Minimizing the Cycle Time of a Roller Hearth Furnace for Hot-Forming Die-Quenching

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Abstract. In most hot forming die quenching (HFDQ) processes, roller hearth furnace parameters, including roller speed, blank layout, and zone temperatures, are adjusted by trial-and-error. The resulting solution is always suboptimal and often leads to incomplete austenitization. This paper presents an optimization procedure for an industrial roller hearth furnace for minimizing cycle time, structured around a thermo-metallurgical model used to determine the total heat load, dropout temperature, and austenite phase fraction. Imposed constraints include minimum fraction austenite and burner capacity, and the optimization problem is solved using nonlinear programming. The outcome highlights the potential of improving process efficiency through design optimization, and the importance of high-fidelity metallurgical modelling.

1. Introduction

Hot forming die quenching (HFDQ) produces lightweight body-in-white automotive components from ultrahigh strength steels (UHSS), such as 22MnB5, in order to save weight without compromising crash performance [1-4]. In this process, steel blanks are heated within a continuous roller hearth furnace to induce a phase transformation from the as-received ferrite/pearlite microstructure to ductile austenite [5, 6]. The austenitized blanks are then formed and quenched simultaneously in a water-cooled die. Often the blanks are coated with a protective Al-Si layer (i.e., Usibor® 1500-AS) that prevents oxidation and decarburization. Upon heating the Al-Si layer reacts with iron from the 22MnB5 and forms a permanent Al-Si-Fe coating that enhances paintability and provides long-term corrosion protection.

These processes usually employ continuous roller hearth furnaces of 30-40 m in length, consisting of multiple independently-controlled heating zones, as shown in Figure 1. In order to fully-austenitize blanks and to avoid excessive coating growth, it is essential to understand how the furnace parameters, including roller speed, gap spacing, and zone set-point temperatures, should be adjusted for different part thicknesses and geometries [5, 7]. In practice, this is done by trial-and-error, a costly, time-consuming procedure that may yield an adequate, but invariably suboptimal solution since an intuitive understanding of the connection between the furnace parameters and blank heating is elusive.

Design optimization is well-suited to address these deficiencies. In this procedure the design problem is transformed into a mathematical problem of multivariate minimization by specifying a vector of design parameters, $\mathbf{x}$, and an objective function, $F(\mathbf{x})$, that quantifies the “goodness” of the design so
that the objective function is minimized by the optimal design outcome. The set of parameters that minimizes the objective function, \( \mathbf{x} = \arg\min_{\mathbf{x}} [F(\mathbf{x})] \), thus specifies the optimal design. Additional constraints can be imposed on \( \mathbf{x} \) to ensure that the design conforms to the process requirements and can be implemented in an industrial setting. The final solution is superior to one found through trial-and-error, and is identified in less design time.

\[
x_{14} = V
\]

\( x_1 = T_{z1} \) \( x_2 = T_{z2} \) \ldots \( x_{12} = T_{z12} \)

\( x_{13} = L_c \)

\( b_{g,\text{min}} \)

**Figure 1.** Schematic of the roller hearth furnace optimization problem: (a) zone temperatures and blank velocity; (b) blank load and cycle length.

This technique has been used to design furnace-based heating processes for a wide range of metallurgical applications [8-10]. Notably, Heng et al. [11] identified the zone temperatures that minimized the energy consumed by a continuous roller hearth furnace used to austenitize steel, based on a heat transfer model that considered only the change in sensible energy of the load when calculating the steel heating profile. Ganesh et al. [12] extended this work by incorporating an austenite growth kinetics model into a design optimization of the same furnace. The difference between the optimal solutions obtained using these two models highlights the importance of considering both the load temperature as well as the metallurgical transformations occurring within the steel.

Specific application of optimization to HFDQ has been more limited. Twynstra et al. [9] identified the power settings for electrical panel heaters that provided the most uniform irradiation of Usibor® 1500-AS blanks in a batch furnace. Tonne et al. [13] performed a multi-objective optimization on a roller hearth furnace used for HFDQ. Their model considered only the sensible energy of the load (Usibor® 1500-AS). The blanks were modelled as grey, and a least-squares minimization procedure was carried out to identify the specific heat and total emissivity from temperature measurements on instrumented blanks. These parameters were then incorporated into the optimization model, which was used to minimize energy consumption and process cycle time, with constraints on the blank heating profile used to ensure adequate austenitization and intermetallic layer growth. These results are suspect, however, since the thermophysical properties obtained from the least-squares minimization were shown to differ considerably from those of Usibor® 1500-AS [7, 14].

