Influence of chemistry and runout table parameters on hot coil collapse in C- Mn steels.

by
Kevin Banks[+], Alison Tuling[+]and Barrie Mintz*
+ IMMRI, University of Pretoria
*City University, London

Abstract

The key metallurgical parameters affecting the incidence of coil collapse (soft slump) of C-Mn steels has been investigated using industrial data and laboratory simulation. Runout table (ROT) cooling/coiling simulations were performed on a Gleeble 1500D to study transformation before and during coiling of thin strip. For low C (< 0.07%) grades, coiling temperatures above 650˚C coupled with high nitrogen contents decreased the transformation-end temperature, Ar_1, and increased collapse. Coiling temperatures above the Ar_1 for ROT cooling increased both dilation and the time to complete transformation during coiling. These effects correlated with industrial conditions where a high frequency of coil collapse was observed.

1. Introduction

For ease of storage and transport, steel strip is commonly produced in the form of coil. Incorrect tension application after hot rolling can lead to stress/strain instabilities during coiling and result in collapse. One form of coil collapse is known as "soft slump". In this case the coil cannot hold up under its own mass to retain its cylindrical form and, as such, presents difficulties when fitting onto a mandrel to unwind the coil.

Research work to date [1,2,3,4] on the problem of "soft slump" has concentrated on coil tension but it is not proposed to deal with it here. The present paper is mainly concerned with the influence of transformation of austenite on the occurrence of coil collapse in thin strip. The reported incidence of coil collapse in thin (1.6-3mm) low C coils is examined and related to the composition, in particular the N and C contents and steel processing route. Analysis of this industrial data indicated that the austenite-ferrite/pearlite transformation may be one of the important factors controlling the incidence of coil collapse. Dilatometer studies were therefore carried out to determine the transformation characteristics of these steels under runout table (ROT) cooling and coiling conditions.

2. Industrial Data Analysis

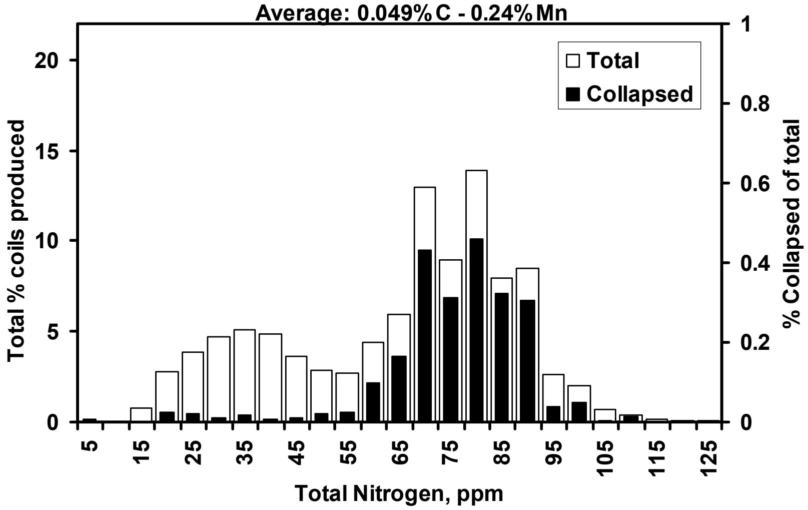
The composition range of low C industrial strip steel data that was analysed is given in Table I.

Table I Analysis of commercial grades.

Grade	C, %	Mn, %	S, %	Al, %	N,ppm
AI	0.02-0.07	0.17-0.29	<0.015	0.02-0.06	15-110
AII	0.03	0.25	*na*	*na*	47

Fig. 1 shows the incidence of coil collpase in low C grade AI and low C-B gradeAII as a function of total N content. Grade AI was produced via both EAF (high N) and BOF (low N) steelmaking routes and showed a bi-modal nitrogen distribution. Grade AII was only produced at BOF. In grade AI, fig.1a, a significant increase in the incidence of coil collapse occurred in the high N steels produced at EAF. There were no coil collapses in grade AII, fig.1b and this was attributed to i)low N content and ii)precipitation of BN during rolling, which negated any detrimental effect solute nitrogen may have had during coiling.

(a) Grade AI (EAF & BOF):
Average: 0.049% C - 0.24% Mn



(b) Grade AII (BOF only):
Average: 0.03% C - 0.25% Mn - 0.0047% B

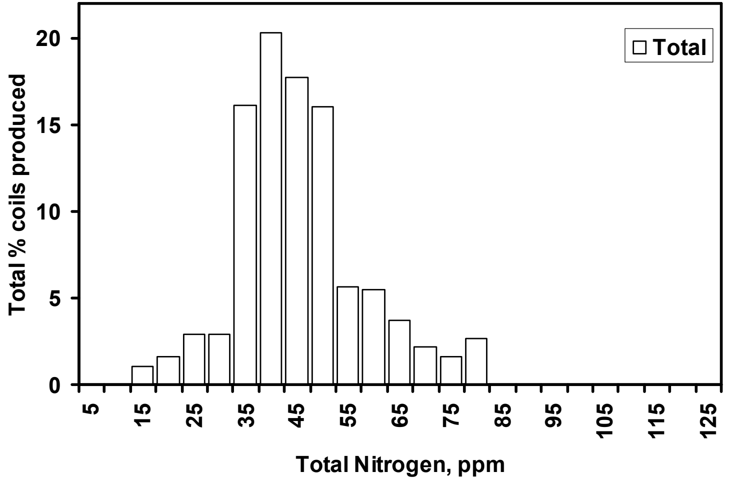


Figure 1. Influence of N content on coil collapse in low C steels AI and AII
Higher N contents in steel AI produced at EAF increased the incidence of coil collapse.
Average composition shown.

