Energy-efficient vacuum carburising of drill bit parts

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M Yu Derevyanov, M Yu Livshitc, E A Yakubovich

Samara State Technical University, 244 Molodogvardeiskaya St., Samara, 443100, Russia

E-mail: mder2007@mail.ru

Abstract. An alternance optimisation method-based energy-efficient technology of vacuum carburising of drill bit parts is proposed. Criteria for optimisation of vacuum carburising process are formulated and proven based on energy consumption analysis; such criteria define energy efficiency of the strengthening process. The acquired control algorithms based on energy efficiency criteria allow dramatically reducing carburising process duration to increase the vacuum oven capacity, to decrease energy consumption, and to enhance production quality.

1. Introduction

The problem of increasing reliability and durability of drill bits is a complex one. One widely used solution of this problem is strengthening of drill bit parts surface by thermochemical treatment [1-7] using vacuum carburising in saturated atmosphere produced by acetylene dissociation at 1050°C and 10^{-1} mbar: this thermochemical treatment process has a number of advantages in comparison with others including absence of oxidation of parts, enhanced metal microstructure, and relatively short process duration contributing to flexibility and cost effectiveness of the process for application in mass production. The characteristics of the strengthened layer are largely dependent on carbon distribution profile over the part depth. Traditional carburisation modes assume selection of fixed thermal and chemical impact parameters [1-3,5,7-9]. As an alternative to this approach, a methodology of optimisation of vacuum carburisation process control is proposed; this methodology allows obtaining a controlled profile of carbon distribution over the strengthened layer at the same time ensuring maximal energy efficiency of the process.

The vacuum carburising process involves obtaining the carbon concentration distribution over the strengthened surface layer $C(x,t)$ as required in accordance with operating requirements.

The carbon concentration profile $C(x,t)$ defines distribution of strength, ultimate stress point, and wear resistance over the part depth [10-12].

The main factors contributing to energy consumption during the vacuum carburisation process are the following [14] (Fig. 1):

- part heating, accounting for about 60% of energy consumption during the part production
- ensuring carburisation conditions, including energy consumed in the process of creation of carbon-saturated atmosphere inside the oven, depressurisation and maintaining of operating pressure (dynamic vacuum), ionisation and creation of protective atmosphere, etc.
• preparatory operations, including (un)loading of the part into (out of) the oven, part transfer inside a multi-chamber oven and between units used for final thermal treatment (quenching, tempering).

The partial criteria shown in Fig. 1 define the certain global criterion of energy efficiency:

**Factors of energy saving**

- Minimisation of energy used for heating
- Minimisation of consumption of gas used for carburisation
- Minimisation of gas consumption for creation of protective oxidation-free
- Quickest actions while maintaining the desired carburisation rate
- Quickest vacuum generation rate
- Maximal carbonisation precision

**Figure 1. Vacuum carburisation energy efficiency structure**

### 2. A problem-oriented mathematical model of the vacuum carburisation process

Due to insignificance of the diffusion layer depth \( h \) in comparison with the part thickness, the diffusion process for the majority of treated parts with surface without any small-radius roundings, fillets, etc. may be described using the second Fick’s law as a one-dimensional parabolic edge problem for a semi-endless plate \([10,13]\):

\[
\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2}, \quad t \in (0,\infty), \quad x \in (0,\infty).
\]  

(1)

The boundary conditions most adequately reflecting the physics of carbon transition from the gas phase onto the part surface are boundary conditions of the third kind \([10,13]\):

\[
-D \frac{\partial C(x,t)}{\partial x}\bigg|_{x=0} = \beta(\varphi) \cdot (\varphi(t) - C(x,t))\bigg|_{x=0},
\]

(2)

\[
\frac{\partial C(x,t)}{\partial x}\bigg|_{x \to \infty} = 0, \quad C(x,t)\bigg|_{x \to \infty} = C_0 = \text{const},
\]

(3)

\[
C(x,0) = f(x),
\]

(4)

where \( C(x,t) \) is carbon concentration, per cent; \( t \) is time, seconds; \( x \) is layer depth, meters; \( D \) is diffusion coefficient, \( m^2 \cdot s^{-1} \); \( \beta(\varphi) \) is mass transition coefficient, \( m \cdot s^{-1} \); \( \varphi(t) \) is atmosphere carbon potential, per cent; \( f(x) \) is initial carbon distribution, per cent.

### 3. Formulation of the problem of the most energy efficient control
Local criteria (Fig. 1) which define the operational quality of the process, i.e. carbonisation precision, have the largest impact on the energy efficiency of vacuum carburisation. Not only do large deviations from the specified carbon distribution profile \( C^* \) negatively influence the final cost of the part but they also lead to significant increase of costs for additional part production due to rapid wear caused by low operational quality as well as to energy consumption for production of non-conforming parts and their repair or disposal.

Deviation \( C(x, \tau^{(i)}_t) \) from \( C^* \) exceeding the allowable threshold value \( \rho(x) \) even over a local area \( x \in [0; h] \) leads to increase in crack appearance, decrease in hardness and causes non-conformity of parts [4, 7, 9, 11, 15, 16]. Therefore, a minimax criterion assuming, unlike an RMS criterion, an absolute deviation of the resulting carbon concentration profile from the specified value, must be used as the criterion of optimal energy efficient production.