This paper presents an optimization procedure for minimizing the cycle time for a twelve-zone, roller hearth furnace used to austenitize Usibor® 1500-AS blanks. The optimization scheme incorporates a thermo-metallurgical model consisting of a heat transfer submodel, used to calculate the blank temperature, and a kinetics model that provides the volumetric fraction of austenite at any instant during the process. The two models are coupled via the temperature-dependent kinetics of austenite formation, \( \frac{d\theta}{dt} \), and the latent heat of austenitization, \( \Delta h_\theta \), in the energy equation. Two candidate kinetics models are considered: (1) an empirical first-order model derived from constant-heating rate dilatometry measurements [6]; and (2) a semi-empirical annealing model that explicitly simulates nucleation, growth, and impingement of austenite grains [15]. Design parameters consist of the blank speed, spacing between the batches, and zone set point temperatures. Linear and nonlinear constraints enforce a minimum gap spacing between batches, minimum fraction austenite, and maximum/minimum zone set point temperatures. Significantly different performance is obtained from the optimal solutions found using the candidate austenitization submodels, highlighting the need for further research in this area. Nevertheless, in both cases the optimal solution is superior to the nominal solution found through trial-and-error, highlighting the effectiveness of this procedure.
2. Optimization Problem

The analysis focuses on a 30-m long roller hearth furnace used to austenitize patched Usibor® 1500-AS blanks. The furnace is subdivided into 12 equally spaced heating zones. Each zone is heated by multiple radiant tubes, as conceptually shown in Figure 1 (a); specified zone temperatures are maintained through hysteresis control of the tube firing rates based on input from a thermocouple located within each zone. The blanks are loaded on ceramic rollers in batches, as shown in Figure 1 (b). The batch length and mass are prescribed, with a minimum gap between batches to facilitate blank loading and unloading.

The first step in optimization is to recast the design problem as a constrained multivariate minimization problem. In this case, the objective function to be minimized is the cycle time, i.e. the interval between batches leaving the furnace. The 14 design parameters are shown in Figure 1, and consist of the zone temperatures, $x_{13}$-$x_{14}$, the cycle length, $x_{13}$, comprising the batch and gap lengths, and the roller speed, $x_{14}$. The cycle time is related to the roller velocity and cycle lengths by

$$F(x) = F(x_{13}, x_{14}) = x_{13} / x_{14} \quad (1)$$

Constraints must be imposed to ensure that the solution fulfills the functional requirements of the HFDQ heating stage, i.e. austenitizing 22MnB5 and, in the case of Al-Si coated steels, formation of an intermetallic layer having the desired properties. The constraints are summarized in Table 1.

### Table 1. Process constraint for the furnace optimization.

| Constraint | Condition | Description |
|------------|-----------|-------------|
| $c_{L1}$-$12$ | $T_{Z,i,min} \leq x_i \leq T_{Z,i,max}, \ i=1..12$ | Max/min zone temperatures |
| $c_{L13}$ | $x_{13} - L_b \geq L_g, min$ | Min batch spacing |
| $c_{N1}$-$12$ | Eq. (2) | Zone burner capacity |
| $c_{N13}$ | $T_{700°C} \geq 30 s$ | Austenitization |
| $c_{N13a}$ | $f_{t,exit} \geq 0.95$ | Austenitization (alt.) |
| $c_{N14}$ | $T_{b,exit} \leq 700°C$ | Layer growth |
| $c_{N15}$ | $T_{exit} \leq 950°C$ | Burning of Al-Si coating |

A constraint is placed on the cycle length, to enforce a minimum gap length between batches, and bound constraints are specified on the zone temperatures. Additional constraints are imposed to ensure that the heating requirements of each zone do not exceed the corresponding burner capacity, i.e.

$$\dot{Q}_{b,exit,i} \leq \frac{1}{\eta_{th}} \left( m_b \left( c_p (T_{b,i+1} - T_{b,i}) + \Delta h_i (f_{t,i+1} - f_{t,i}) \right) \right) + \dot{Q}_{loss,i}$$ \quad (2)

where $\eta_{th}$ is the thermal efficiency of the radiant tubes (typically ~70%), $m_b$ is the mass flow rate of blanks through the furnace, $c_p$ is the specific heat, $T_b$ is the blank temperature, $f_i$ is the austenite phase fraction, indices $i$ and $i+1$ denote the state of the blank at the beginning and end of each zone, and $\dot{Q}_{loss,i}$ accounts for heat losses through the furnace walls and door, summarized in Table 2. The latent heat of austenitization is assumed to be 30 kJ/kg, derived from the transformation energies for pearlite-to-austenite (85 kJ/kg [16]) and ferrite-to-austenite for pure iron (16.11 kJ/kg [17]), assuming the steel is 80%/20% ferrite/pearlite in the as-received state.