If transformation during coiling is a key factor in determining whether coil collapse occurred then there should be a correlation between the incidence of coil collapse and the coiling temperature. Fig.2a shows the percentage of coils collapsed against the average coiling temperature for grade A1 over a period of four years. EAF material is prone to collapse most frequently at coiling temperatures above 650°C. Collapsing of low N (BOF) steel is not as sensitive to coiling temperature and reached a maximum of about 2% at 675°C. The combined influence of coiling temperature and total N content is shown clearly in fig.2b. For coiling temperatures below 650°C, the number of coils collapses was restricted to below 1%, irrespective of N content. However, above 650 °C, the annual collapses increased from about 2% for coils with 30-50ppm N to ~6-14% for coils with N contents of 70-90ppm.   A simple solution is to restrict the N content to less than 50ppm and/or coil below 650°C. This, however, is not always practical, particularly if capacity at the BOF is limited or if high coiling temperatures are required to achieve specific microstructures.

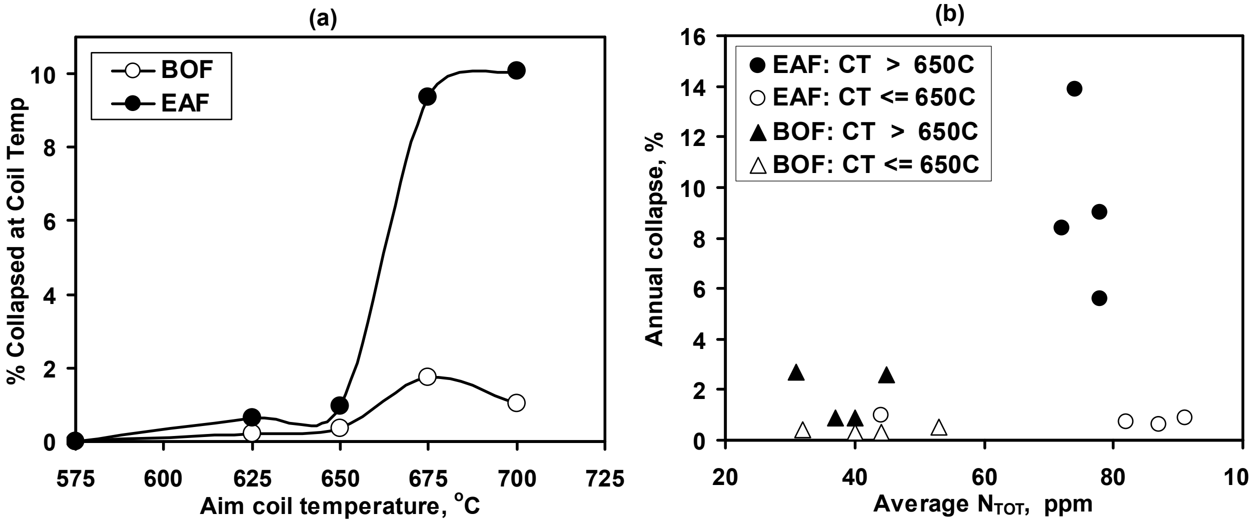


Figure 2. Grade AI: Influence of (a) average target coiling temperature over four years and (b) average total [N] content on coil collapse (each point in (b) represents the average of one year).

Estimated transformation end temperatures

EAF steels generally have lower transformation-end, Ar_1, temperatures due to their higher C and Mn contents. Equation 1 was used to calculate the average Ar_1 temperature as a function of C and Mn only[7], *i.e.* cooling rate is not varied. Equations for Ar_1 are extremely scarce and are, at best, formulated for constant cooling rates.

$Ar_1 = 706.4 - 350.4C - 118.2Mn$ [ref. 7] ....[1]

However, the cooling path during ROT cooling and subsequent coiling is complex, with the cooling rate frequently changing between the air, water, air and coiled conditions. The end of transformation in this work is a result of these changes in cooling rate. Fig.3 shows that, considering only C and Mn levels, BOF steels have on average, a predicted Ar_1 temperature under constant cooling rate about 5˚C higher than the average value of 665˚C at EAF. This suggests that, for a given target coil temperature above 665˚C, EAF grades are slightly more prone to collapsing due to less transformation occurring on the ROT above the Ar_1 temperature. Fig.3 showed that, whilst the calculated Ar_1 shows a normal distribution at EAF, it is continuous but skewed towards the left at BOF. In both steelmaking routes, almost all (>95%) steels had a calculated Ar_1 above 650˚C, which coincided with the data in fig.2, where 650˚C was found to be the dividing line for high and low occurrences of coil collapse.

