Sādhanā (2021)46:106
https://doi.org/10.1007/s12046-021-01629-w

Optimization of run-out table cooling parameters to control coil collapse in carbon-manganese steels

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MS received 6 November 2020; revised 9 March 2021; accepted 19 April 2021

Abstract. In the production of carbon-manganese hot rolled steel strips, less than 6 mm thickness, the wound coil had a shape defect associated with coil collapse. The defect was overcome by the assessment of physical simulation of the associated phase transformations in the run out table using Gleeble. It was found that when the steel strips had a lower Ar_1 temperature than the coiling temperature, the occurrence of coil collapse was common. The coil collapse is due to the secondary phase transformation taking place during coiling and coil holding, where the liberation of the transformation heat softens the coil that leads to the coil collapse. Hence, by optimization of the hot rolling conditions such that the phase transformation is completed at the ROT before coiling, it is possible to avoid the coil collapse. Gleeble based physical simulation of the cooling pattern was correlated with the theoretical Ar_1 temperature to enable prediction of the coil collapse possibility. Based on the physical simulation of the different cooling conditions, imposition of the correct cooling condition at the industrial ROT enabled elimination of coil collapse. In addition to avoiding coil collapse, the production loss associated with 4 to 5 min holding at the down coiler was overcome.

Keywords. Coil collapse; phase transformation; run-out table; optimizing rolling parameters; cooling condition; Ar_1 temperature.

1. Introduction

In the hot rolling of steel strip, the hot strip is wound on a mandrel in the down coiler. When the wound coil is removed in the hot condition from the mandrel, it must retain the cylindrical shape as shown in figure 1(a). However, in some cases the wound coil collapses and takes an ellipsoidal shape, as shown in figure 1 (b). This change in shape is due to the mass of the coil, the temperature evolution in the coil and associated dilation, which changes the circular cross section to elliptical cross section popularly termed as coil collapse or coil slumping [1]. Such a shape change is an undesired feature at the customer end, where fine circular tolerances are required for insertion in the unwinding mandrel, during further processing. Mounting a collapsed coil becomes difficult, time consuming and problematic, if the inner bore of the coil is even mildly distorted (slumped) [2]. Hence, the coils that fail to maintain its axial circularity are downgraded, which affects the product cost and productivity. In order to avoid the coil collapse, the hot coil is held in the down coiler for 4 to 5 min. additional time and cooled with water, to complete the phase transformation and improve the strip strength. The higher mandrel holding time results in additional loss in productivity.

The final stages of a hot rolling process, especially, the conditions at the Run Out Table (ROT) cooling can be related to the coiling temperature, during winding influences the coil collapse phenomenon. At the ROT, the convective heat transfer associated with water spray and the radiative heat transfer of the coil, controls the strip temperature. During further cooling, the secondary phase transformation of austenite to ferrite and pearlite, evolves heat and the dilation characteristics of the steel strip that affects the coil collapse [3].

In the present study, the temperature evolution in the hot rolling process at the finishing end at JSW Steel was carefully monitored in some steel grades prone for coil collapse. A set of modified cooling cycles were carried to alleviate coil collapse, among which one cycle could be optimized to prevent the coil collapse. The temperature evolution in the ROT and the coiling temperatures were simulated using physical simulation in Gleeble and the results were used to modify the cooling parameters during the plant trials to overcome coil collapse.

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Published online: 24 May 2021

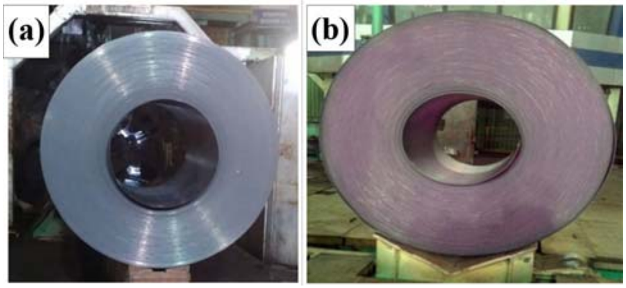

Figure 1. The shape of wound coil with (a) good spherical shape, (b) coil collapse with ellipsoidal shape.

2. Experimental

Plant trials were monitored in medium carbon high manganese steels for temperature at various banks during cooling in some of the steel grades, where coil collapses [figure 1(b)] were observed. The steel chemistry was assessed using a calibrated ARL make optical emission spectrometer, at JSW Steel Lab.