### Table 2. Heat loss through the walls in each zone of the roller hearth furnace, in units of [kW].

| $i$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-----|---|---|---|---|---|---|---|---|---|----|----|----|
| $Q_{loss,i}$ | 36 | 8 | 8 | 8 | 9 | 18 | 18 | 18 | 18 | 18 | 18 | 36 |

Additional constraints are imposed to ensure that the blank is adequately austenitized, and that the intermetallic layer is fully formed but not excessively thick. Since the austenitization and coating states
cannot be measured directly, surrogate constraints are imposed on the heating curve. For example, it is commonplace to ensure that the blank is soaked at a temperature exceeding 900°C for at least 30 minutes [1, 3, 18] to allow adequate austenitization, and the maximum heating rate does not exceed 12 K/s (or 700°C after 60 s of heating) [2, 19]. The latter constraint is sometimes mistakenly assumed to prevent the Al-Si coating from melting, but Grauer et al. [2] show that the coating liquefies under all conditions, and instead this constraint was specified in the original Usibor patent to prevent excessive layer growth. Finally, the blank temperature should not exceed 950°C, to avoid burning of the eutectic Al-Si coating.

While the bound constraints on the zone temperatures and cycle length are easy-to-implement through nonlinear programming, the other constraints are nonlinear functions of \( x \) and cannot be imposed directly. Instead, these constraints are redefined in terms of weighted logarithmic barrier penalty functions, added to the objective function, which penalize the objective function if any constraint is violated. Thus, the following optimization problem is considered:

\[
\min F(x, \mu) = \frac{x_{13}}{x_{14}} + \mu \sum_{j=1}^{15} \log \left[ c_{nj}(x) \right]
\]

subject to:

\[
x_{1b} \leq x_j \leq x_{ub}, i \in [1,12] \]

\[
x_{13} - L_b \geq L_{b,min}
\]

where \( \mu \) is the weight applied to the logarithmic barrier function and \( c_{nj}(x) \leq 0 \) are the nonlinear constraints. For this particular problem, \( \mu = 10^3 \) and the NLP was solved in MATLAB\textsuperscript{TM} using an interior-point algorithm [20].

### 2.1 Blank Thermo-metallurgical Model

The nonlinear design constraints, \( C_{N1-15} \), require knowledge of the blank temperature, and in the case of \( C_{N13,a} \), the instantaneous phase fraction austenite. The blank is assumed to be thermally-lumped, and the heating profile is calculated by solving Eq. (3) [5]

\[
\rho c_p w \frac{dT}{dt} = 2h \left[ T_{Z,i} - T_b(t) \right] + 2\sigma \left[ \alpha T_b(t)^4 - \epsilon T_b(t)^4 \right] - \rho w \Delta h \frac{df_g}{dt}
\]

where \( \rho \) and \( c_p \) are the temperature-dependent density and specific heat of 22MnB5, \( w \) is the blank thickness, \( h \) is the average convection coefficient over the top and bottom surfaces, \( \sigma \) is the Stefan-Boltzmann constant, and \( \alpha \) and \( \epsilon \) are the total absorptivity and total emissivity of the blank, respectively. The radiative properties vary dramatically as the Al-Si layer melts, re-solidifies into the Al-Si-Fe intermetallic layer, and then grows/roughens [14]. The emissivity also varies due to the shift in spectral incandescence towards shorter wavelengths as \( T_b \) increases.

While the left-hand side of Eq. (3) accounts for the increase in sensible energy of 22Mn5 during heating, the last term on the right-hand side is the increase in latent energy due to austenitization. Previous studies either ignore this term [13], or heuristically-increase \( c_p \) by “distributing” \( \Delta h \) between the austenite start and finish temperatures, \( T_{Ac1} = 720°C \) and \( T_{Ac3} = 880°C \) [7, 9]. In contrast, here we exploit two recently-developed austenitization kinetic models to obtain the instantaneous austenite phase fraction, \( f_g \), which is then used to find the latent heat term in Eq. (3).