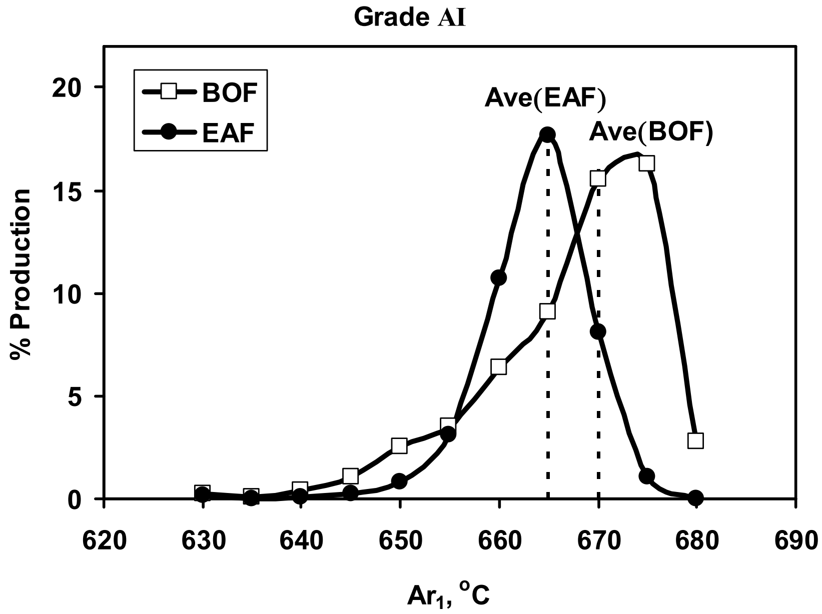


Figure 3: Calculated Ar_1 temperature for EAF and BOF low C steel grade A1 using equation 1 [7].
The Ar_1 is, on average, about 5˚C lower in coils produced at EAF.

3. Experimental

Dilatometry was carried out on grade AI steels using a Gleeble 1500D thermomechanical simulator to determine whether coil collapse could be related to cooling conditions on the ROT and thus the austenite-to-ferrite/pearlite transformation. A number of steels with varying total nitrogen, N_{TOT}, and carbon levels were used, Table II. Boron treated steel AII was also included in the table, the addition of boron being expected to remove all the free N as boron nitride.

Table II Composition of strip steels investigated

Grade	CID HSM	C %	Mn %	N_{TOT} ppm	Al %	S %	B ppm
AI	4090	0.046	0.22	14	0.044	0.015	na
AI	9108	0.030	0.18	28	0.034	0.015	na
AI	0038	0.040	0.18	28	0.039	0.013	na
AI	8091	0.049	0.22	101	0.028	0.011	na
AI	5021	0.069	0.20	52	0.052	0.009	na
AI	9026	0.060	0.21	99	0.040	0.009	na
AII	AC7-33	0.03	0.25	40	na	na	47
B	AC5-31	0.100	0.45	50	0.040	na	na
C	AC5-34	0.160	0.75	50	0.040	na	na
D	AC5-37	0.160	1.00	50	0.040	na	na

The C and Mn levels ranged between 0.03 to 0.07% and 0.18 to 0.22% respectively. The N level varied by an order of magnitude from 15 to 101ppm. Al levels also covered a wide range from 0.028 to 0.052%.

Strip specimens of dimensions 80(l) x 5.5(w) x 2-2.5(t) mm^3 were subjected to simulated ROT cooling cycles typical for 2mm strip, shown in figs. 4a and 4b below. In previous research, specimens for transformation studies were either (i) heated to just above the Ae_3 temperature followed by cooling or (ii) austenitised at typical reheat furnace temperatures followed by deformation and cooling. It is the free N content, [N], rather than the total N that influences transformation. However, in order to study the effect of solute N on transformation, specimens had to be soaked at a sufficiently high temperature (1114-1200°C) to dissolve any nitrides present, in this case AlN. This was unfortunately at the expense of commencing the ROT cooling simulation with a fairly large austenite grain size, which lowers the transformation temperature. To minimise this, the soak time was restricted to 2min. After soaking, specimens were cooled to the simulated last finish rolling stand, F7 temperature of 890°C and cooled at a typical water cooling rate for 2 mm thick strip, ~ 100K/s.

Thereafter, the specimen was subjected to an air cooling rate of about 12K/s until the simulated coiling temperature between 725 and 575°C was reached, where the specimen was cooled 10K over a period of 1-2min to simulate slow cooling in the coil, fig.4a. The dilation was recorded across the specimen width during the test. Similar dilatometry tests were also carried out on higher carbon (0.1-0.16%) steels B, C and D.

The [N] content corresponding to each soak temperature, Al and total N content was calculated from an expression developed by Sun *et al* [8] and is based on mass balances. Included in this equation is the Leslie *et al* [5] formula for AlN dissolution:

$$[\mathrm{Al}] = \left(\frac{\mathrm{Al}_{TOT} - \mathrm{N}_{TOT}}{2}\right) + \left(\left[\frac{\mathrm{Al}_{TOT} - \mathrm{N}_{TOT}}{2}\right]^2 + \exp\left(\left[1.03 - \frac{6770}{T}\right] / 0.4343\right)\right)^{0.5} \quad \text{.........................[2]}$$

$$[\mathrm{N}] = \frac{10^{1.03-6770/T}}{[\mathrm{Al}]} \quad \text{...[3]}$$

where *T* is the soak temperature in K and composition is in mass-%. Although deformation may accelerate precipitation during rolling, the formation of AlN is noted for being very sluggish [6]. It is thus reasonable to assume that the values quoted henceforth for the free N level are representative of [N] prior to cooling on the ROT.

It must be noted that the austenite grain size before the ROT is expected to be larger in the laboratory simulations than in the industrial condition where deformation refines the grains, which will also influence the transformation behaviour.

