, specimens were cooled at 14 ºCs^{-1} to a “coiling’ temperature of 600 ºC, held for 5min and etched in a 2 % nital solution. The recrystallized fraction between passes, X, was determined using the double stroke method with a true strain offset of 0.03. The X fractions below 0.15 were considered to be due to recovery only [4]. A strain of 0.04 was applied in F2 to determine X after F1, but is so small to affect the final microstructure and is not considered further here. Austenitized specimens were quenched to reveal the initial austenite grain size, d_0, using a heated saturated aqeous picric acid solution.

Table 1 Composition of steels studied - mass % (V < 0.001%, Mo < 0.01%)

Steel	C	Mn	Si	Nb	Ti	Cr	Ni	Cu	P	Al	N	S
HMn	0.051	1.55	0.19	0.072	0.011	0.31	0.01	0.01	0.015	0.057	0.0053	0.0028
LMn	0.054	0.25	0.16	0.088	0.010	0.48	0.16	0.29	0.016	0.033	0.0032	0.0001

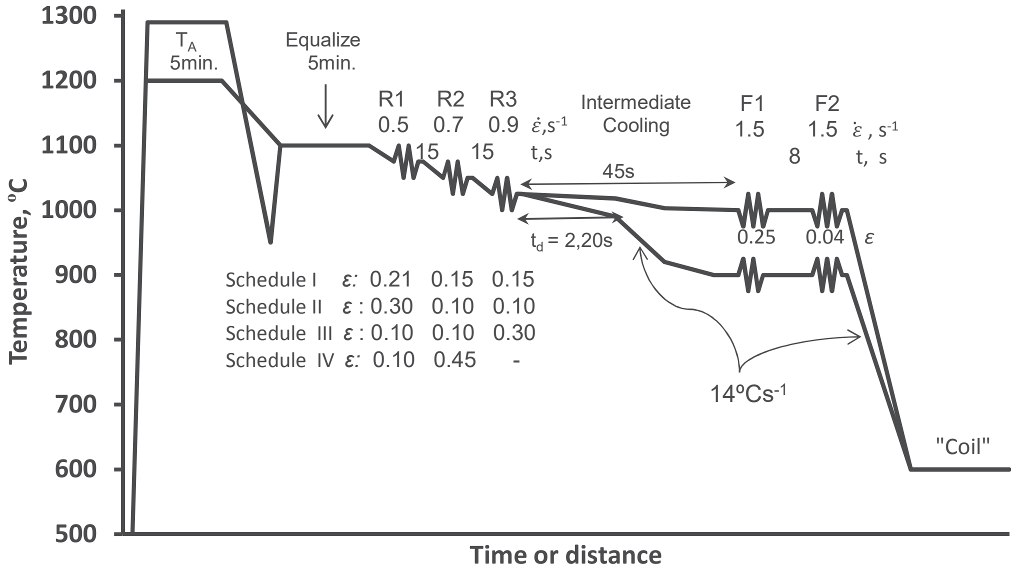
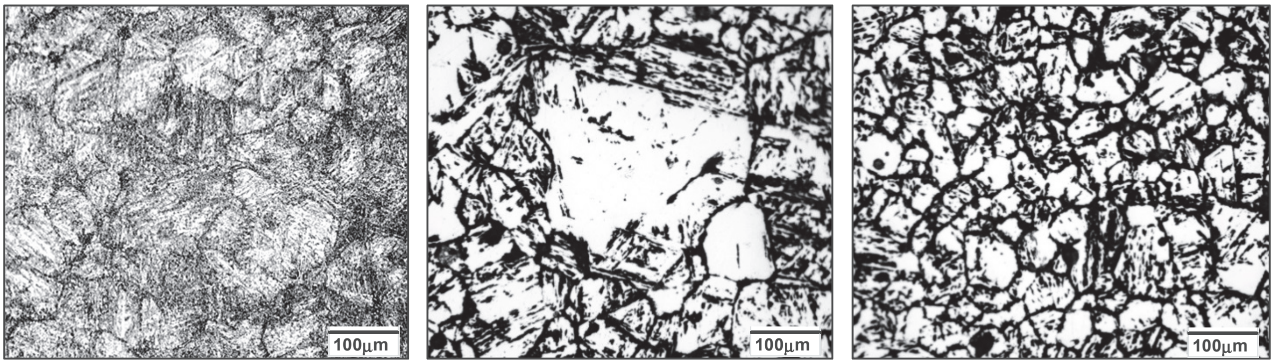


Fig. 1 Schematic diagram of rolling simulations

3. RESULTS

3.1 Initial austenite grain size

Fig. 2 shows the austenite microstructure after soaking at 1290 ºC, where d_0 for grade *HMn* is similar, 115 μm, to that found in grade *LMn*,125 μm.The d_0 was much smaller for steel *HMn* at 1200ºC, 40μm.



