Optimized Heating of Steel Slabs with Radar Measurements

Patrik Ottosson[1], Jonas Engdahl[2], Daniel Andersson[1], Tomas Ekman[3], Fredrik Blomqvist[1]

[1]Radarbolaget
Box 975, 801 33 Gävle, Sweden
Phone: +46 73 988 55 41
Email: patrik.ottoson@radarbolaget.com

[2]SSAB
781 84 Borlänge, Sweden
Phone: +46 243 712 89
Email: jonas.engdahl@ssab.com

[3]Linde Gas
Varuvägen 2-10, SE-125 30 Älvsjö, Sweden
Phone: +46 70 512 7724
Email: tomas.ekman@linde.com

Keywords: Radar, Sensor, Distance Measurement, Thermal Strain-Rate, Temperature Rate of Change, Furnace Control, Heat Optimization, High Accuracy, Increased Productivity, Energy Savings

INTRODUCTION

The steel companies SSAB and Sandvik Material Technology (SMT) have implemented internet-based radar sensors to acquire feedback to their furnace optimization and control systems within the so-called OPTIMUS project. These systems estimate the temperature differences of slabs over time, which are then transformed to the *estimated* thermal strain-rate (expansion speed per meter). The radar systems measure expansion speed with high accuracy (about ±0.1 millimeter/minute) to determine the *actual* thermal strain-rate. This strain-rate can also be translated to a temperature rate of change if steel expansion data are known. Differences between estimated and actual strain-rates or temperature rate of change are used to adjust the furnace optimization and control systems. This adjustment leads to optimized heating of the steel slabs in the senses of quality increment, productivity increment, energy savings, and cost reductions.

METHOD AND MATERIAL

UWB Radar – high accuracy and robust technology

Robust digital UWB radar technology

In order to perform highly accurate distance measurements in harsh industrial environments or by wall penetration, UWB (ultra-wideband) radar sensors are needed. An UWB radar signal can be generated by i) analogue ignition of the signal, ii) frequency sweeping through FMCV (Frequency Modulated Continuous Wave), or iii) digital correlation of a transmitted PRBS-code (pseudorandom binary sequence). Radarbolaget has a digital UWB radar based on PRBS-code correlation (Fig. 1) and it is called DiRP (Digital Radar Processor). The PRBS-technology is flexible (programmable), robust (repeatable signals), and easy to modify (different frequencies and system amplification through different lengths of the PRBS-code).

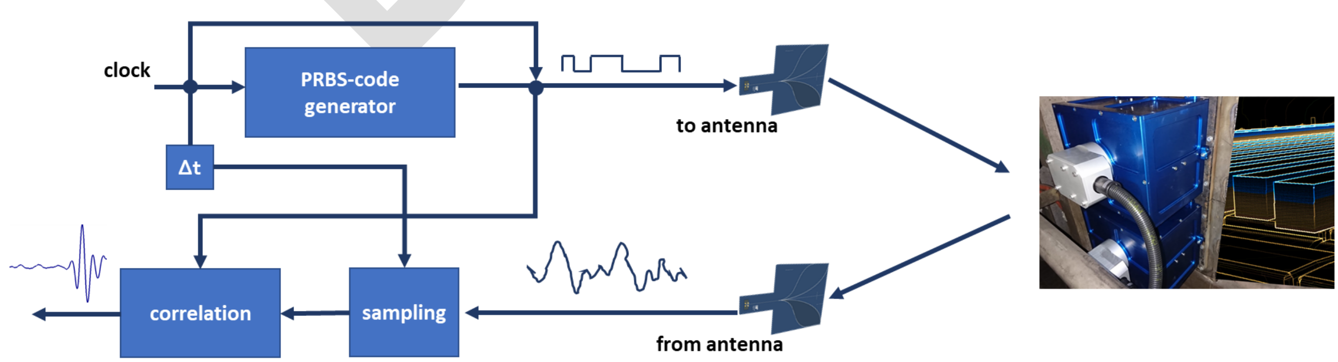

Figure 1. Digital UWB radar (DiRP) based on correlation of a transmitted PRBS-code.

Narrow-banded systems are sensitive to radio interference and disruptions due to harsh environments and wall penetration, while UWB-systems are relatively immune to such interference and disruptions. The radar signal of narrow-banded systems must be analyzed in the frequency-domain, which is quite complicated, while radar signals from UWB-systems can be analyzed in the time-domain. In the time-domain, the distances can be determined directly from a point of fidelity and propagation time, *i.e.* a robust point in the signal, *e.g.* crossing a threshold [1]. In this case, the distance is determined at the points of fidelity illustrated in Fig. 2 by following steps: i) Normalize signal by dividing amplitude values with the highest absolute amplitude value, ii) Determine the distance at the first positive peak above a given threshold, here above a threshold of 0.5, and iii) Determine the distance to the first zero crossing before the first positive peak.

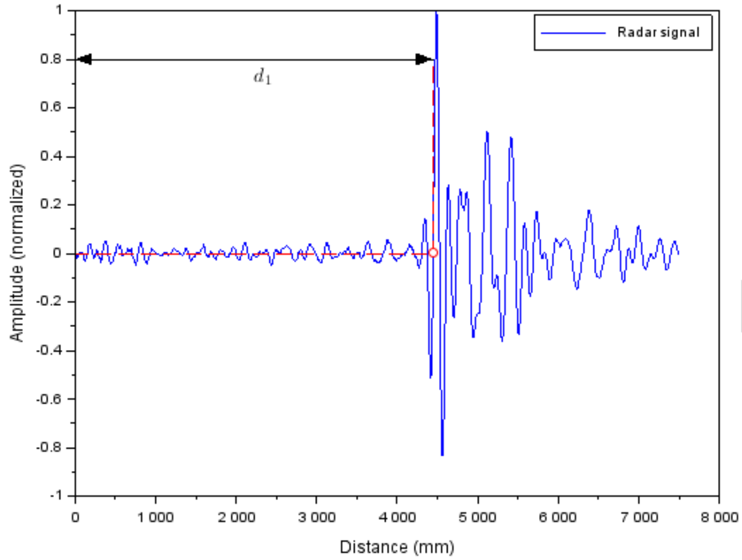

Figure 2. Time-domain UWB radio signals (normalized) and reflection measurement.

High accuracy of relative measurements

The radar system measures relative distances with high accuracy. These distances can be used to determine expansion speeds. During a short time <10 min, environmental furnace parameters are relatively stable, *e.g.* temperatures in the sensor, in the insulation wall, and in the atmosphere. The accuracy in the used radar system is influenced by (see Fig. 3):

- Averaging of the raw radar signals (here: 10 raw signals are used to compute the average signal),
- Numbers of measurements per second (here: 4 measurements per second), and
- Measured distance interval (here: 1, 2, 3, …, 100 mm).