4. Results and Discussion

C < 0.07%

Influence of cooling path on transformation: Typical cooling paths for the simulated ROT cooling and coiling of a 2mm strip are shown in fig.4a. After rolling in the austenite region, the air and accelerated water cooling on the ROT, results in strip contraction. Once the transformation from the fcc austenitic structure to the bcc ferritic phase starts, expansion of the strip takes place. When transformation is complete the strip again contracts due to the temperature decrease. Because of the complexity of the thermal path after rolling in austenite, completion of transformation can occur at various locations: i)on the ROT, ii)during the coiling process or iii)after coiling. This is further complicated by partial transformation during rolling at different strip locations, particularly the edges. Cooling is non-linear and another consideration is the exothermic re-calescence due to the latent heat of the pearlite transformation, which potentially reduces the subsequent cooling rate.

Fig.4a shows that in the time available from the end of finishing to the start of coiling, ~11 seconds, the coiling temperature controls the expansion/contraction behaviour during the coiling operation, fig 4b. In this figure, the maximum amount of dilation during coiling is defined as θ in µm/mm. To get an indication of the transformation kinetics for various chemistries and coiling conditions, the time to transformation-end from the start of coiling, t_e, was determined at the point of maximum dilation.

At low coiling temperatures, in this case 575^{o}C, transformation is completed before the start of coiling, leading to either a nett contraction or no dimension change during coiling. Increasing the coiling temperature to 675^{o}C, results in most transformation occurring on the ROT but completion occurs during the early stages of coiling, as seen by the rapid dilation followed by quick (within 3s) leveling off of the expansion. Further raising the coiling temperature to 725^{o}C intensifies the extent of transformation during coiling. Because the strip is in the early stages of transformation coincident with the upper region of the CCT curve, the dilation occurs at a slower rate than at 675^{o}C. If coiling took place at sufficiently high temperatures, there will be little or no dilation because the strip temperature is in the single austenite phase. Coiling *before* the onset of transformation is a strategy that is often used to successfully coil medium C steels. Similar dilation curves were observed in delayed ROT tests, not shown.

Slower rolling speeds associated with thick strip result in longer times on the ROT and hence, more time for transformation to go to completion. This is partially the reason why a higher fraction of collapses are found in thin strip coils.

Influence of C and N on transformation: In order to establish the influence of [N] on the transformation start temperature during cooling, the transformation trough temperature, T_s, (approximate Ar_3 under ROT cooling conditions) was plotted as a function of coil temperature for steels with similar C contents and soaking temperature, fig.5. It was assumed that the steels had similar austenite grain sizes at a given soak temperature. As expected, T_s decreases with decreasing coiling temperature because of increased undercooling, thereby increasing hardenability. For a soak temperatures of 1114^{o}C, fig.5a, the steel with higher [N] commenced transformation approximately 20˚C lower than the low [N] steel.