LMn steel: T_A=1290ºC, d_0=115μm *HMn* steel: T_A=1290ºC, d_0=125μm *HMn* steel: T_A=1200ºC, d_0=40μm

Fig. 2 Initial austenite grain size

3.2 Flow curve analysis

Fig. 3 shows flow curves and softened fractions during roughing and F1 in schedules I to IV. Some general observations relevant to all strain schedules: i) there is little influence of Mn on stress during roughing, ii) the pass stress is higher in grade *LMn* and iii) an F1 temperature of 900 ºC produces no recrystallization.

Schedule I: Partial SRX occurs after each of the three roughing passes in both steels. A smaller d_0 increases the flow stress by 5-10 %, *cf*. **Fig. 3 (A,B), (C,D)**.

Schedule II: In both grades, *X* increases (0.6 to 0.8) after the larger strain in R1, followed by no softening after the reduced strain in R2. In *HMn* steel, recrystallization does not occur after R3 for t_d below 20s. In the *LMn* steel however, *X* after R3 depends on the delay time: Complete recrystallization (*X* = 1) for t_d of 20s, **Fig. 3**(E vs G) and **Fig. 3**(F vs I), and only recovery (*X* = 0.1) for a very short t_d of 2s, **Fig. 3(H)**.

Schedule III: No recrystallization occurs in both grades after the small strain in R1, followed by significant partial SRX after R2 (*X* = 0.7). In R3, the flow stress approaches a peak at the end of the pass. Recrystallization is always complete after R3. Reducing either d_0 or t_d had minimal effect on *X* for F1 = 900 ºC. Increasing F1 from 900 ºC to 1000 ºC increases *X* from 0 in grade *LMn* to 0.4, **Fig. 3 (N vs O)**, and to 0.95 in grade *HMn*, **Fig. 3 (J vs K)**. In schedule II, pass R3, the intermediate t_d (20 s), the small strain (0.1) and high temperature (1025ºC) results in complete recrystallization in grade *LMn*, but no softening is found in grade *HMn*. The opposite effect on softening occurs in schedule III, pass F1 (1000 ºC), where retardation of recrystallization is more effective in grade *LMn*. In 0.05C-0.25Mn grade *CLMn,* DRX begins earlier and is more complete in pass R3 compared to grade *LMn.* The *X* fraction due to SRX is higher in all other passes.

Schedule IV: The most favourable conditions for promoting DRX are found in schedule IV. In both grades, the R1 strain is retained into pass R2 where, together with the very large applied strain (0.45), results in extensive dynamic/metadynamic recrystallization, as indicated by the presence of a peak stress. *X* is always 1 in R2. As in schedule III, there was little influence of d_0 or t_d on the flow stress.

3.3 Ferrite microstructure

Selected microstructures from the rolling simulations in **Fig. 3** are presented in **Figs. 4-6. Fig. 4** shows that, for a given strain schedule, the average grain sizes in the *HMn* steel are generally finer and more evenly distributed. Schedule IV produced the finest and most uniform microstructure in both grades. The ferrite morphology is mixed allotriomorphic and polygonal after cooling from an F1 temperature of 900 ºC. A mixed microstructure of acicular and polygonal ferrite is formed in *HMn* when cooling commences from a higher F1 temperature of 1000 ºC, **Fig. 5 (K)**, but was unaffected in grade *LMn*, **Fig. 5 (O)**. In schedule III, the grain size of grade *CLMn* is double that of grade *LMn* for similar C and Mn contents, **Fig. 6 (M)** vs **Fig. 4 (N)**.