The hot rolled steel used for the study was made at JSW Steel Ltd., Vijayanagar unit. The input size of the rolled steel was reduced to a final strip thickness between 1.6 and 6 mm. The initial hot band temperature was maintained at about 1220°C and the finishing temperature of the strip was between 850 and 870°C. During subsequent cooling, a midway temperature was maintained between 660 and 690°C and the coiling temperature at the down coiler was usually maintained between 600 and 650°C. The coil was held in the mandrel for 4 to 5 min. The shape of the coil was monitored. It was observed that the coil collapse takes place immediately after its removal from the mandrel. Two steel grades prone for coil collapse, HTA1BES and HCM41A00 were selected for Gleeble simulation to assess the phase transformation parameters and the Ar_1 temperature.

In order to simulate the cooling conditions maintained in the ROT, a series of cooling simulation trials were carried out in Gleeble 3400 at the R&D unit at JSW Steel Ltd. The steel grade chosen for Gleeble simulation was HTA1BES. Cylindrical steel samples of dimension 85 mm lengths x 10 mm diameter were prepared for a thermo-mechanical simulation (dilatometry) experiment on the Gleeble. The specimen was heated up to 900°C in vacuum at a heating rate of 5°C/sec, and cooled to room temperature with cooling rates varying between 1 and 50°C/sec. The data was used to assess the Ar_1 temperature of the steel as a function of cooling rate. The dilation was always measured exactly at the center of the sample, where a thermocouple is attached along with a LVDT dilatometer. This measurement of temperature at the same vertical plane eliminates the effects associated with thermal gradient.

The dilation of the sample during the Gleeble simulation trials was monitored. From the inflexion points on the dilation curves, the maximum phase transformation temperature, phase transformation start- temperature (Ar_3) and phase transformation complete temperature (Ar_1) was studied. Four different cooling strategies were examined, out of which one trial was representing the actual ROT cooling cycles at the plant.

3. Results and discussion

The hot rolling process adopted to make the steel strips involves cooling in the run-out-table with water, after the finishing stand as per the schematic shown in figure 2. The details of the ROT cooling parameters are shown in table 1. Typically, the temperatures at the finishing mill exit are about 850 to 870°C, which get reduced to between 580 and 670 °C at the down coiler.

The temperature evolution at the ROT involves radiative and convective heat transfer using water jets to reduce the coil temperature to the acceptable coiling temperature. Several others have examined the process A_{r1} temperature, along with temperatures at the finishing stage, midway temperature and coiling temperature. The simulations experimentally validated the heat transfer data by laboratory experimental trials or plant level studies as shown in table 2 [4–7].

Coil collapse phenomenon was found to be dominant in a range of C-Mn family of steels. The chemical compositions of some of the steel grades prone to coil collapse is listed in table 3. It is seen that the steel grades with higher carbon contents are prone to coil collapse.

3.1 *Physical simulations using Gleeble*

Four different cooling simulations were carried out in the Gleeble in the steels studied. The cooling cycle was started from the temperature at the starting of the ROT. The cycles chosen include;

(1) Original cycle being practiced in the plant where coil collapse was dominating.
(2) Slower cooling than the original cooling where Ar_1 temperature becomes higher.
(3) Faster cooling than the original cooling cycle being practiced in the plant.
(4) Highest cooling rate practical in the various cooling banks in the plant.

The composition of the two steel grades studied, conforming to grades HTA1BES and HCM41A00 is shown in table 3.

Thermo-mechanical simulations to assess the effect of the coiling temperature were carried out for a range of coiling temperatures between 550°C and 630°C, at a constant cooling rate 15°C/sec. The steel dilation as a function of time and temperature is shown in figures 3 (a) and (b). It

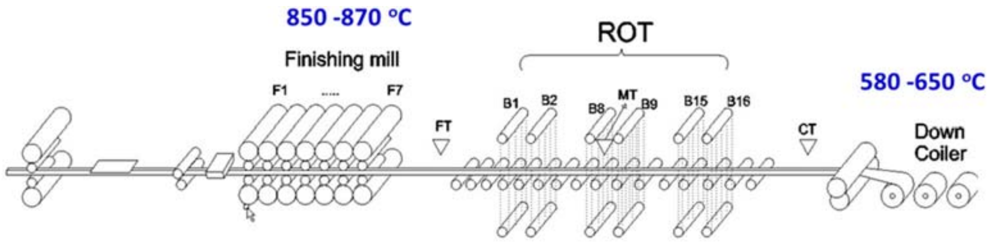

Figure 2. Schematic diagram of ROT cooling system.