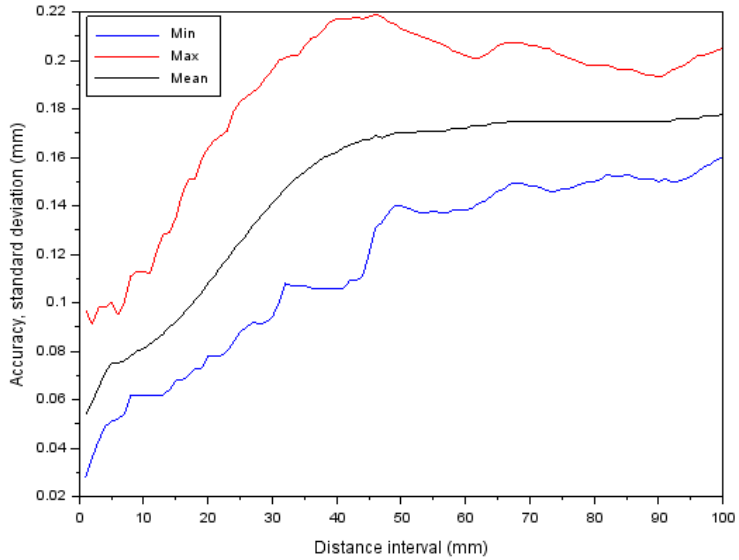

Figure 3. Accuracy of distance measurement: standard deviation for measurement of a specific expansion (distance interval).

Expansion speed and thermal strain-rate (expansion speed per meter slab) can be computed from distance measurements over time. In general, a steel slab is expanding sideways about 1 mm/min per 10 meters and 10°C. Different steel grades have different thermal strain-rate, which can be determined with dilatometer measurements. The accuracy of expansion speed (see Fig. 4) is influenced by:

- Accuracy of distance measurement (see Fig. 3),
- Measured distance interval (normally 0, 1, 2, …, 10 mm for a 10-meters slab), and
- Expansion speed (normally 0.5-3 mm/min for a 10-meters slab).

For distance measurements ≥0.3 mm and at expansion speeds ≥0.5 mm/min, the accuracy of the expansion speed is ≤0.3 mm/min (1σ). For a 10 meters slab, this results in a thermal strain-rate of 0.03 mm/min/m. For 3σ (99.73 percent of all measurements), the thermal strain-rate will therefore be <0.1 mm/min/m. This limit (0.1 mm/min/m) corresponds to a temperature gradient in the steel slab of about 7°C, which has been defined as an important temperature limit. This limit defines that the slab has a well-distributed temperature. To meet this accuracy, radar measurements shall be performed >1 minute. Longer measurements will give higher accuracy, because of more measurements.

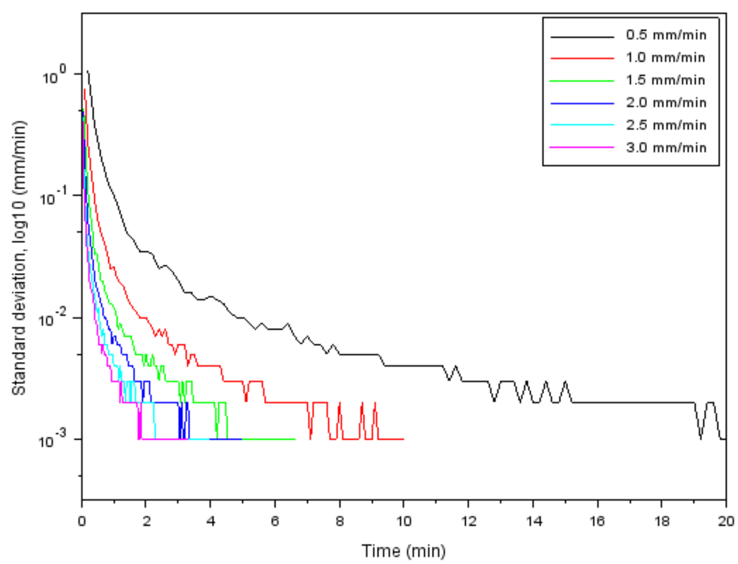

Figure 4. Accuracy of expansion speed measurements, standard deviation (log10) for measurement of different expansion (distance interval) and expansion speeds (different colored curves).

Furnace optimization and control systems

The Furnace Optimization Control System, FOCS, is used to control the heating furnaces at SSAB. Today 90 percent of all steel produced in Scandinavia is heated in furnaces controlled by FOCS [2]. Typical energy savings is in the range 5-20 percent. On top of reduced energy consumption, the system increases production capacity by intelligent pacing control of the furnace and surrounding processes. Productivity increases with up to 28 percent have been realized. FOCS is calculating the material temperatures inside the furnace in real time for each slab, billet, or bloom. Since the material temperature is calculated both on the surface and in-depth, the FOCS controls heating and pacing of the furnace to reach the wanted discharge temperatures with minimal energy consumption. Each slab, billet, or bloom is given its own target heating profile depending on dimension, material type, and quality aspects.

Within the OPTIMUS project, a furnace optimization calculator (FcalcLive), developed by AGA (member of the Linde Group) will be used to control and optimize a radar-adapted furnace at SMT. This furnace system is based on real time computations of all energy fluxes and of the total energy and mass balance of the entire furnace. The system is built to set the zone set-points in order to optimize the heating of blooms in furnaces and it can handle radar sensor data to achieve more accurate optimization. Thus, the radar sensors will be integrated with two different furnace systems. The sensors support the furnace systems by measuring the actual outcome of the thermal strain-rate, calculated to the average temperature differences in the measured slabs and blooms.

Thermal expansion and strain-rate

Steel expands upon heating and contracts when cooled. The change in length with temperature is called thermal expansion. The thermal expansion of metal can be expressed as:

$$\left(L_f - L_0\right)/L_0 = \alpha\left(T_f - T_0\right) \text{ or } \Delta L / L_0 = \alpha \cdot \Delta T \text{ or } \alpha = \frac{1}{L_0}\cdot\frac{\partial L}{\partial T} \qquad \text{(Eq. 1)}$$

where L_0 and L_f are original and final lengths, T_0 and T_f are original and final temperatures, and α is expressed as a reciprocal temperature (°C^{-1}) such as 10^{-6}/°C [3]. The change in thermal expansion with time is called thermal strain-rate and can be expressed as:

$$\left(L_f - L_0\right)/L_0 = \varepsilon\left(t_f - t_0\right) \text{ or } \Delta L / L_0 = \varepsilon \cdot \Delta t \text{ or } \varepsilon = \frac{1}{L_0}\cdot\frac{\partial L}{\partial t} \qquad \text{(Eq. 2)}$$

where t_0 and t_f are original and final time, and ε is expressed as the reciprocal time (min^{-1}). It can be noticed that thermal expansion, α, and thermal strain-rate, ε, is the same if the change in time and temperature is equivalent. In a heating furnace when heating steel slabs, it is *not* possible to have this condition. The furnace consists of multiple temperature zones to increase and stabilize the temperature in a slab in a controlled manner. The steel slab is also moved forward within and between the zones. Therefore, the temperature of each steel slab will always strive to reach the surrounding temperature of the zone. The thermal expansion can be measured with a dilatometer by placing a small piece of steel inside a heating chamber. The volume or length change is measured and connected to the temperature, see Fig. 5. Notice the phase transformation in the interval of 720-830°C. The thermal expansion is relatively stable before and after this phase transformation for most steel grades. The thermal expansion, before and after the phase transformation, is changing with different steel grades, and will consequently do the same for the thermal strain-rate. Nevertheless, there are large similarities between different steel grades, wherefore steel grades can be categorized into groups. In the case of SSAB, 1-3 expansion curves are needed, and for SMT 10-15 curves are needed, even if the companies produce thousands of different steel grades.