Di Ciano et al. [6] recently proposed an empirically-derived, first-order kinetics model

\[
\frac{dg}{dt} = A \exp \left[-\frac{E_A}{RT_b(t)} \right]
\]

and

\[
f_g(t) = 1 - \exp \left[-g(t) \right]
\]

where \( g(t) \) is an intermediate variable and \( R = 8.314 \text{ [J/(mol-K)]} \) is the universal gas constant. Model parameters \( E_A \) and \( A \) were inferred from dilatometry measurements on 22MnB5 coupons heated at constant rates within a Gleeble thermomechanical simulator. For heating rates relevant to furnaces (1-5 K/s), these parameters were found to be \( E_A = 402 \text{ kJ/(mol-K)} \) and \( A = 3.42 \times 10^{18} \text{ s}^{-1} \). Predicted austenite
Two scenarios for the order model prediction: the first one, which predicts inadequate austenitization. This reflects the current industrial practice, and the other model parameters are defined in Ref. [15]. The optimization models that incorporate di Ciano et al.’s model [6], which presumes that austenitization proceeds to completion, Li’s model is intended to simulate intercritical annealing and features a detailed treatment of austenite nucleation, grain growth, and grain impingement. This amounts to solving four coupled differential equations that govern the nucleation sites, volume growth, extended austenite volume fraction (neglecting impingement), and the real austenite phase fraction, $f_a$. The other model parameters are defined in Ref. [15]. The optimization models that incorporate di Ciano et al.’s model [6] and Li et al. [15] metallurgical submodels will, hereafter, be referred to as models A and B, respectively.

3. Results and Discussion
The nominal furnace settings, summarized in Table 3, served as an initial point for the optimization procedure. The roller speed and batch spacing corresponds to a cycle time of $F(x^0) = 29$ seconds. Optimization proceeds from the initial point until the default convergence criteria, which approximately satisfy the Karush-Kuhn-Tucker conditions, are met. Optimization progress is summarized in Figure 2.

The optimal solutions are summarized in Table 4 for Models A and B. Two scenarios for the austenitization constraint are considered: the first one is a temperature-based criterion, $C_{N13}$, which reflects the current industrial practice, and the second explicitly enforces a minimum-modelled austenite phase fraction at the furnace exit, $C_{N13a}$. The optimal furnace parameters, and the optimized cycle time, for these four scenarios differ greatly. The biggest improvement in cycle time is seen from Model B and constraint $C_{N13}$, of 18 seconds faster than the nominal solution, while the improvement realised using constraint $C_{N13a}$ is significantly less. It is worth noting, however, that, even though $C_{N13}$ is satisfied, Model B predicts inadequate austenitization. In the case of Model A, the opposite is true; the constraint based on predicted austenitization allows for a slightly shorter cycle time than does the temperature-based constraint. This reflects the fact that the temperature-based constraint is more conservative, and the first-order model predicts adequate austenitization without requiring the blank to spend 30 s above 900°C.

Table 3. Initial start point, $x_0$, $x_1^0$-$x_{13}^0$ [°C], $x_{14}^0$ [m], $x_{14}^0$ [cm/s], and cycle time [s].

| $x_1^0$ | $x_2^0$ | $x_3^0$ | $x_4^0$ | $x_5^0$ | $x_6^0$ | $x_7^0$ | $x_8^0$ | $x_9^0$ | $x_{10}^0$ | $x_{11}^0$ | $x_{12}^0$ | $x_{13}^0$ | $x_{14}^0$ | $F(x^0)$ |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|----------|----------|----------|--------|
| 815    | 825    | 850    | 855    | 880    | 920    | 930    | 925    | 920    | 915      | 1.745    | 6.0      | 29       |          |

Table 4. Optimal solutions and associated cycle time for the optimization problem based on the two candidate kinetic models and nonlinear constraints $C_{N13}$ and $C_{N13a}$.