Table 1. Typical detail of ROT parameters.

Sl. No	Configuration	Value
1.	ROT Length (m)	150
2	No. of banks	16
3	No. of upper headers	16
4	No. of bottom headers	8
5	Intensive cooling zones	B1 to B3 & B9 to B14
6	Normal Cooling zones	B4 to B8
7	Fine Cooling zone	B15 to B16
8	Water cooling	Water curtain
9	Temperature monitor: finishing temperature (FT) IMS multifunctional gauge	Close to finishing mill F-7
10	Middle temperature (MT)	Between 8th and 9th bank
11	Coiling temperature (CT)	Before down coiler

Table 2. Simulated and experimental data on temperature evolution in the ROT.

			Simulation			Experimental/ Plant trials			
Sl. No.	Steel Grade	Ar_1, at (15°C/sec)	FT	MT	CT	FT	MT	CT	References
1	HTA1BES	475	860	680	610	860	676	603	Suebsomran et al. [4]
2	HTA1BES	475	860	695	610	860	661	609	Suebsomran et al. [4]
3	HTA1BES	475	860	685	610	857	681	609	Serajzadeh [5]
4	HTA1BES	475	860	687	610	859	690	611	Biswas et al. [6]
5	HCM41A00	392	870	710	630	872	787	639	Jahanian et al. [7]
6	HCM41A00	392	870	715	630	872	792	650	Jahanian et al. [7]

is seen from figure 3(a) that the time available from the finishing temperature of 870°C to the coiling temperature 550°C to 630°C varies between 12 and 16 seconds. Depending on the coiling temperature and phase transformation, the thermal expansion and the contraction behaviour in the steel varies. The maximum amount of dilation during coiling occurs at 630°C and the minimum amount of dilation occurs at 550°C, as shown in figure 3(b). If these temperatures are considered as the coiling temperatures, the expansion and the contraction associated with the secondary phase transformation (austenite to ferrite and pearlite) can be assessed. It can be observed that at 550°C, the phase transformation of austenite to ferrite is completed much earlier than in coiling and at 630°C, the phase transformation progresses more after coiling as per the large dilation observed. This is because more time is available for the transformation to complete as steel cools to a lower temperature.

The complete phase transformation was assessed in the steel grades HTA1BES and HCM41A00 by imposing a heating rate of 5°C/s and cooling rate varied between 1 and 50°C/s. The results are given in table 4.

Table 3. Typical chemical composition of the steels with and without coil collapse (wt.%).

Grades	C 0.13–0.53	Mn 0.40–1.52	Si 0.018–0.248	P 0.01–0.018	S 0.003–0.0049	Al 0.030–0.038	Cr 0.009–0.234	N (ppm) 35–70	Ar_1, °C (using eq. 1)
Chemistry of coils where no coil collapse was not observed									
HC130NA0	0.0271	0.1	0.005	0.009	0.003	0.049	0.028	47	685
HZ230T0F	0.0013	0.14	0.003	0.01	0.0049	0.05	0.011	68	689
HGL05A00	0.015	0.14	0.005	0.01	0.004	0.06	0.014	70	684
HC335N00	0.002	0.67	0.004	0.04	0.0047	0.035	0.014	50	626
HTRS1AE0	0.061	0.51	0.017	0.012	0.0048	0.045	0.013	50	624
Chemistry of coils where coil collapse was observed									
HTA1BES	0.1708	1.33	0.012	0.013	0.008	0.042	0.012	58	489
HTD1AES	0.2091	1.37	0.15	0.018	0.0049	0.039	0.04	55	471
HDR10AJS	0.119	1.34	0.018	0.013	0.0041	0.033	0.016	70	506
HCM41A00	0.4124	1.52	0.172	0.018	0.0048	0.04	0.054	55	382
HCM55T00	0.531	0.75	0.259	0.016	0.0047	0.027	0.192	66	431