However, it is neither feasible nor necessary to ensure the precise profile \( C^* \) at the end of the process as in practice, the process is always influenced by a number of uncontrolled disturbances such as variations in initial carbon distribution in steel \( f(x) \), instability of atmosphere gas composition, irregularities in atmosphere flow, etc. Moreover, the specified profile \( C^* \) may not belong to the solutions of the boundary problem (1)–(4) which means it cannot be practically achieved. Therefore, considering actual allowable ranges of parameters and conditions of the model (1)–(4), the required resulting state of the carburisation process is transformed from the specified concentration distribution \( C^* \) to a specific tube-shaped area \( \Omega = \{ C(x, \tau^{(i)}_t) : \varepsilon \leq \mathcal{E} \} \) of allowable deviations \( C^* \pm \rho(x) \) characterised by the following Chebyshev measure [3, 4, 7, 8, 15, 16]:

\[
\varepsilon = \max_{x \in [0; h]} \left| C^*(x) \pm \rho(x) \right|,
\]

where \( |\rho(x)| > 0, x \in [0; h] \). The highest wear resistance is achieved when \( \mathcal{E} \) is minimal.

Condition satisfaction

\[
\min \max_{0 \leq \phi(t) \leq \varphi_{\text{max}} \in [0; h]} \left| C^*(x) - C(x, t) \right|, t = \tau^{(i)}_t,
\]

where \( \tau^{(i)}_t \) is the carburisation process end time that defines the extremum of operating requirements for the vacuum carburisation process.

The problem of achieving the maximal capacity of the vacuum carburisation oven while keeping quality at a satisfying level, i.e. ensuring shortest carburisation duration \( \tau^{(i)}_t \) while meeting the condition \( \varepsilon = \varepsilon_c \), is also relevant for the task of carburisation of mass produced items such as drill bit parts. The reduction of carburisation duration also enhances the metal structure [2, 3, 10, 12].

In case the threshold carbon concentration \( C_{\text{max}} \) is exceeded, a carbide network may appear over the carburised surface. This network is highly fragile and therefore decreases wear resistance of the part, hence the maximal carbon concentration [5, 8, 10, 11] must be limited:

\[
C(x, t) \leq C_{\text{max}}, \forall t \in \left[ 0, \tau^{(i)}_t \right], x \in [0; h].
\]

The design and capacity of vacuum carburisation ovens define limitations for the maximal acetylene consumption as acetylene dissociation defines maximal carbon potential \( \varphi_{\text{max}} \) of the oven atmosphere [4, 5, 7, 9, 10, 12]:

\[
0 \leq \phi(t) \leq \varphi_{\text{max}},
\]

which is viewed as a control input (Fig. 2).
Therefore, for the controlled object (1)–(4) subject to limitations (7), (8) the following tasks are technically feasible:

- quickest actions while maintaining the desired carburisation rate:
  \[
  J_{\tau}^{opt} = \min_{0 \leq \tau(t) \leq \tau_{\max}} \int C(x,\tau_i(t)) \; dx ;
  \]

- maximal carburisation precision:
  \[
  J_{\varepsilon}^{opt} = \min_{0 \leq \varepsilon(t) \leq \varepsilon_{\max}} \max_{x \in [0,6]} \left| C\left(x,\varepsilon_i(t)\right) - C'\left(x\right) \right| , \; t = \varepsilon_i(t) .
  \]

The above tasks are tasks of ensuring optimal control with the movable right side of the trajectory in an infinitely dimensional imperfect area

\[
\Omega = \left\{ C(x,t) : \max_{x \in [0,6]} \left| C\left(x,\varepsilon_i(t)\right) - C'\left(x\right) \right| \leq \varepsilon \right\} .
\]

of allowable resulting states for specified \( \varepsilon = \varepsilon_z \) or maximum achievable \( \varepsilon = \varepsilon_{\min} \) precision in the area of allowable controls of \( i \) th class [10,11,16].

4. Solution of the problems of the most energy efficient control of vacuum carburisation of drill bit parts

A solution of formulated optimisation problems is achieved using the alternance optimisation method [10,11,16] that defines number \( i \) and durations \( \Delta^{(i)}_n \), \( n = 1,2,\ldots,i \) of control consistency intervals \( \varphi(t) = \varphi\left(\Delta^{(i)}_n\right) \) (Fig. 2).

The optimal control problem by the criterion of absolute precision of carbon distribution over the surface layer depth (10) was solved for an actual case of vacuum carburisation of a drill bit roller cone with experimentally defined process precision parameters \( \varphi_{\max} = 4.1(\%) \), \( \beta_1 = 2.22 \cdot 10^{-7} (ms^{-1}) \), \( \beta_2 = 6.94 \cdot 10^{-8} (ms^{-1}) \), \( D = 6.194 \cdot 10^{-11} (m^2s^{-1}) \). As a result, minimal possible errors in the specified control class and corresponding intervals of carbon potential consistency (Fig. 3) were defined.

Fig. 3 shows that the four-interval control \( \varepsilon^{(4)}_{\min} = 0.025(\%) \) ensures error \( \varepsilon_r = 0.05(\%) \) within limits specified by process instructions. Comparison of the total duration of the existing six-period control process suggested by equipment designers and the optimum four-interval control shows an advantage of 4001.6 seconds.
However, the resulting precision sometimes exceeds actual production requirements. Therefore the optimal control problems by the criterion of the quickest action (9) with specified precision (Fig. 4) have been solved for the allowable $\varepsilon_d$ and recommended $\varepsilon_r$ errors. The comparison with the algorithm optimal for the quickest action that satisfies the recommended error threshold with the existing six-interval control satisfying the allowable error shows the time advantage of 4775 seconds.

Figure 3. Optimal vacuum carburisation process control, precision-wise

Figure 4. Optimal vacuum carburisation process control, quickest action-wise
5. Conclusion
The acquired control algorithms based on energy efficiency criteria allow reducing vacuum carburising process duration dramatically which increases capacity of the carburisation oven, decreases energy consumption, and enhances production quality. Test example shows the possibility of practical use of the proposed method to increase the carburizing energy efficiency for drill bits cones provided that the required performance of the products is ensured.

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