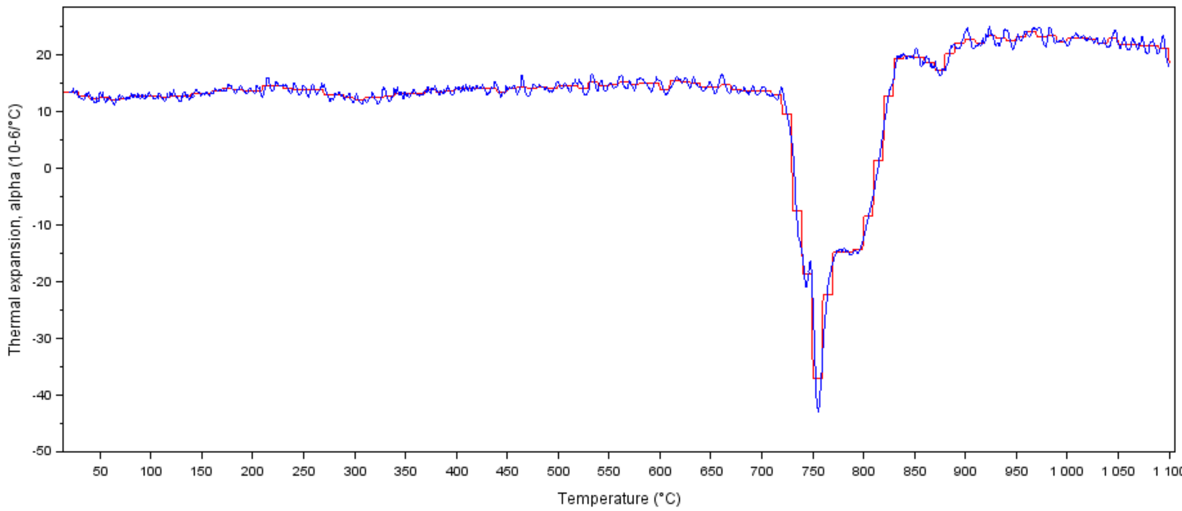

Figure 5. Thermal expansion of a general steel grade (blue) and stepwise adaption of the expansion (red).

In heating furnaces due to temperature zones, large differences between zone and slab temperature, and inhomogeneous slab temperature, the relation between temperature and thermal expansion is more complicated. Beyond that, it is challenging measuring absolute lengths with a radar system or other measurement devices with high accuracy due to temperature differences in the insulation, calibration of sensors, repetition of measurement point, and unprecise initial slab length and mean temperature. Therefore, relative length changes in relation with time are required to be measured. During the same time, absolute temperatures and temperature changes over time can be computed with a furnace control system. The relation between thermal expansion and thermal strain-rate (equations above) can be used to express the temperature difference (Eq. 3) or its derivative and the temperature difference over time (Eq. 4):

$$\partial T = \frac{\partial L}{L_0 \cdot \alpha(T)} \qquad \text{(Eq. 3)}$$

$$\frac{\partial T}{\partial t} = \frac{\partial L}{\partial t \cdot L_0 \cdot \alpha(T)} \qquad \text{(Eq. 4).}$$

To solve Eq. 3 and 4, an approximative value of the temperature is needed, as well as the steel grade or sub-group of steel. The largest differences between thermal expansion can be found in the area of phase transformation. It is challenging to retrieve high accuracy in this temperature interval (connecting radar measurement with control data), so measurements are preferably performed before and after the phase transformation.

Radar sensors on heating furnaces

Radarbolaget has installed 12 systems (6 sensor pairs) at SSAB and SMT. The systems are continuously measuring distance to slabs and are calculating the thermal strain-rates of each slab. In the future, the systems will have the possibility to communicate with the furnace control system to deliver the temperature rate of change over time (Eq. 4). In order to do that, the approximated temperature, *T*, is needed. This temperature can either be retrieved from the furnace control system or by using the measured absolute expansion.

An installation consists of three parts: i) replacement of ceramics with insulation fiber, ii) cutting up metal shell and placement of antenna housings, and iii) shielding, cooling, internet connection, and placement of radar central unit (DiRP), see Fig. 6. At SSAB, the sensors are placed at 8 meters and 23 meters, which corresponds to an average temperature of slabs of 600°C and 1,200°C, respectively.

Figure 6. a) Installation of insulation fiber in front of sensor. b) Installed sensor housings at furnace.
c) Radar central unit (DiRP) in apparatus housing with sensors.

RADAR MEASUREMENT

Radar measurements from furnace and temperature difference

A radar measures the shortest distance to an object and has no direction like laser. Therefore, geometry conditions must be considered. On the other hand, radar is not sensitive to small concave pits or convex tops since it measures a distance to a larger surface. The radar measures through the wall, which is not possible with a laser. In a furnace, the slabs are in general moved and placed in front of the radar 3-10 minutes. The walking beam moves the slabs forward for 1 minute. During this minute, it is possible to measure the slab and its expansion as well, but since different parts of edge is measured when it is moved, it is not preferable to take such measurements into account. In Fig. 7a-b, 15 minutes of measurements is shown for three scenarios: i) first slab is fix, ii) second slab is moving, and iii) second slab is fixed. A movement is sometimes carried out in two phases due to correction of the discharge-slab position. This can be seen in Fig. 7b, representing the measurements only from the left side.

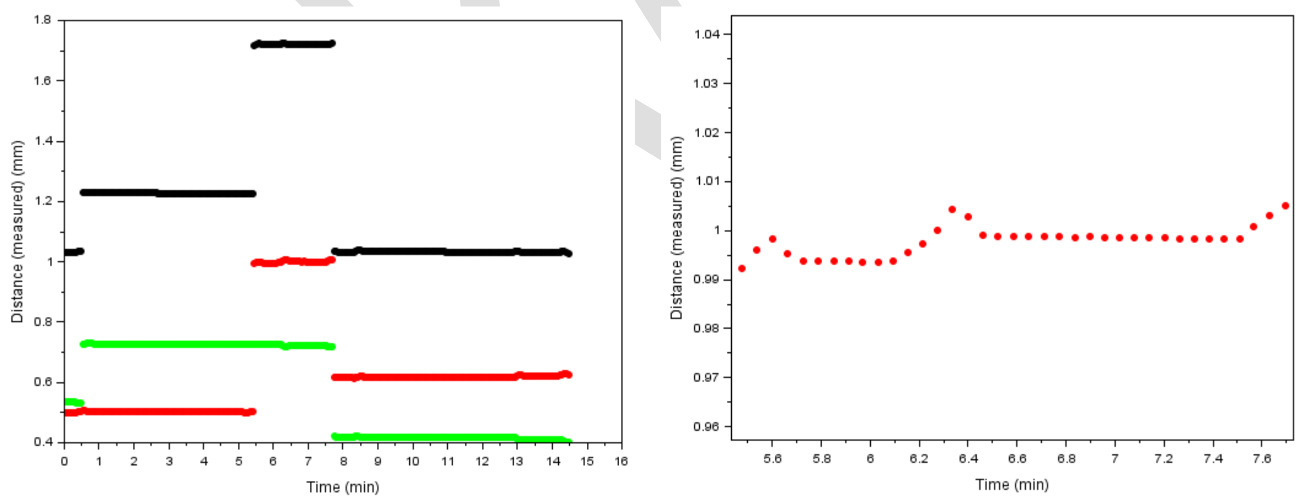

Figure 7. a) Radar measurements of two slabs for 15 minutes in a heating furnace at SSAB. Distance measurements from left (red) and right (green) is added into the total distance (black). b) Left-side measurements during a walking beam movement.