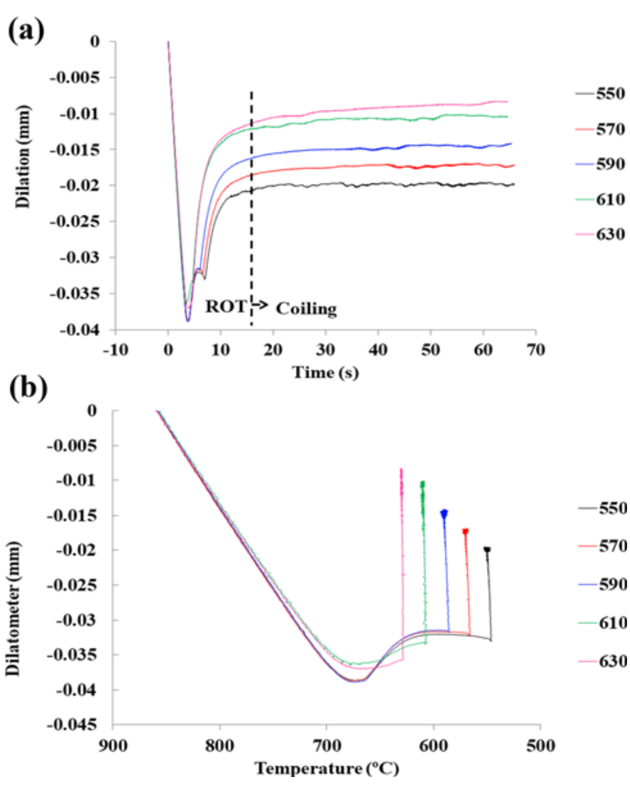

Figure 3. Gleeble simulation of coiling temperature recording dilation as a function of (a) time, (b) temperature at a constant cooling rate of 15 °C/s.

The results reflect dilation as a function of temperature, which is influenced by the volume changes associated with phase transformation and thermal contraction with decreasing temperature. Some of the inflexion points in figures 4(a)-(b) give the phase changes in the steel namely the A_{r3} and A_{r1} [8]. The A_{r1} and A_{r3} temperatures were determined as a function of cooling rate, experimentally as shown in table 4. This can be compared with the theoretically available equation (1), derived for a cooling rate of 20 °C/s [9].

Table 4. The evaluation of Ar_1 and Ar_3 temperatures for grade HTA1BES and HCM41A00 using Gleeble.

	HTA1BES		HCM41A00	
Cooling rate °C/sec	A_{r3}, °C	A_{r1}, °C	A_{r3}, °C	A_{r1}, °C
Theoretical data				
15	–	489	–	382
Measured value				
1	753	585	744	535
5	750	520	705	448
10	746	480	704	422
15	742	475	701	392
20	740	471	702	295
30	727	459	465	260
40	721	461	450	265
50	705	454	430	262

$$Ar_1 = 706.4 - 350.4\,C - 118.2Mn \qquad (1)$$

The A_{r1} temperatures as per equation 1 for the grades HTA1BES and HCM41A00 were found to be 489°C and 382°C, respectively. Similar eq. (1) for Ar_1 temperature under constant cooling rate of 20°C/s was reported by Kevin Banks *et al* [1]. The theoretical data and measured data differed by <5%. Thus, the A_{r1} as a function of C and Mn content of other grades can be roughly evaluated within a known error. It may be seen that A_{r1} decreases with increasing C and Mn content, with carbon having greater effect. The A_{r1} temperature found from the eq. (1) was for 20°C/sec and in the present thermo-mechanical simulator at 15°C/s was carried out which is very close.