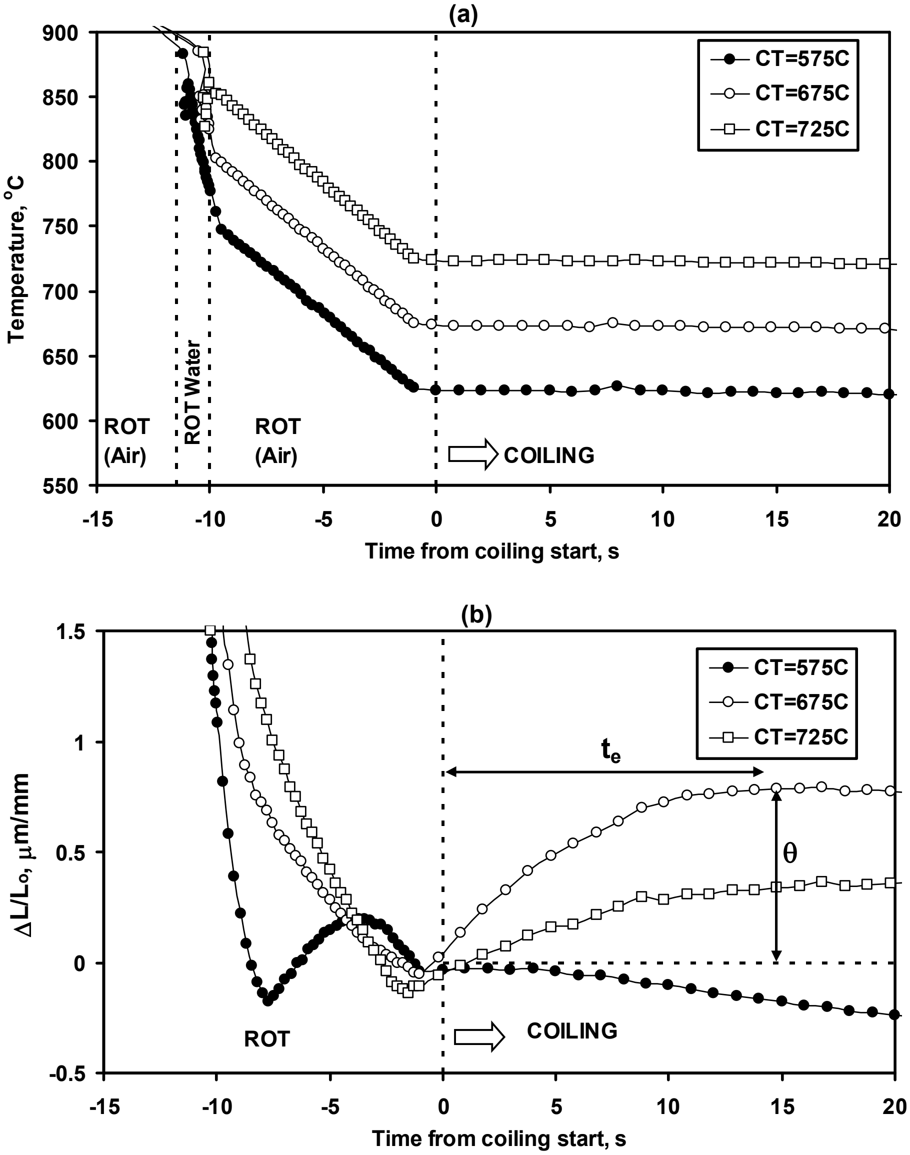


Figure 4 Gleeble simulations of conventional ROT cooling and coiling for 2mm strip showing (a) temperature-time and (b) dilation-time. Steel 9026 (high N). Soaked at 1200˚C, accelerated cooled from simulated F7 temperature of 890˚C.

A similar result was found for a soak temperature of 1200°C, fig. 5b.The actual mechanism for N lowering the transformation is not fully understood, but it has been suggested [9] that nitrogen may hinder nucleation or growth of the pearlite reaction by interfering with diffusional processes or that N rapidly partitions to the last transforming austenite, increasing hardenability.

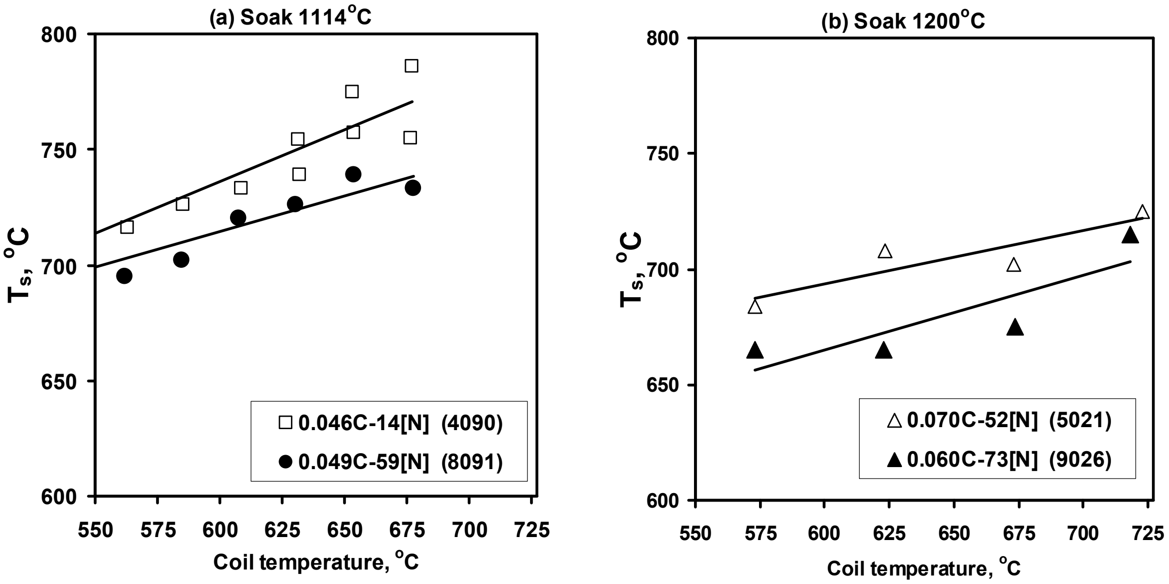


Figure 5. Gleeble simulations: Influence of free N on approximate Ar_3 temperature (transformation start trough temperature, T_s) in low C steels under ROT cooling conditions. (a) 0.046-0.049%C soaked at 1114˚C and (b) 0.06-0.07%C soaked at 1200˚C.

Dilation-temperature curves are shown in figs. 6a-c as a function of decreasing [N] for steels soaked at 1114°C and in figs.6d-f for steels soaked at 1200°C. In these figures L is the dilation in μm and L_0 is the initial specimen width in mm. These figures have the following distinguishing features:

- Specimens experiencing complete transformation prior to coiling have a well-defined dilation trough and peak, indicating the temperature region where the bulk of the transformation occurs. A well-defined peak is usually followed by a nett contraction during simulated coiling.
- Specimens not displaying a distinct peak in dilation, experience a nett dilation during simulated coiling, indicating that the austenite transformation was not completed on the ROT.

For similar C and Mn contents, as the [N] content increases, the necessary coiling temperature to avoid dilation decreases. Comparison of figs. 6a-c for a soak temperature of 1200°C shows the steel with a [N] content of 72ppm displays significant dilation at a coiling temperature of 675°C, whilst that of the 28ppm [N] steel only displayed dilation at a coiling temperature of 725°C. Increasing the “safe” coiling temperature region with decreasing [N] was also found by comparing steels in fig.6d-f at a lower soak temperature of 1114°C.