| $x_1^*$ | $x_2^*$ | $x_3^*$ | $x_4^*$ | $x_5^*$ | $x_6^*$ | $x_7^*$ | $x_8^*$ | $x_9^*$ | $x_{10}^*$ | $x_{11}^*$ | $x_{12}^*$ | $x_{13}^*$ | $x_{14}^*$ | $F(x^*)$ |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|----------|----------|----------|--------|
| A      | $C_{N13}$ | 842    | 842    | 856    | 860    | 879    | 906    | 906    | 908     | 908      | 907      | 906      | 903      | 1.8     | 13.2    | 13      |
|        | $C_{N13a}$ | 856    | 854    | 861    | 863    | 878    | 896    | 896    | 896     | 896      | 897      | 896      | 895      | 1.8     | 14.3    | 12      |
| B      | $C_{N13}$ | 891    | 877    | 871    | 871    | 876    | 876    | 876    | 867     | 867      | 873      | 876      | 878      | 1.8     | 16.0    | 11      |
|        | $C_{N13a}$ | 819    | 828    | 851    | 856    | 880    | 918    | 918    | 926     | 926      | 922      | 918      | 913      | 1.8     | 7.1     | 25      |
Further insights can be obtained from the optimized heating and austenitization profiles, shown in Figure 3. A comparison of Figures 3 (a) and (b) confirms the fact that, when Model A is used, constraint \( c_{N13} \) is more conservative than \( c_{N13a} \). In fact, Model A predicts that the blank is nearly fully-austenitized before the blank even reaches \( T_{AC3} \), since most of the austenitization takes place close to the \( AC_1 \) temperature, as reported by Jhajj et al. [7].

In contrast, Model B generally predicts a much slower rate of austenitization. In fact, according to this model, the temperature-based constraint, \( c_{N13} \), is insufficient to ensure full austenitization of the steel; the blank is only 80% austenitized as it leaves the furnace, even though its temperature has exceeded \( T_{k3} \). Consequently, Model B requires higher zone temperatures, longer residence time, and hence a longer cycle time, compared to the other three scenarios, to adequately austenitize the blank.

The optimal zone temperatures found using Models A and B are higher than the nominal case for the first five zones to promote austenitization earlier in the heating process, while preventing excessive Al-Si coating growth. Interestingly, the 12 K/s constraint is inactive for all four optimal solutions. The optimal solution with Model A in general suggests that high zone temperatures from Zones 6-12, are not needed as adequate austenitization is achievable with lowered operating conditions with double the blank speed. In contrast, the optimal solution found with Model B generally has higher zone temperatures. High zone temperatures, from Zones 6-12, are needed to transform pearlite and ferrite into austenite, while promoting volumetric growth of the austenite grains. A notable difference between the first-order kinetics model and the detailed physics model is that the latter includes declining rate of

![Figure 3](image-url)
austenitization due to grain impingement, which may account for the slower rate of austenitization at higher temperature [15]. The differences in the performance of Models A and B, and the austenitization constraints, highlights the crucial role that the kinetics model plays when selecting feasible furnace parameters. This result was also highlighted by Ganesh et al. [12], in their optimization study of austenitizing roller hearth furnaces.

4. Conclusion and Future Work

Currently, the parameters of furnaces used in HFDQ processes are set through trial-and-error, often resulting in suboptimal solutions, since the complexity of the problem precludes an intuitive connection between these parameters and blank austenitization. This study addresses this problem by proposing an optimization methodology based on a thermo-metallurgical model of blank heating and austenitization. This model is comprised of a heat transfer submodel, and two candidate austenite kinetics submodels: a first-order empirical model; and one that explicitly accounts for nucleation, growth, and impingement. Blank speed, cycle length and zone temperatures are optimized to minimize the cycle time. A set of linear and nonlinear constraints were imposed to ensure satisfactory austenitization and the Al-Si layer transformation and growth.

Two austenitization constraints are considered in this study: one based on soaking time; and one on modelled austenite formation within the blanks leaving the furnace. The performance of the optimal solutions differed depending on the kinetics model and constraint. In general, the first-order model provides greater improvements compared to the physics-based kinetics model, since the latter predicts a much slower rate of austenitization, and inadequate austenitization if a soak-time constraint is applied. In the context of the first-order model, the constraint based on the austenitization volume faction produces a shorter cycle time compared to a defined soak time, since the latter is more conservative. These findings indicate that the austenitization constraint and kinetics model are vital when selecting the operation parameters that will minimize the cycle time while ensuring complete austenitization.

Future work will focus on incorporating the transformation of the Al-Si coating during the heating cycle to prevent excessive coating growth and potentially decrease pollution to ceramic rollers. In parallel, the optimization model will be improved by considering a multi-objective scheme that minimizes the energy consumption and cycle time while ensuring batches are fully austenitized. Since the optimal solution is heavily dependent on the austenitization constraints and kinetics model, further research will be devoted into better understanding how the austenite kinetics is related to the heat transfer.