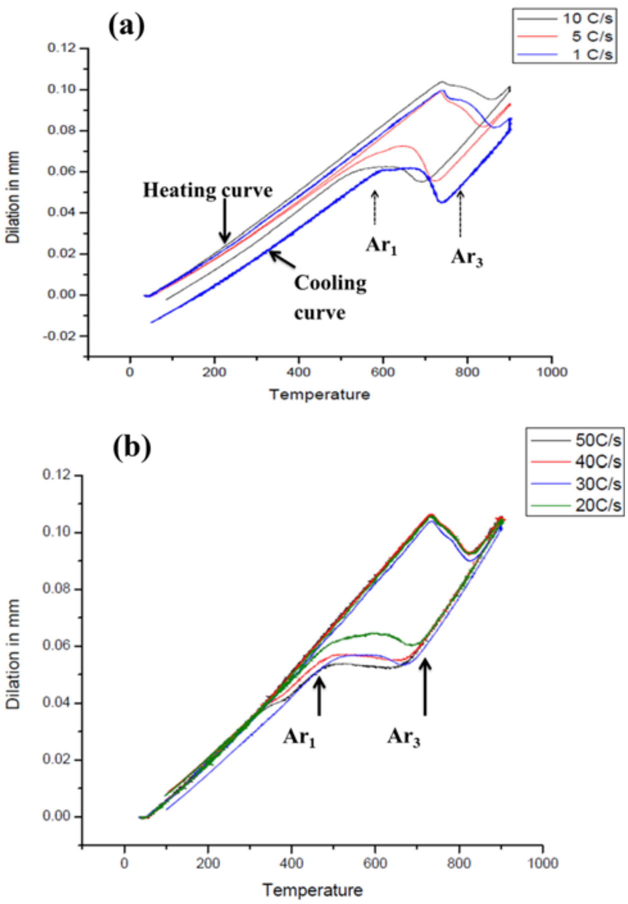

Figure 4. Dilation behaviour of steel grade HTA1BES, in thermo-mechanical simulator depicting the phase transformation at a cooling rate of (a) 1 to 10°C/sec., (b) 20 to 50 °C/sec.

The physical simulation was carried out as per the four different cycles mentioned. The Gleeble parameters such as the maximum temperature, heating rate, soaking time, cooling rate, finishing temperature (FT) and coiling temperature (CT) for the plant cycle and the modified cycles, is shown in figures 5 (a)&(b) and table 5.

The dilation curves obtained as per the varying cooling rates are shown in figure 6. The dilation of the specimen associated with expansion and contraction, as a function of temperature is observed. It is seen that initially the negative dilation value decreases with fall in temperature from 870°C to a minimum value. This is due to the fact that there is contraction associated within the austenite phase due to the fall in temperature. There is the first inflexion point after reaching the lowest dilation value. There is an increase in dilation with decreasing temperatures. The dilation trend reverses signifying the expansion of the specimen. The slope of the dilation increases as a function of the type of the cooling rate imposed. After the inflexion point 1, the dilation curve, as a function of decreasing temperature shows a hump, where there is initially an increase in dilation [expansion] to a peak value at inflexion point 2. This is followed by a decrease in dilation to another inflexion point 3, where further continuous dilation increase is observed, as shown in table 6. The region from inflexion point 1 to point 4 indicates the phase transformation that takes place in the steel in ROT conditions. Along with the austenite to ferrite formation, which increases the volume of the lattice, the drop in temperature results in thermal contraction of the residual austenite and the ferrite phases fraction decreases the volume. The combined effect is what is seen as the dilation. The inflexion point 1 is where the austenite decomposes to ferrite phase. From inflexion point 1 to 2, there is increasing amount of pro-eutectoid ferrite formation. The slope of the curve indicates that there is an expansion associated with the ferrite formation and gradual decrease of the austenite content. The entire transformation is complete at the peak dilation. Thereafter, the volume shrinkage associated with the transformation predominates. When the samples are isothermally held at the holding temperatures [630 to 550°C], the residual austenite transforms to ferrite and pearlite between inflexion points 3 and 4. This dilation data is critical because this dilation takes place at the coiling temperature. This dilation is one reason for the observed coil collapse.

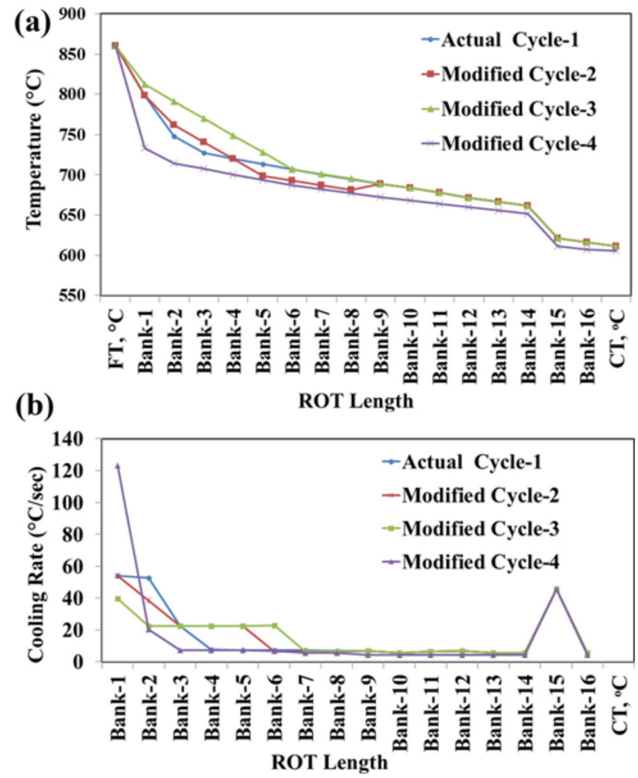

Figure 5. Actual ROT cooling parameter length wise as a function of (a) temperature drop, (b) cooling rate.