Fig.7 shows plots of θ and t_e during coiling for low C steels having various [N] contents. Clearly seen is that, above 650°C, both θ and t_e increase with temperature, especially in the high [N] grades. This would imply that large dilations, coupled with long transformation-end times, present a high-risk condition for coil collapse. This is consistent with the argument that dilating strip towards the tail-end will interfere with the pinch roll tension settings on leaving the finishing mill. The 650°C “dividing line” was in good agreement with industrial observations, fig.2, and the approximate calculated Ar_1 temperature for over 95% of all grade A steels, fig.3.

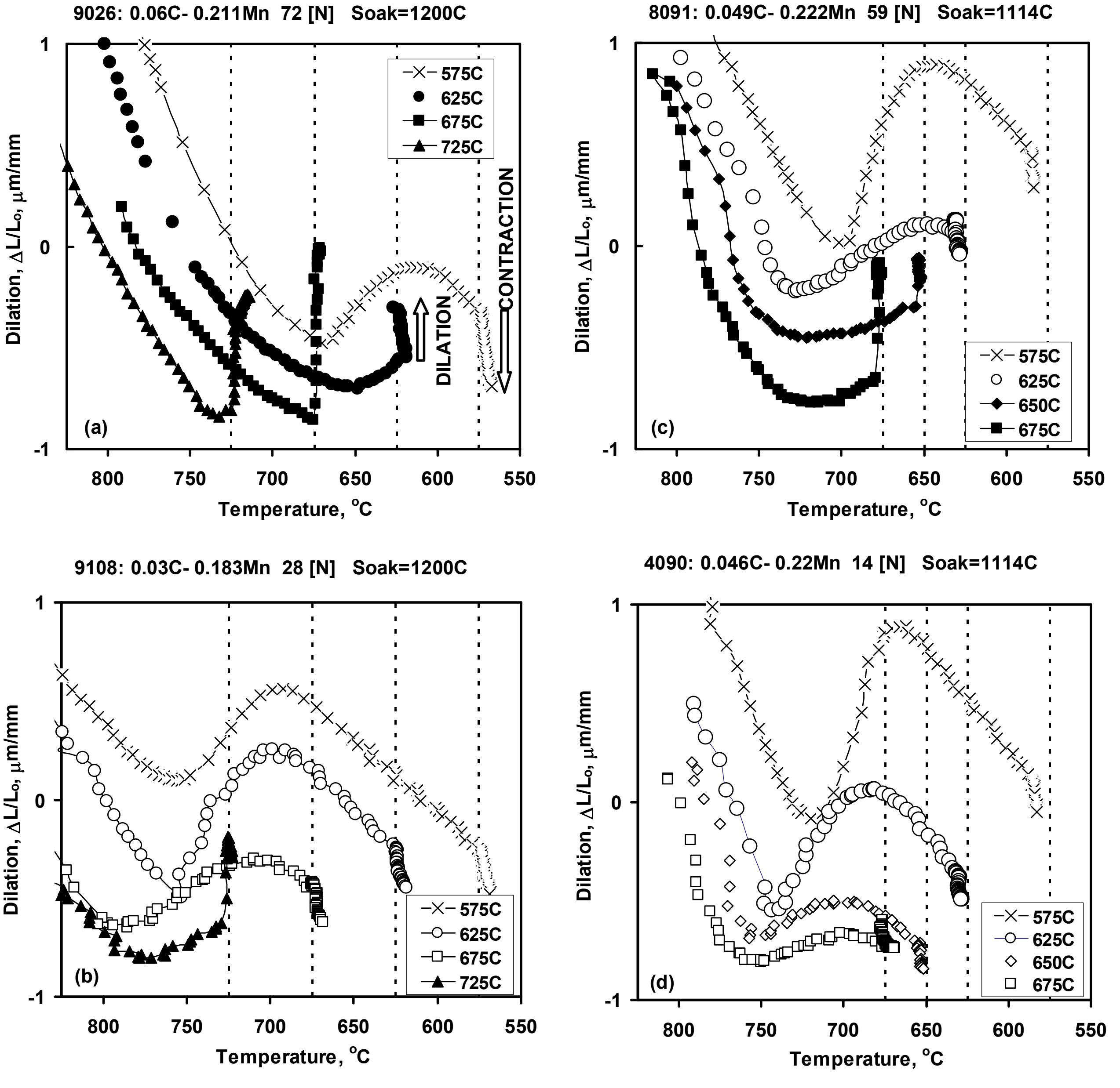


Figure 6. Influence of [N] on dilation of low C steels under simulated ROT cooling of 2mm strip. Plots (a) and (c) are high [N]. Plots (b) and (d) are low [N]. Dashed line: coiling temperature. Open symbols: contraction during coiling. Closed symbols: expansion during coiling.