Fig. 7 shows that data must be filtered and synchronized with furnace data, like walking beam movements and for too short measurements (Fig. 8a). After filtering data, the thermal strain-rate is computed (thermal expansion divided by the length of the slab), see Fig. 8b. To obtain highest accuracy in computation of the thermal strain-rate, furnace data must be considered. In normal case with large differences between the temperatures of the slab and the furnace, the expansion is linear. With smaller differences, the expansions will be negative exponential, *i.e.* the expansion speed will converge to zero.

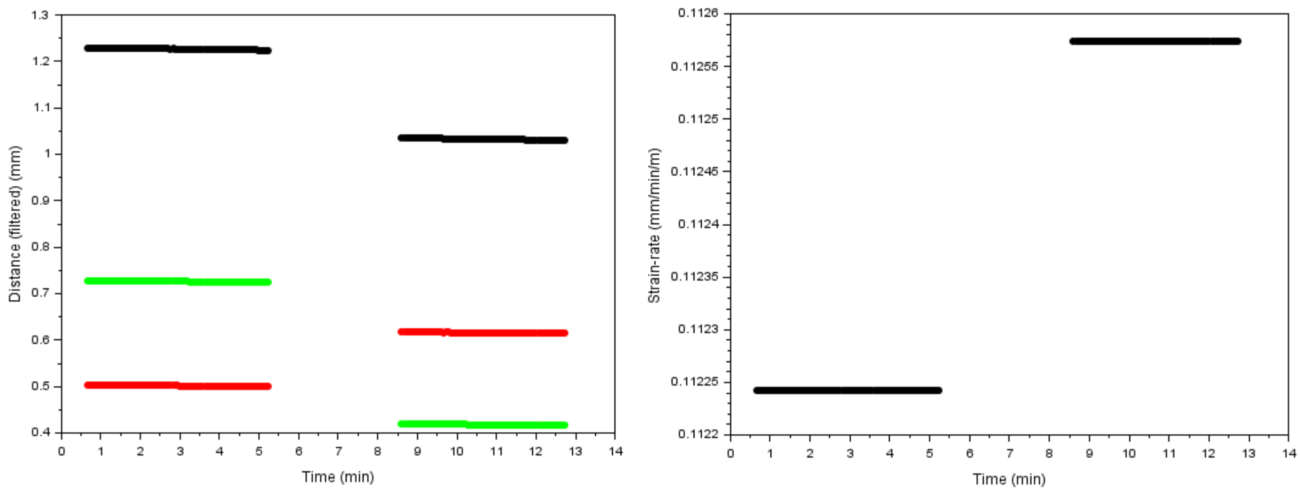

Figure 8. a) Filtered distance measurements of two slabs from Fig. 7. Distance measurements from left (red) and right (green) is added into the total distance (black). b) Computed thermal strain-rate of slabs.

If Fig. 8a is magnified concerning the total distances (black), Fig. 9a-b are obtained. The graphs show each individual distance measurement, 18 measurements per minute. In a normal furnace implementation, the standard speed will be 4 measurements per second, *i.e.* 240 per minute. The thermal strain-rates, in Fig. 9a-b, are computed with linear regression for all data points and they are similar for both slabs. Linear or logarithmic regression of all data points gives highest accuracy. Sometimes moving average may be practical for nonstop data streams. Moving average will have lower accuracy. Both methods demand filtering and synchronization with furnace data. Using Eq. 3 with T=600°C and alpha-curve of Fig. 5, the thermal strain-rates from Fig. 9a-b give temperature changes and temperature changes per minute of:

First slab: $\partial T_1 = 34.0°C, and\ \frac{\partial T_1}{\partial t_1} = 7.480°C/\min$

Second slab: $\partial T_2 = 31.0°C, and\ \frac{\partial T_2}{\partial t_2} = 7.502°C/\min$.

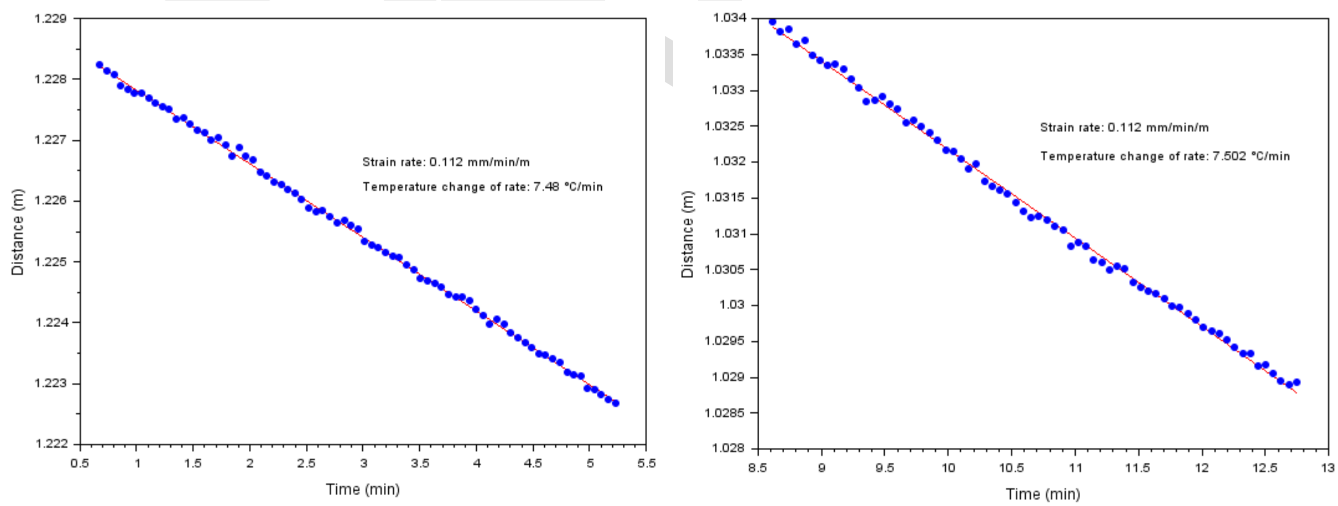

Figure 9. a) Thermal expansion and strain-rate for first slab. b) Thermal expansion and strain-rate for second slab.