Out of the 4 cycles, the modified cycle 2 shows largest dilation at 630°C (inflexion point 3 to 4 in figure 6). The residual austenite that transforms to ferrite and carbide is highest. The next largest dilation is seen in cycle 3 which

Table 5. Physical simulation data.

Cycle	Maximum Heating Temp. °C	Heating rate °C/s	Soaking time s	Cooling rate, °C/s	FT, °C	CT, °C	Remarks
Actual Cycle 1	860	5	0.92	15.81	860	610	Actual ROT in Plant
Modified Cycle 2	860	5	0.94	32.02	860	610	Slower cooling rate at B1 to B5
Modified Cycle 3	860	5	0.94	25.85	860	610	Slower cooling rate at B1 to B5 and much lower cooling rate subsequently
Modified Cycle 4	860	5	0.95	71.67	860	603	Very fast cooling rate in B1 and B2; very slow cooling till B15 and moderate cooling till coiling

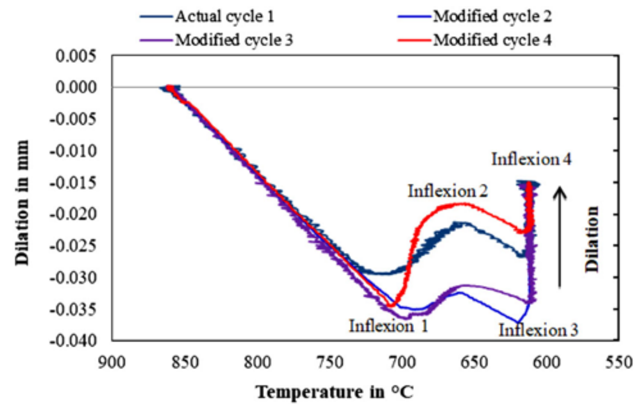

Figure 6. Gleeble simulations of conventional ROT cooling and coiling dilation temperature show that the fall in the above curve indicates contraction and rise in the curve implies expansion.

has cooling parameters close to that of cycle 2. The next largest dilation is observed in cycle 1 which is the actual plant cycle followed. All the above cycles where dilation is large, have the potential for coil collapse. The lowest dilation is seen in cycle 4 which had potential to reduce coil collapse. This cycle has highest cooling rate and initial temperatures are rapidly decreased. Hence, the austenite transforming in the coil is minimized. This has led to a reduction in coil collapse. The dilation-temperature curves are a function of the cooling rate. Specimen experiencing complete transformation prior to coiling has a well-defined dilation peak, indicating the temperature region, where the bulk of the transformation occurs (figure 6).

The specimen which shows lowest peak, indicates that the phase transformation is not complete at the ROT and the transformation takes place during coiling. The influence of the cooling cycles on phase change at ROT and during coiling is shown in Figures 7 (a) & (b). It may be observed that in modified cycle-4 where there is maximum dilation observed (figure 7(a)), the phase transformation is complete. The cooling strategy in the actual cycle showed lower dilation values than the other modified cycles 2 and 3. Hence, for industrial practice the cooling strategy of modified cycle-4 may be used for the ROT cooling. This ensures that the phase transformation is complete before the coil is wound in the down coiler and there is minimum dilation during cooling. Slower rolling speeds associated with thick strip ($\geq$7 mm) resulted in longer times on the ROT and hence, more time is needed for transformation to complete. The average speed for strip thickness below 6 mm is, 550 to 850 meter per minute (mpm) and above 6 mm thickness it varies from 150 to 350 mpm. Hence, the coil collapses found in thin strip coils ($\leq$6) can be controlled by maximizing the phase transformation at the ROT and minimizing the phase transformation at the coiling stage. During the phase transformation, there are two phenomena.

Table 6. The inflexion points at different cooling conditions.