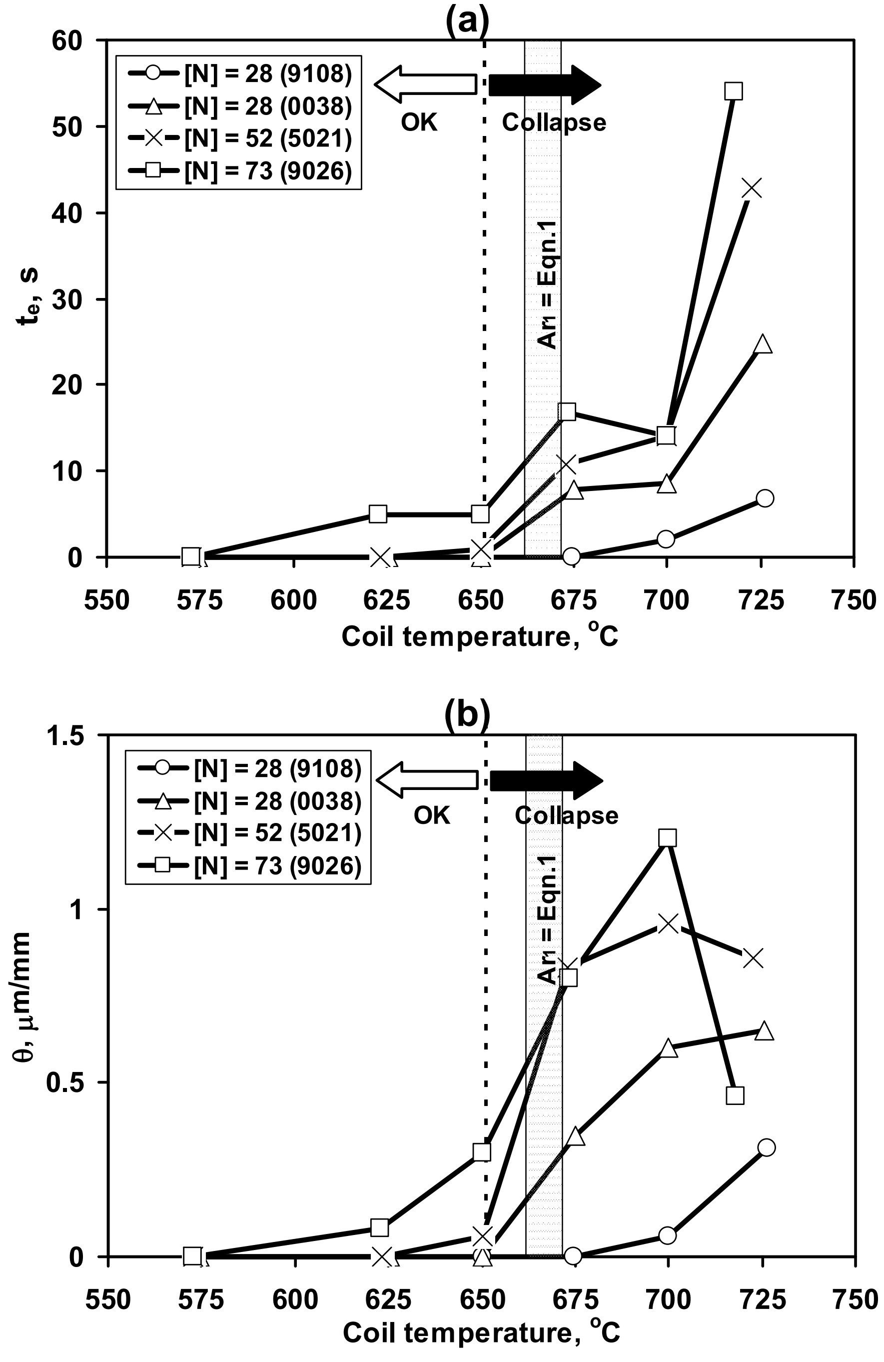


Figure 7. Grade Al steels: Influence of simulated coiling temperature, [N] and C on (a) time to the end of transformation from coiling start, t_e and (b) the maximum dilation. Ar_1 calculated from eqn.1. Conventional ROT cooling of 2mm strip. Soak 1200˚C.

In all tests the Ar_1 temperature calculated from equation 1 generally overestimated the transformation-end temperature, since t_e was greater than zero. The exception was steel 9108, which had low C and low [N]. This is further evidence that N lowers the transformation-end temperature and should be included as a parameter when calculating Ar_1. Thus, from fig.7, it appears that t_e gives a clearer, more consistent indication of collapse than θ, since full dilation can occur in a very short time and the tension can still be corrected. The findings in fig.7 are consistent with the industrial results in fig.2.

Thus, increasing the N content lowers the transformation temperature region, particularly the Ar_1, so that coils containing higher N levels may not have fully transformed on the runout table and transformation could take place during coiling and subsequent cooling. The dilation observed during the last stages of transformation is attributed to the latent heat of transformation [4] of mostly pearlite, which is the last to transform in these steels under ROT cooling conditions. This observation coincides with an industrially observed *rise* in coil temperature when transformation is still in progress during coiling. Of course, this temperature rise is not observed in laboratory simulation since the test temperature is controlled and forced to remain isothermal in the coiling stage. Generally, to help prevent coil collapse due to transformation, the targeted coil temperature should be either below Ar_1 or comfortably higher than Ar_3 for the relevant ROT system.