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References

[1] Karbasian H and Tekkaya A E 2010 “A Review on Hot Stamping”, J. Mater. Process. Technol. 210(15), pp.2103-2118.
[2] Grauer S J, Caron E J F R, Chester N L, Wells M A and Daun K J 2015 “Investigation of Melting in the Al–Si Coating of a Boron Steel Sheet by Differential Scanning Calorimetry”, J. Mate. Process. 216, pp.89-94.
[3] Güler H 2013 “Investigation of Usibor 1500 Formability in a Hot Forming Operation”, Mater. Sci. 19(2), pp.144-146.
[4] Altan T 2011 “Hot-Stamping Boron-Alloyed Steels for Automotive Parts”, Stamp. J. 12, pp. 40–41.
[5] Verma M, Culham J R, Di Ciano M and Daun K J 2017 “Development of a Thermo-Metallurgical Model to Predict Heating and Austenitization of 22MnB5 for Hot Forming Die Quenching”, ASME 2017 IMECE, American Society of Mechanical Engineers (Florida, Miami, USA).
[6] Di Ciano M, Field N, Wells M A and Daun K J 2018 “Development of an Austenitization Kinetics
Model for 22MnB5 Steel”, JMEPEG, 27(4), pp. 1792-1802.

[7] Jhajj K S, Slezk S R and Daun K J 2015 “Inferring the Specific Heat of an Ultra High Strength Steel During the Heating Stage of Hot Forming Die Quenching, through Inverse Analysis”, Appl. Therm. Eng. 83, pp.98-107.

[8] Chakrborti N, Deb K and Jha A 2000 “A Genetic Algorithm Based Heat Transfer Analysis of a Bloom Re-heating Furnace”, Steel Research Int., 71(10), pp.396-402.

[9] Twynstra M G, Daun K J, Caron E, Adam N and Womack D 2013 “Modelling and Optimization of A Batch Furnace for Hot Stamping”, Proceedings of the ASME 2013 Heat Transfer Summer Conference (Minnieapolis, MN, USA).

[10] Pal D, Datta A and Sahay S S 2006 “An Efficient Model for Batch Annealing using a Neural Network”, Mate. and Manuf. Processes, 21(5), pp.567-572.

[11] Heng V R, Ganesh H S, Dulaney A R, Kurzawski A, Baldea M, Ezekoye O A and Edgar T F 2017 “Energy-Oriented Modeling and Optimization of a Heat Treating Furnace”, J. Dyn. Sys., Meas., Control, 139(6), p.061014.

[12] Ganesh H S, Edgar T F and Baldea M 2017 “Modeling, Optimization and Control of an Austenitization Furnace for Achieving Target Product Toughness and Minimizing Energy Use”, J. Process Control. (in press)

[13] Tonne J, Clobes J, Alsmann M, Ademaj A, Mischka M, Morgenroth W, Becker H and Stursberg O 2013, “Model-Based Optimization of Furnace Temperature Profiles with regard to Economic and Ecologic Aspects in Hot Stamping of 22MnB5”, in 4th Int. CHS2 (Lulea, Sweden) pp. 177-184.

[14] Shi C, Daun K J and Wells M A 2015 “Spectral Emissivity Characteristics of the Usibor® 1500P Steel During Austenitization in Argon and Air Atmospheres”, Int. J. Heat and Mass Transfer, 91, pp.818-828.

[15] Li N, Lin J, Balint D S and Dean T A 2016 “Modelling of Austenite Formation During Heating in Boron Steel Hot Stamping Processes”, J. Mater. Process. Technol., 237, pp.394-401.

[16] Krielart G P, Brakman C M and Zwaag S 1996 “Analysis of Phase Transformation in Fe-C Alloys using Differential Scanning Calorimetry”, J. Mat. Sci., 31, pp. 1501-1508.

[17] Stull D R and Prophet H, JANAF Thermochemical Tables, No. NSRDC-NBS-37

[18] Naderi M, Saeed-Akbari A and Bleck W 2008 “The Effects of Non-isothermal Deformation on Martensitic Transformation in 22MnB5 Steel”, Mat. Sci. Eng. A, 487(1-2), pp.445-455.

[19] Kolleck R, Veit R, Hofmann H and Lenze F J 2008 “Alternative Heating Concepts for Hot Sheet Metal Forming”, Ist Int. CHS2 (Kassel, Germany) pp. 239-246.

[20] Waltz R A, Morales J L, Nocedal J and Orban D 2006 “An Interior Algorithm for Nonlinear Optimization that Combines Line Search and Trust Region Steps”, Math. Program. Series A, 107(3), pp.391-408.