Starting temperature = 860°C

Cycle	Cooling rate	Inflexion point 1 Temp (°C)	Peak inflexion Point 2 Temp (°C)	Mean slope between Points 1 & 2	Peak inflexion Temp (°C)	Inflexion point 3 Temp (°C)	Mean slope between points 2 & 3	Dilation at Inflexion point 4 Expansion
Actual Cycle 1	15.81	720	665	− 0.00018	665	612	0.000208	0.0092
Modified Cycle 2	32.02	705	663	0.000024	665	621	0.00016	0.01
Modified Cycle 3	25.85	680	660	− 0.0001	665	619	− 0.00004	0.018
Modified Cycle 4	71.67	720	670	0.00022	665	622	0.000096	0.009

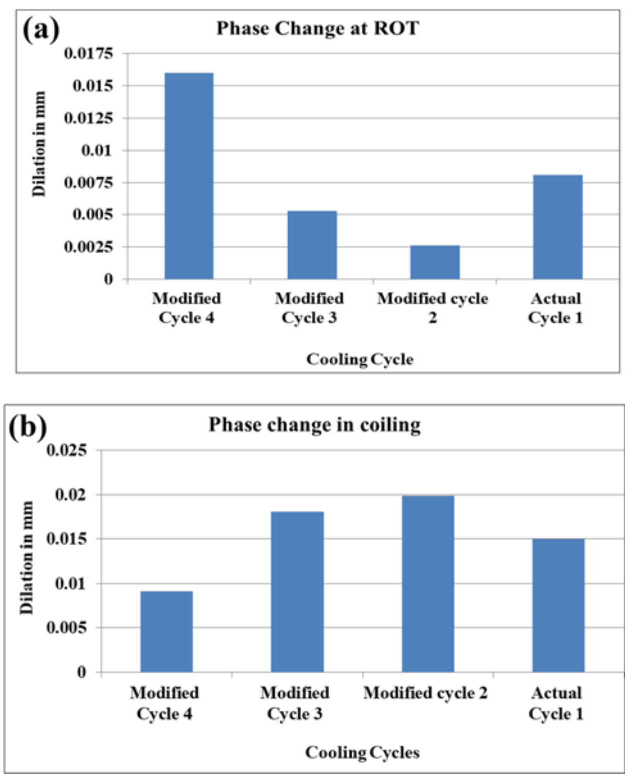

Figure 7. (a) Simulated phase change at ROT from actual cycle to 4th cycle. (b) Simulated phase change in coiling from actual 1st cycle to 4th cycle.

There is latent heat of transformation evolved and there is change in crystal structure that leads to volume change. Both these factors put together result in coil collapse.

3.2 *Plant scale trials*

The occurrence of coil collapse was found in grades such as HTA1BES and HCM41A00. The chemical composition and cooling parameters are shown in table 3 and figures 5(a) and (b), respectively. The mill temperature of coils with and without coil collapse is shown in table 7. The modified cycle was implemented at plant level.

Table 7. Cooling Conditions of the steel grades studied in the plant trials.

Grade	Avg. FT, °C	Avg. CT, °C	Coil Holding time, min	Ar_1 (using eq. 1)
Grades without coil collapse				
HC130NA0	830	660	Zero	685.1
HZ230T0F	850	680	Zero	689.4
HGL05A00	880	680	Zero	684.6
HC335N00	830	640	Zero	626.5
HTRS1AE0	850	610	Zero	624.7
Grades with coil collapse				
HTA1BES	870	610	4–5	381.4
HTD1AES	860	670	4–5	468.7
HDR10AJS	890	610	4–5	509.4
HCM41A00	860	630	4–5	508.3
HCM55T00	880	650	4–5	497.5

The initial cooling rate for the cycle with coil collapse was 15.81 °C/s, which is attained by maintaining a water cooling rate maintained around 1500 m^3/h which is decreased to 0 at the end of Bank no. 4. This was modified in the cooling cycle 4 where the coil collapse was completely avoided had water cooling rate from 3250 m^3/h to 0 m^3/h within 3 banks. Hence greater cooling rate decreases the temperature considerably and the phase transformation is facilitated early in fast cooled samples. The mill built has a level II automation system of Siemen's and the calibrated temperature is measured. The actual cycle was replaced with the modified cycle -4 evaluated by the Gleeble study to avoid the coil collapse.

The effect of carbon content on the Ar_1 temperature for the grades with and without coil collapse, was examined in figure 8. The carbon and manganese effect on the phase

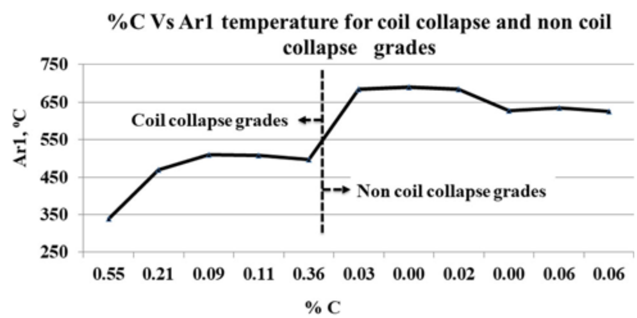

Figure 8. Percentage carbon as a function of Ar_1 temperature.'