ADJUSTING FURNACE CONTROL AND OPTIMZATION

The fundamental approach to adjusting the furnace control system is to compare the radar measured strain-rate with the calculated thermal strain-rate given from the furnace control system or the corresponding rate of change of the temperature. Eq. 3 shows the relation between the thermal strain-rate and the change of temperature. Eq. 4 is the derivative form of Eq. 3. Eq. 4 can be rewritten as:

$$\alpha(T)\cdot\frac{\partial T}{\partial t}=\frac{\partial L}{\partial t\cdot L_0} \qquad \text{(Eq. 5)}$$

Thus, with a radar measured strain-rate, it is thereby possible to estimate the rate of change of the temperature within a slab. Normally, a furnace control system, *e.g.* FOCS, includes temperature calculations of the slab based on boundary conditions like furnace temperature, heat transfer parameters, and material properties. The numerical approach could differ, but generally, the heat to a slab could be expressed as:

$$\frac{\rho\cdot c_p\cdot\partial T}{\partial t}=\nabla_{div}\cdot(\lambda\cdot\nabla_{grad}T)+Q \qquad \text{(Eq. 6)}$$

where ρ is the density of conduction material (kg/m³), c_p is the specific heat capacity of conducting material (J/kg°C), λ is the thermal conductivity of conducting material (W/m°C), T is the temperature (°C), t is time (s), ∇_{div} and ∇_{grad} are the divergence and gradient scalar operators, and Q is the heat source, radiation, convection etc. (W/m³). Eq. 6 can thus be expressed in the two-dimensional domain as:

$$\underbrace{\frac{\partial(\rho\cdot c_p\cdot T)}{\partial t}}_{transient\ term}=\underbrace{\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)}_{conduction}+\underbrace{Q}_{heat\ source} \qquad \text{(Eq. 7)}$$

where x and y are the cartesian coordinates (m).

Eq. 7 is solved numerically by the furnace control system for a presumed heat source and it is integrated in time and space for a given temperature distribution within the slabs at each calculation time. If the material properties are correct in the physical model, an error of the calculated temperature and consequently $\partial T/\partial t$ will be fully dependent on the error of the heat source, prior or at the instance of the calculation.

Adjusting furnace control and optimization

As stated above, a deviation of the calculated $\partial T/\partial t$ compared by radar derived $\partial T/\partial t$ from measured thermal strain-rate could be explained by errors of the assumed heat source or boundary conditions into the furnace control model. For furnace application, the major heat source, Q, in Eq. 6 and 7 is radiation even though other heat transfer mechanisms as convection also exists. The Stefan-Boltzmann law (Eq. 8) gives a net heat generation proportional to $T_{surr}^4 - T_{slab}^4$:

$$P=A\varepsilon\sigma(T_{surr}^4-T_{slab}^4) \qquad \text{(Eq. 8)}$$

Consequently, if there is large differences of the surroundings temperature and the surface temperature, the net energy going to the slab is very sensitive to the accuracy of those temperatures. For a furnace control system, the temperatures of the surroundings are measured by thermocouples, which can degrade over time and must therefore be adjusted to work properly with the furnace control system. Obviously, this adjustment is challenging without independent control measurement systems.

The common and most conventional way to adjust a furnace temperature prediction model is to use a thermocouple equipped test-slab, recording the temperature history for the slab during heating via a data logger (Fig. 10). By comparing the measured temperatures against the calculated, information of the quality of the prediction model can be made and, if necessary, adjustments of the model parameters can be done. The benefit with this approach is that deviations are obtained for the whole furnace in one test. Nevertheless, the method also has many disadvantages. First, it is time consuming and rather expensive. The slab must be prepared carefully with drilled holes and positioning of the thermocouples. A test will take some time from production, both when charging the test slab and when discharging. Beside that, one test only covers the conditions that exist during that single test, and therefore multiple tests must be performed to cover different running conditions. Thus, having continuously present measurement devices, like radar strain-rate sensors, to improve the quality of the temperature prediction model is therefore very valuable.

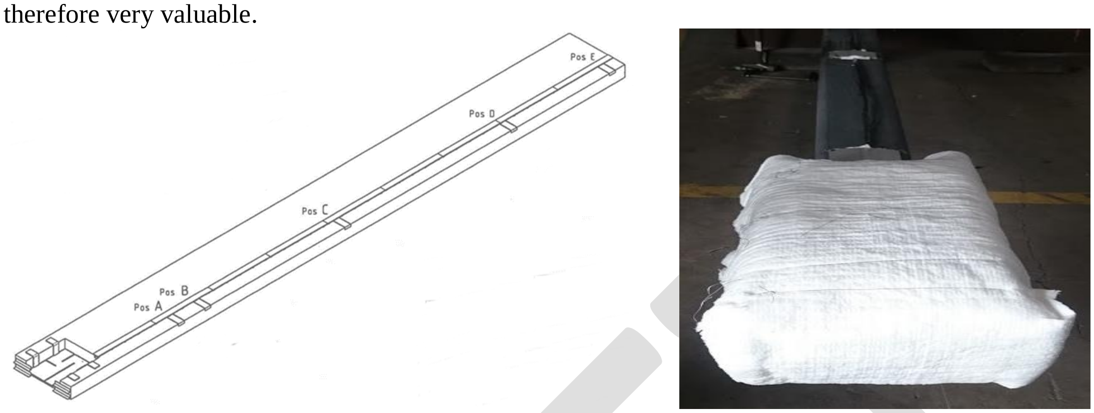

Figure 10. Thermocouple equipped test-slab, recording the temperature history for the slab during heating.

Interpretation of differences in temperature differences

SSAB has collected radar measurements from its two sensors at 8 meters and 23 meters in a database. Corresponding data from FOCS estimations have been acquired, as well. The data acquisition period was 15-22 January 2019. In Fig. 11a-b, these data are converted into temperature rate of change $\partial T / \partial t$ and presented towards each other. The linear regression says that estimated $\partial T / \partial t$ shall be corrected with:

8 meters: $$\frac{\partial T_{FOCS\_new}}{\partial t} = 0.691 - 0.918 \cdot \frac{\partial T_{FOCS\_old}}{\partial t}$$

23 meters: $$\frac{\partial T_{FOCS\_new}}{\partial t} = 1.533 - 0.809 \cdot \frac{\partial T_{FOCS\_old}}{\partial t}.$$