4. DISCUSSION

Strain accumulation and DRX: DRX is initiated at the austenite grain boundaries if sufficient strain is accumulated and if SRX is prevented from taking place during the inter-pass times [5]. DRX takes place at some fraction of the peak strain associated with a peak stress [6]. DRX is more easily initiated under roughing conditions, rather than finishing, where large strains are applied at low strain rates and high temperatures, *i.e.* a small *Z* value. However, strain accumulation can be difficult to achieve in roughing as SRX occurs easily if reduction is limited. In schedule I, **Fig. 3**, DRX did not occur in either steel due to moderate strains, which result in partial SRX after each roughing pass and limited strain accumulation. DRX could also not be initiated in schedule II, despite the relatively large first pass. In schedule III, some strain is accumulated from R2 to give an effective strain of 0.33 and an associated peak stress. The critical strain to initiate DRX, ε_C, was calculated from Eqn.1 [7] as 0.34, comparable to the peak strain and suggests that DRX may have been initiated. In schedule IV, extensive DRX occurs since the strain accumulation from R1 provides an effective strain in R2(0.55), to exceed both the peak strain and the predicted ε_C of 0.35.

$$\varepsilon_C = 0.048\ln(Z) - 0.96 \quad (1)$$

$$Z = \dot{\varepsilon}\exp(300000/RT) \quad (2)$$

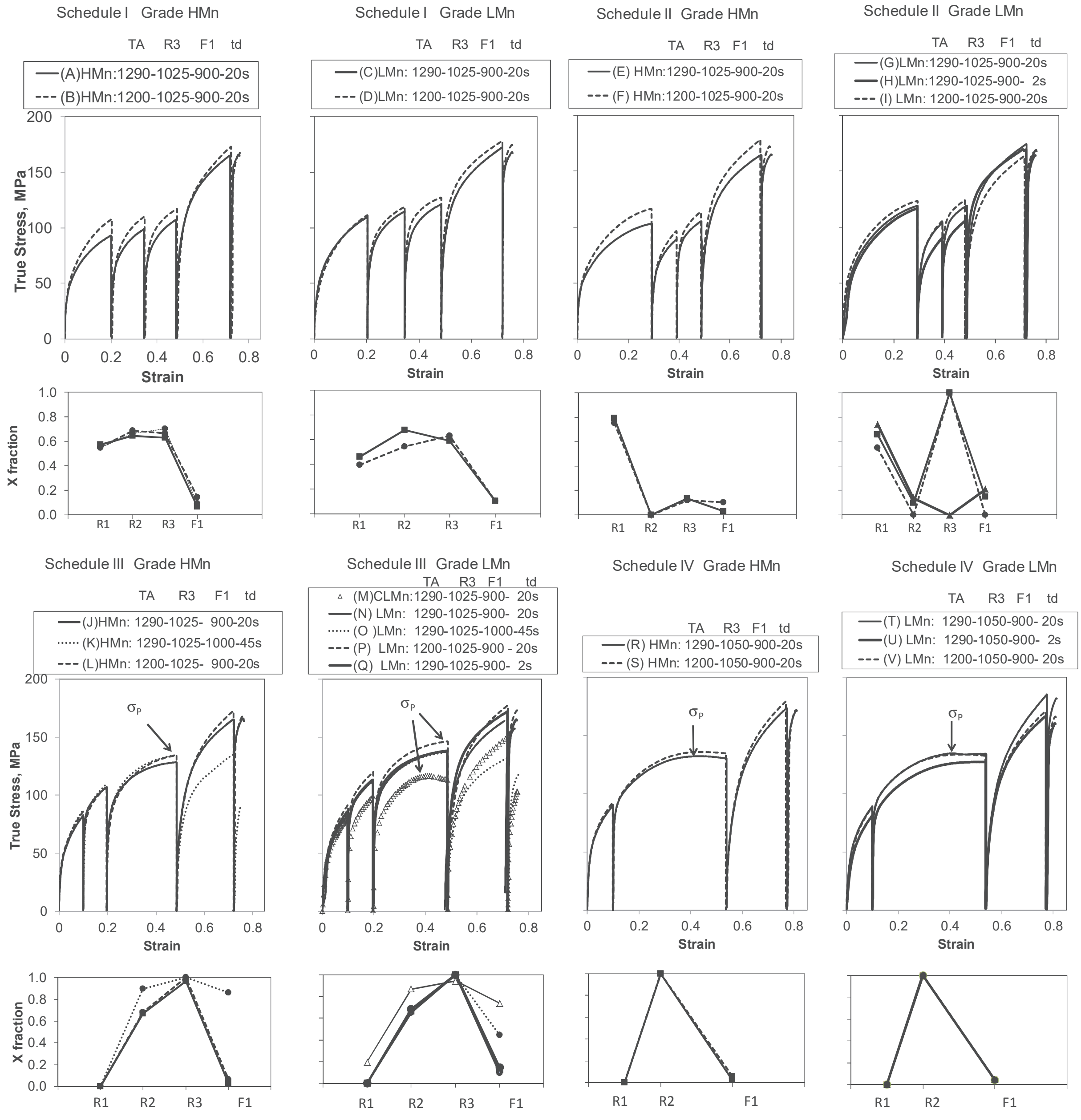


Fig. 3 Flow curves and softening fractions for schedules I - IV

Precipitation density and volume fraction: In *LMn* steel, the change in softening behaviour from fully recrystallized austenite in pass R3 (1025ºC),schedule II, to partial (*X*=0.45) recrystallizion in pass F1 (1000 ºC),schedule III, is attributed to faster precipitation kinetics at low Mn levels [8,9]: In steel *LMn,* a higher nucleation density occurs after the relatively short processing time before pass R3,schedule II, which retards recovery and promotes SRX [2]. Conversely, the longer processing time prior to F1 (1000 ºC) in schedule III produces a larger volume fraction of NbC, increases Zener pinning at grain boundaries, favours recovery and retards recrystallization. The smaller recrystallized fraction in schedule III, F1 (1000 ºC) in *LMn* steel confirms earlier observations [2] that low Mn levels shift the T_{NR} to higher temperatures in Nb-Ti steels. For an F1 of 900 ºC, extensive Zener pinning occurs in both steels to completely suppress recrystallization.

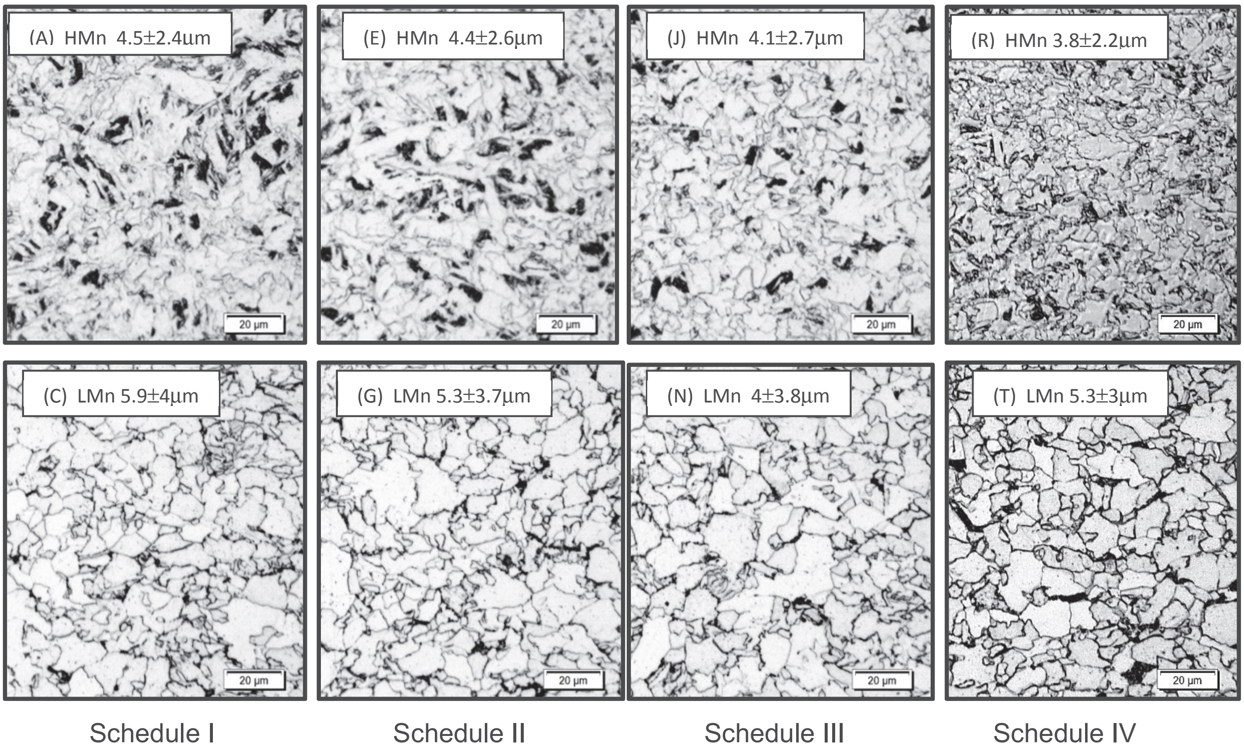
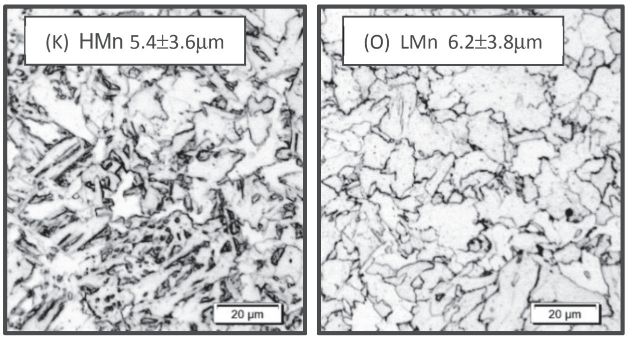