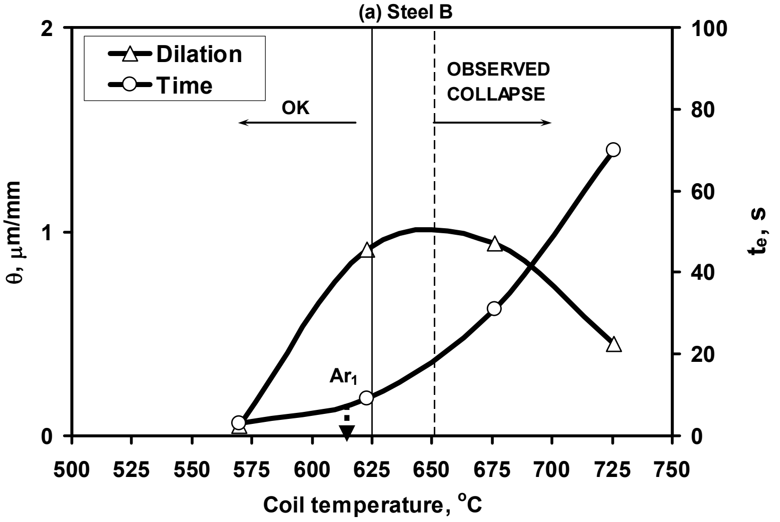
C = 0.10 - 0.16%

Similar trends to those found in low C steels between t_e, θ and coiling temperature were found in higher carbon steels B,C and D, fig.8 . The Ar_1 calculated from equation 1 coincided with t_e being early in the coil, 0-20s in all three steels. High incidence of coil collapse corresponded to coiling temperatures above Ar_1, and when t_e was greater than 20s, indicated by the broken lines in the figure. Little or no collapses occurred at coiling temperatures between the solid vertical lines, which corresponded to t_e less than 20s.

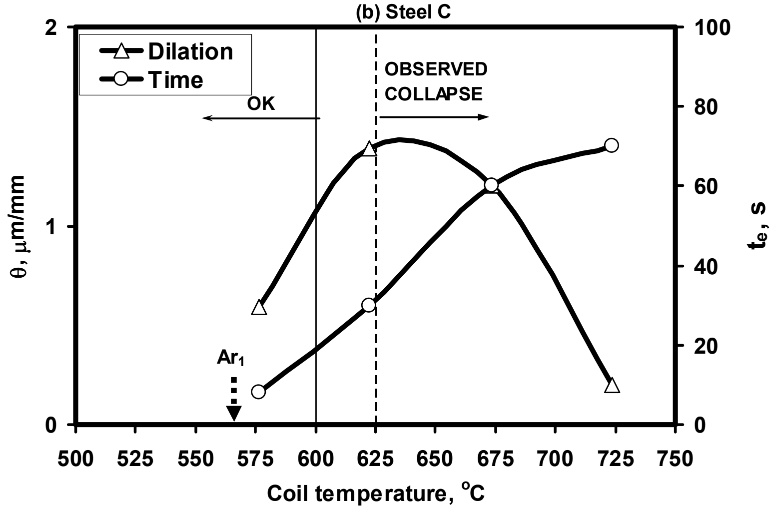
Summary and commercial implications:

It is clear from this work that if transformation is complete before coiling then there should be no problems with coils collapsing. Hence, the Ar_1 temperature is very important in dictating the coiling temperature that should be aimed for. For simple C-Mn-Al steels, the Ar_1 calculated from equation 1 can be used taking into account that the experimental work indicates that for these coiling conditions it is ~25°C too high. When transformation occurs during coiling then there is a need to have as short a time as possible for transformation to complete so that there is time to adjust the coil tension for the dilation. Dilatometry is therefore required to establish whether a particular composition and coiling temperature will lead to coil collapse.

(a) Steel B



(b) Steel C



(c) Steel D

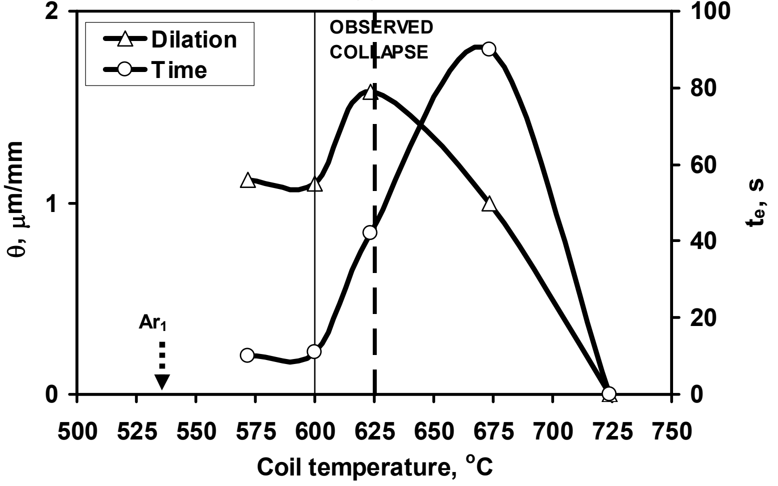


Figure 8. Gleeble simulation: Influence of coiling temperature on θ and t_e in 0.1-0.16%C steels under simulated conventional ROT cooling conditions for 2mm strip.

Soak = 1200˚C. Ar$_1$ calculated from eqn.1.

5. Conclusions

1. Industrial data has shown that, in low C steels, coil collapse is more significant as the nitrogen content increases and coiling temperature increases above 650°C due to transformation occurring during the coiling process.

2. Lower Ar_1 temperatures increase the likelihood of coil collapse. Whilst lower C and Mn contents decrease Ar_1, this work has shown that higher N levels are also detrimental to coil collapse due to further lowering the temperature for the end of transformation. Thus, steels produced at electric arc furnace are more likely to result in coil collapse if corrective action is not taken.

3. A laboratory method has been established that successfully correlates transformation behaviour during simulated runout table cooling and coiling with coil collapse.

4. Laboratory processing conditions resulting in long times to complete transformation, especially associated with large dilation, corresponded to industrial cooling conditions associated with frequent coil collapse.

6. References

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