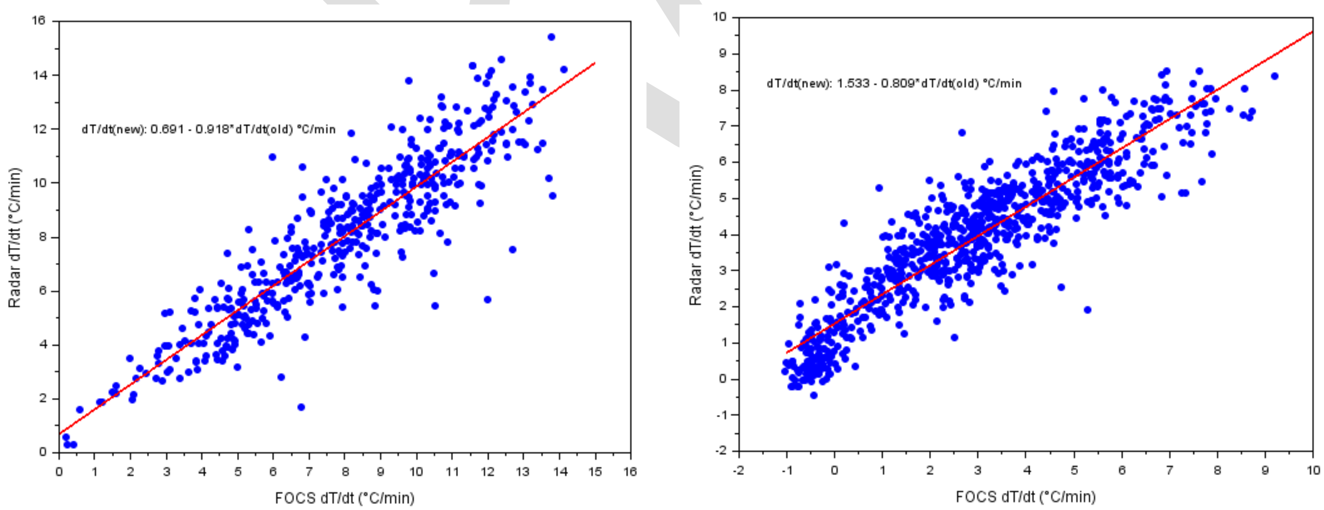

Figure 11. Estimated and actual temperature rate of change towards each other at a) 8 meters, and b) 23 meters.

Fig. 12 shows the differences between radar and FOCS. Interpretations of Fig. 11-12 are that FOCS estimates, in general, too high temperature rate of change at 8 meters and too low at 23 meters, compared to the by radar derived temperature rate of change. Thus, the radar measurement indicates that at 8 meters, most slabs are heated slower and less than estimated by FOCS, and at 23 meters, most slabs are heated quicker and more than estimated by FOCS. In table 1, corrections of FOCS' temperature rate of change (°C/min) are presented. Estimated differences show that the target temperature rise shall decrease at and before 8 meters ($\partial T / \partial t$ >6°C/min) and increase between 8 and 23 meters ($\partial T / \partial t$ <7°C/min). This information could be interpreted in what direction the FOCS model parameters should be corrected in.

Table 1. Required corrections of temperature rate of change in FOCS.

$\partial T / \partial t$ **(°C/min)**	**8 meters (Δ°C/min)**	**% error**	**23 meters (Δ°C/min)**	**% error**
-1			+2.3	-232%
0	+0.7	-	+2.0	-
1	+0.6	+59%	+1.7	+173%
2	+0.5	+22%	+1.4	+72%
3	+0.3	+11%	+1.1	+38%
4	+0.2	+5%	+0.9	+21%
5	+0.1	+1%	+0.6	+11%
6	-0.1	-1%	+0.3	+5%
7	-0.2	-3%	-0.0	-0%
8	-0.3	-4%	-0.3	-4%
9	-0.5	-5%	-0.6	-5%
10	-0.6	-6%	-0.9	-7%
11	-0.7	-7%		
12	-0.8	-7%		
13	-1.0	-8%		
14	-1.1	-8%		
15	-1.2	-8%		

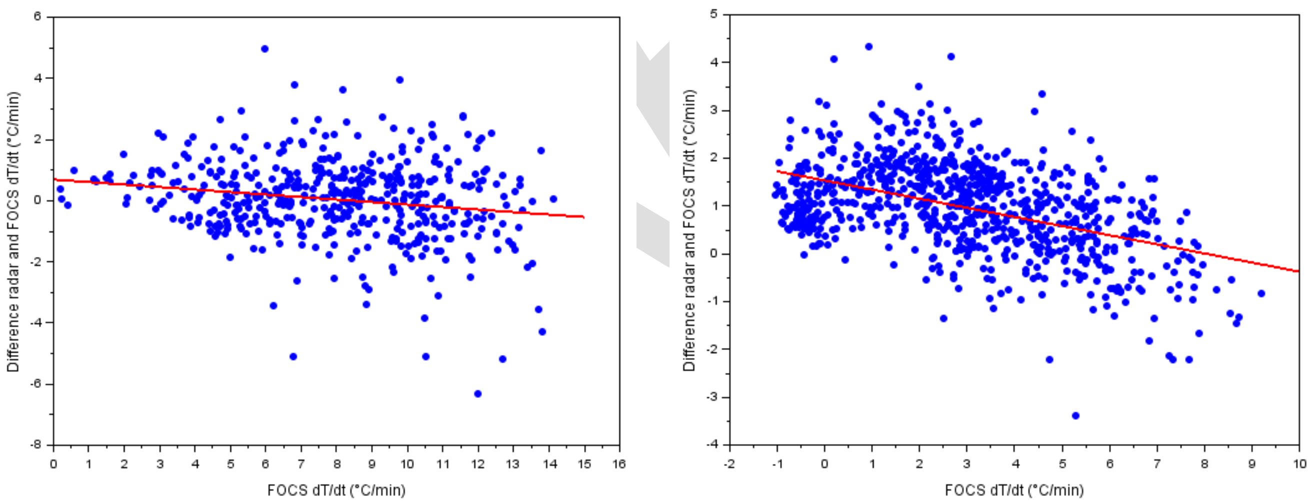

Figure 12. Differences between estimated and actual temperature rate of change at a) 8 meters, and b) 23 meters.

In Fig. 13, it is possible to investigate how FOCS estimates and the radar measures the actual strain-rate continuously at 8 meters. FOCS estimations and the radar measurements are following each other well. SSAB has optimized their furnace control system for years, so expectantly the deviations were small. Thus, it is noticeable that FOCS has a moving average or delay when the strain-rate is decreasing. Fig. 13 shows data for 9 hours during 19 January.