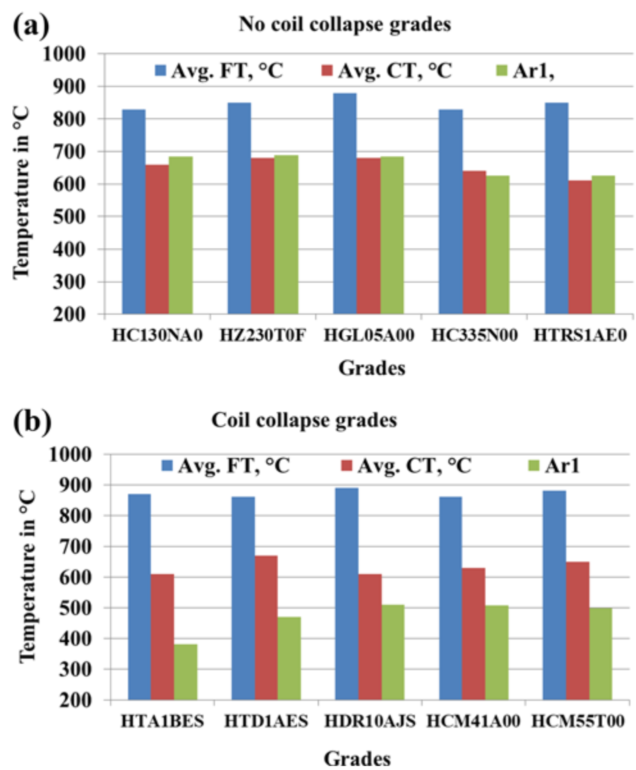

Figure 9. (a) The FT, CT and Ar_1 temperature in coils without coil collapse. (b) The FT, CT and Ar_1 temperature in coils with coil collapse.

transformation complete temperature (Ar_1) under constant cooling rate about 15°C, for the non-coil collapse grades have on average, a predicted Ar_1 temperature (625 to 690°C) higher than the CT of the strip (610 to 630°C) as shown in figure 9 (a) and for coil collapse grades have predicted lower Ar_1 (380 to 510 °C) than the CT of the strip (610 to 630°C) as shown in figure 9 (b).

From figure 3, it may be seen that lower Ar_1 temperature for the target coiling temperature (CT), high carbon (0.5%) and Mn grades are slightly more prone to collapsing due to less transformation occurring on the ROT lower the Ar_1 temperature. If the Ar_1 temperature is above the coiling temperature, then the phase transformation is completed on the ROT.

The steel strip of thickness (≤6 mm), C-Mn alloyed grade steel after the removal of the mandrel the coil cannot hold up under its own mass to retain its cylindrical form and loses its circular cross-section and forms an ellipsoid shape (coil collapse) and it is also called soft slump as shown in figure 1(b).

Based on the present study, the plant parameters were modified and implemented, which resulted in the control of coil collapse. The parameters like Ar_1 temperature, average finishing and coiling temperature are shown in table 8. The modified parameters ensure reduced dilation and heat evolution in the final stages.

Table 8. The ROT parameters during coil collapse and conditions imposed based on modified cycle 4.

			With coil Collapse			With modified cycle		
Sl. No.	Steel Grade	Ar_1	FT	MT	CT	FT	MT	CT
1	HTA1BES	475	860	695	610	860	676	603
2	HCM41A00	392	870	792	650	870	780	640

4. Conclusions

Thermo-mechanical simulation by Gleeble is utilized to predict the dilation and phase transformations during ROT cooling of C-Mn alloyed steel grades. The comparison between the experimental and theoretical results showed a good agreement. The following conclusions were derived from the results:

- From the Gleeble thermo-mechanical simulation results it was found that that higher cooling rate lowers the Ar_1 temperature.
- Higher cooling rate results in a higher volumetric change on the ROT (0.016 mm) and slower cooling rate lower the volumetric change on ROT (0.0026 mm).
- A laboratory method has been established that successfully correlates transformation behaviour during simulated ROT and coiling with coil collapse.
- The plant implementation has been successfully done and coil collapse issue has been solved.
- Reduced mandrel holding resulted in improved process productivity.

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