Fig. 4 Microstructures after T_A=1290 ºC, t_d=20s, F1 =900 ºC. *cf*. **Fig. 3**.



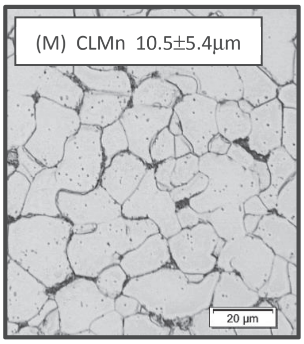


Fig. 5 Schedule III. Microstructures after T_A=1290 ºC, t_d=20 s, F1 =1000 ºC. *cf*.**Fig. 3**.

Fig. 6 Schedule III. Grade *CLMn* afterT_A=1290 ºC, t_d=20 s, F1 = 900 ºC,*cf*. **Fig. 3**.

Delay after roughing: When roughing conditions favour the initiation and propagation of DRX, as in schedules III and IV, X is insensitive to t_d . This is because the time for completion of DRX, t_{MDRX}, calculated from Eqn. 3 [10] in the last roughing pass is very fast and lies between 1.5 and 3.2s for all conditions tested - close to the shortest applied t_d of 2s. However, in roughing sequences where partial SRX in prominent, such as schedule II, a short t_d significantly reduces X, **Fig. 3 (G vs H)**. Thus, if process conditions favour partial recrystallization, the location of an intermediate watr cooling facility becomes critical.

$$t_{MDRX} = 6.3\times10^{-4}d^{0.4}\varepsilon^{-0.4}\exp(67000/RT) \qquad (3)$$

As-coiled microstructure: The finer ferrite grain size in grade HMn is primarily a result of its lower Ar3 temperature, which decreases the mobility of random α-γ boundaries and where the coherent interfaces with

Kurjamov-Sachs relationships dominate [11]. Accelerated cooling refines the grains by increasing nucleation and hinders the growth of existing ferrite. The mixed acicular-polygonal ferrite formed in HMn steel when cooled from 1000 ºC, **Fig. 5 (K)**, is due to its higher hardenabilty. Under these conditions, the austenite is relatively coarse and partially recrystallized. The hardenability of grade LMn did not affect the ferrite morphology significantly, **Fig. 5 (O)**. To achieve a uniform, final microstructure after rolling Nb steels, the dislocation structure in the pancaked austenite prior to transformation must be "saturated", which requires a strain of about 0.7 [12]. The strain in passes F1/F2 here was 0.29 and partially accounts for the mixed dα.

CONCLUSIONS

- The flow stress during roughing is unaffected by the Mn content, but increases with Nb content.
- Sufficient strain accumulation, coupled with low Zener-Hollomon values during roughing, produce extensive dynamic recrystallization and grain refinement in low and high Mn steels.
- The location of an intermediate water cooling facility is important for complete softening if partial, static recrystallization dominates during roughing. It becomes less critical for conditions favouring rapidly completed dynamic and/or metadynamic recrystallization.
- For a finishing entry temperature of 1000ºC, a low Mn content reduces the recrystallization rate. Softening is completely suppressed at 900ºC, irrespective of Mn content.
- Low Mn contents produce coarser ferrite grains that are relatively insensitive to roughing conditions.

ACKNOWLEDGEMENTS

Thanks to J.M. Gray and CBMM for financial support and permission to publish, D. Ramatsitsi for metallography , A.Tuling and W.Stumpf and S. Subramanian for valuable suggestions.

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