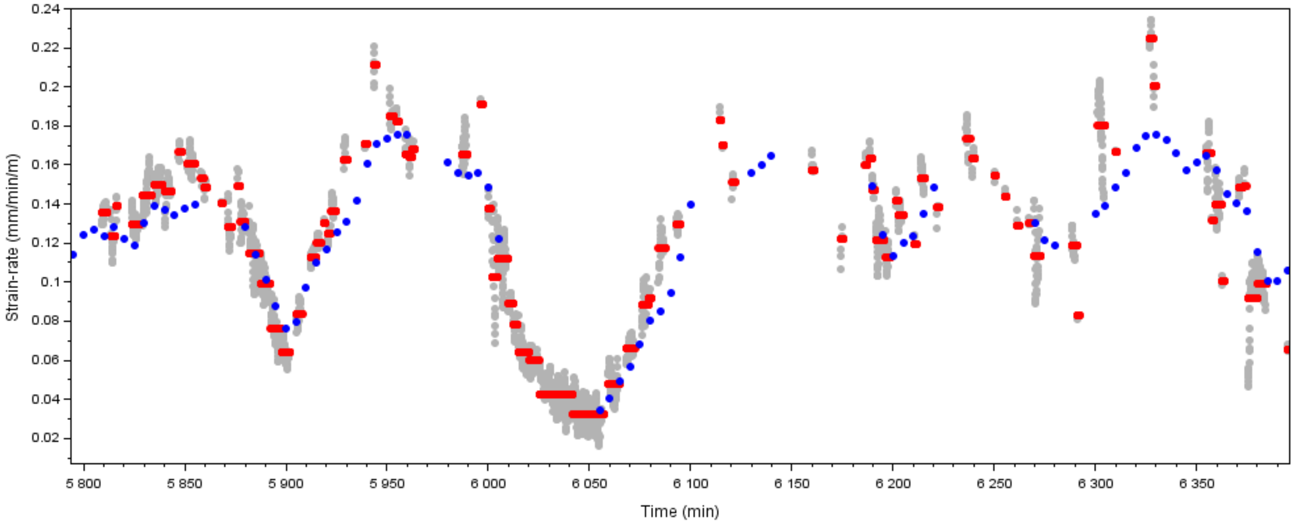

Figure 13. Thermal strain-rate for FOCS (blue), average radar (red), and continuous radar per 60 seconds (grey) at 8 meters.

Changing boundary conditions

Boundary conditions are, for example, temperature, throughput speed, and environment parameters. At SSAB, the furnaces can be fed with different kind of gases (propane and methane), oxygen, and air. It is complicated to calibrate the furnace control system for different environmental parameters. Therefore, it is practical to have a direct feedback system, like the radar strain-rate sensors. Such sensors give trend changes fast and simple after measuring indicator slabs for a few days. Trend changes are an early indicator that shows that the furnace control system has deviations due to changes in boundary conditions. The easiest and most likely parameter to adjust is the surrounding temperatures in each zone of the furnace. The Stefan-Boltzmann law (Eq. 8) is related to the temperature change over time:

$$P = A\varepsilon\sigma(T_{surr}^4 - T_{slab}^4) = V \cdot \rho \cdot c_p \frac{\partial T}{\partial t} \qquad \text{(Eq. 9)}$$

where P is the heat radiation (W/m^2), ε is the heat transfer coefficient (W/m^{2}°C), A is the area (m^2), V is the volume (m^3), $\sigma=5.6696E\text{-}8$ is the Stefan-Boltzmann constant (W/m^{2}°C^4). By minimizing Eq. 9 with least square adjustment, it is possible to adjust the parameters T_{surr}, T_{slab}, or ε, and perform possible corrections of the furnace control system. In two experiments at SSAB, different boundary conditions were applied, and hundreds of slabs were measured:

1. The furnace had varying temperature difference between the furnace and the slabs at 8 meters (Fig. 14), and
2. The nearby zone burners using only air or oxygen enriched combustion, respectively (Fig. 15).

In Fig. 14a-b for varying temperature difference, the investigation shall be interpreted as i) the difference between radar and FOCS values is not significant at 8 meters, and ii) the radar measurements indicate a higher temperature rise at low temperature differences between the furnace and the slabs. The investigation, in Fig. 14, is the same data as in Fig. 11, and shall be interpreted in the same way. To adjust the furnace, the red dots in Fig. 14 shall be moved towards the blue dots by changing the parameters for boundary conditions for the FOCS system nearby the sensor. Since the results indicates that the estimated heat rate (heat transfer to the slab) by FOCS seems to be alright at 8 meters, no corrections of the model is needed around this point. At 23 meters, FOCS seems to underestimate temperature rise and heat rate at low temperature differences between furnace and slab. A reasonably way is therefore to increase the value of the measured temperature of the furnace wall nearby the radar sensor

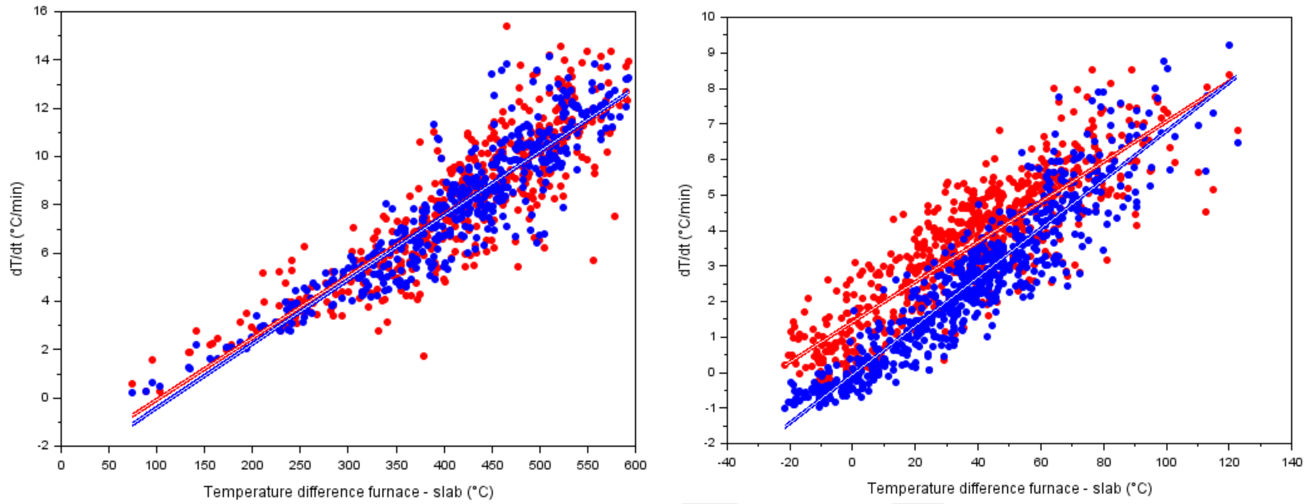

Figure 14. Varying temperature differences between the furnace and the slabs and its effect on temperature change of rate $\partial T / \partial t$ (radar - red, FOCS - blue) a) 8 meters, and b) 23 meters.

In Fig. 15 for air and oxygen enriched case, the experiment shall be interpreted as i) the deviation between radar and FOCS rate of temperature is greater and more negative when using oxygen compared to using only air feeding. The error in the FOCS model is consequently larger when oxygen enriched combustion is used compared to when only air is used.

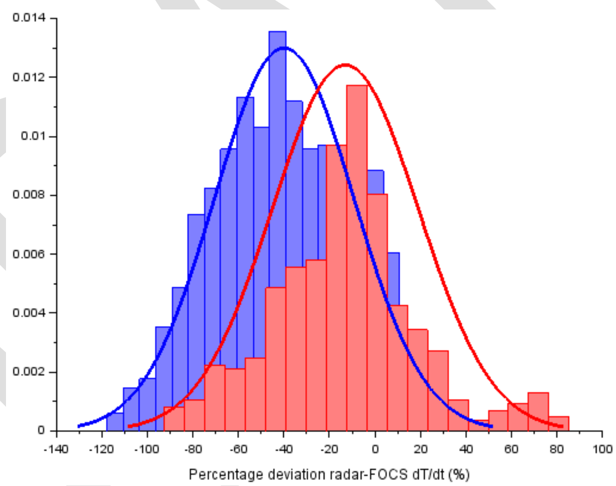

Figure 15. Different boundary conditions: feeding of air (red) and oxygen (blue) and temperature difference (radar-FOCS).

DISCUSSION

The radar sensors were developed to measure relative distance and to determine the thermal strain-rate with high accuracy. The strain-rate is used to compute temperature difference and to adjust the furnace control system, *e.g.* FOCS and FcalcLive. Of course, the sensors can be used for other purposes, as well. Other possible applications that has been tested are:

- *Replacement of temperature logging*. The expansion of a steel slab is measured at a fix place in the furnace during the whole heating. This measurement was performed in the project (see Fig. 16) to calibrate the mathematical model of a heating simulation,
- *Passage detection*. The radar sensors can communicate with each other, and therefore be used to detect passages and positions, *e.g.* at the discharge. This feature has been tested in a real furnace,
- *Absolute centering and slab size*: Even though the sensors have been developed for high relative accuracy, the absolute distance can be used for centering and determining the slab size. The absolute accuracy will be some millimeters,

- *Curvature*: In pusher furnaces and in furnaces with hearth, the slabs will bend up due to uneven temperature distribution from the top to the bottom of the slab. The curvature can be 10-20 cm. This feature has been tested in a real furnace.
- *"Ready button"*: When the expansion is zero or close to zero (equilibrium state), the slab has the same temperature as the furnace. This feature can be used in simpler furnaces, like soaking pit furnaces and heating furnaces with hot charged slabs.

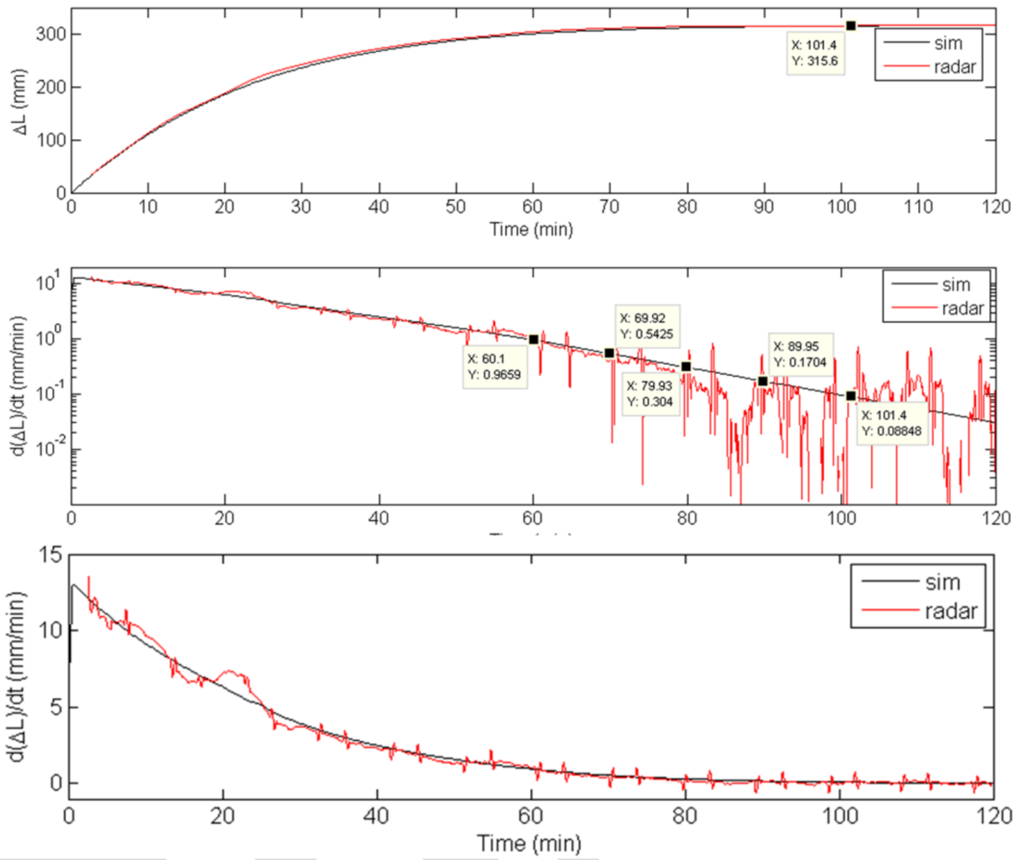

Figure 16. Expansion measurement of a steel slab at a fix place during the whole heating (red) and simulation (black). Top: expansion, Middle: log10 expansion speed (log10 dL/dt), Bottom: expansion speed (dL/dt)

CONCLUSIONS

Laboratory tests and implementations at SSAB and SMT have shown that the accuracy of the radar sensors gives a thermal strain-rate of 0.1 mm/min/m. This corresponds to a temperature gradient of about 7°C.

Radar distance measurements at SSAB was performed on large slabs (width: 0.6-1.4 m, height: 0.2-0.25, length: 8-10 m). Mostly, measurements in production can be performed on an immovable slab for 3-5 minutes. During roll changes, measurements can be performed for 10-15 minutes. The sensor system works best with long slabs for long measurement time, since the expansion is greater than for short slabs over short measurement time. The system also works best with wide and high slabs since it gives the best radar signals and it is also easier to distinguish the slab in front of the sensor from adjacent slabs. The furnace control system at SSAB (FOCS) will be adjusted from radar measurements by adaptive change. This should lead to better synchronization between the furnace control system and the radar sensors, which should show that boundary conditions (temperature) are better set. In the future, feedback data (temperature measurement of rolled strip) will be used to confirm that the slab has a more even temperature distribution than before. Expectantly, the slab should pass the furnace is shorter time and by that save energy, reduce costs, and increase productivity.

It is quite straightforward to find the difference between estimated by FOCS and measured with radar temperature rate of change of the slab. The major challenge is to understand how and where to change the boundary conditions, which represents the furnace temperatures in different zones. At a first look, Eq. 8-9 looks easy to minimize, but T_{slab} must be compensated for each slab's temperature history, wherefore a furnace control or an equivalent model is needed to calculate the deviations in T_{slab} . More radar sensors give more accurate temperature history of each slab. Even T_{surr} must be compensated differently for each slab, foremost in relation to gas bias and temperature. In the future, it may be possible to use the absolute expansion of the slab to estimate the absolute temperature. Anyhow, radar measurements are the new way to give pointwise feedback to a furnace control system about the temperatures of slabs, blooms, and billet of a specific place in the furnace.

REFERENCES

1. J. Sachs, *Handbook of Ultra-Wideband Short-Range Sensing*, Wiley-VCH, 2012, pp. 32-85.

2. *PREVAS FOCS FURNACE OPTIMIZATION CONTROL SYSTEM*, https://www.prevas.com/download/18.6ad369e14a01dd9f36d40/1421846449602/Focs_Prevas_information_eng.pdf.

3. F. Cverna, *Thermal Properties of Metals*, ASM International, 2002, pp. 9-10.

4. B. Leden: User's Manual STEELTEMP®, MEFOS Metal Working Research Plant, Sweden, (1997)