Modeliranje in procesna kontrola VAD-postopka

Modelling and Process Control of VAD Treatment

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VAD-proces (vacuum arc degassing) predstavlja danes standardno tehnologijo za izdelavo kvalitetnih jekel. Po podatkih iz literature v svetu deluje že okrog 80 naprav, kapacitete 20 t (Rathy Alloys and Steel) do 180 t (Fabrique de Fer).

Železarna Ravne je inštalirala prvo 50-tonsko VAD-napravo že leta 1983 v novo jeklarno in danes je več kot 80 % celotne proizvodnje vezano na tehnološko linijo: EOP+ VAD+ LITJE.

VAD-naprava v Železarni Ravne ima 8 MVA transformator, ki omogoča ogrevanje taline do 4° C/min pri vakuumu ca. 500 mbar. Vakuumski sistem črpalk in injektorjev omogoča doseg nizkih vrednosti vakuuma (pod 1 mbar) pri maks. porabi pare 5000 kg/h in tlaku 12 barov.

Praktične izkušnje z VAD-napravo so pokazale, da je za optimalno delovanje celotne tehnološke linije potrebno temeljito poznavanje vseh tehnoloških faz, upoštevajoč proizvodni program in nadaljno obdelavo jekla (valjarna+ kovačnica).

V članku so zbrani rezultati dosedanjih raziskav VAD-procesa, in sicer modeliranje termičnega in metalurškega procesa s ciljem razvoja računalniško podprtega sistema vodenja VAD-tehnologije v Železarni Ravne.

1. TEHNIČNE KARAKTERISTIKE VAD-NAPRAVE V ŽELEZARNI RAVNE

VAD-naprava v Železarni Ravne je sestavljena iz naslednjih elementov:

— vakuumska ponev, kapacitete ca. 45 ton (dimenzije: D = 2500 mm, H = 3210 mm) z vgrajenim drsnim zapiralom in argonskim kamnom za vpihovanje plinov. Vakuumska ponev ima več funkcij in služi kot: transportna posoda, peč za ogrevanje taline in v zadnji fazi služi kot livna ponev;

— pokrov za tesnjenje z odprtinami za elektrode, priključek na dozirni sistem, naprava za legiranje in jemanje vzorcev, prirobnica za nošenje zaščitnega pokrova, odprtina za opazovanje procesa in naprava za vpihovanje prašnih materialov;

— regulacijski transformator, moči 8 MVA, z možnostjo izbire napetosti od 120 do 250 V in maks. jakostjo toka 24 kA;

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VAD (Vacuum Arc Degassing) treatment has become a standard technology for the production of high grade steels. To day there are about 80 VAD units operating all over the world ranging in capacity from 20 tons (Rathy Alloys and Steel) to 180 tons (Fabrique de Fer).

Železarna Ravne ironworks commissioned its first 50 ton VAD unit in 1983 already in the new steelwork. To day more than 80 % of production is related to EAF-VAD-CASTING technologic line. The VAD unit has a 8 MVA transformer, heating is carried out at a rate of 4° K/min at a vacuum of 500 mbar. Vacuum is achieved by the use of pumps and ejectors and the final degassing stage is carried out at a level less than 1 mbar. Steam consumption amounts to 5000 kg/hr and the steam pressure is 12 bars.

Operational experience has shown that the optimum operation of the whole technologic line requires a profounded knowledge of all technologic stages taking into account the production program and subsequent working of steel (rolling, forging).

The work presents collected results of investigations of VAD treatment carried out up to now i. e., modelling of thermal and metallurgical process aimed to the development of computer supported process control of VAD technology in Ravne ironworks.

1. MAIN TECHNICAL CHARACTERISTICS OF VAD UNIT

The VAD unit in Ravne ironworks is composed of:

— VAD ladle of 45 tons capacity (diameter 2500 mm, height 3210 mm) with slide gate and flushing plug. The ladle serves for transfer, reheating and pouring;

— cover with openings for electrodes, alloying hopper, sampling device, a flange for the support of protection heat shield, a lance for the injection of powdered materials and observation hole.

— 8 MVA transformer with voltage selection ranging from 120 to 250 V and 24 kA maximum current intensity;

— vacuum system with pumps and ejectors with maximum steam consumption of 5400 kg/h and max. steam pressure of 12 bars.

2. TECHNOLOGIC CHARACTERISTICS OF VAD TREATMENT IN RAVNE

Technologic characteristics of VAD treatment in Ravne ironworks have been described previously[1,2,3]. Therefore, only main stages are given here to facilitate

— vakuumski sistem s črpalkami in injektorskimi napravami z maks. pretokom pare 5400 kg/h in maks. pritiskom pare 12 barov.

2. TEHNOLOŠKE ZNAČILNOSTI VAD-PROCESA V ŽELEZARNI RAVNE

Tehnološke značilnosti izdelave jekel po VAD-procesu v Železarni Ravne bomo opisali le osnovne faze, kar bo olajšalo nadaljnje spremljanje opisa modeliranja VAD-procesa.

Na **sliki 1** je razvidna tehnološka shema izdelave jekla VCMo140 s spremljajočimi fazami, katere opišemo na kratko takole:

— Temperatura taline — T_f v peči pred prebodom 1660° C.

— Po končanem prebodu temperatura taline pade za ca. 44 ± 25° C, v odvisnosti od termičnega stanja ponovce A, v kateri se nahaja celotna talilna skupaj s pečno žlindro.

— Nato sledi transport ponovce A, ki se postavi nad VAD-ponovco (z oznako B) in se izvrši prelivanje taline s ciljem, da se zadrži celotna količina pečne žlindre. Pri tem, kot je razvidno s slike 1, pride do močnega padca temperature, ki znaša v povprečju 98 ± 32° C. V ponovco B se dodajo tudi potrebne legure. Pred naslednjo opera-

further following of the decription of VAD process modelling.

*Technologic scheme of the production of VCMo 140 is seen in **Fig. 1.***

The technology includes the following particular steps:

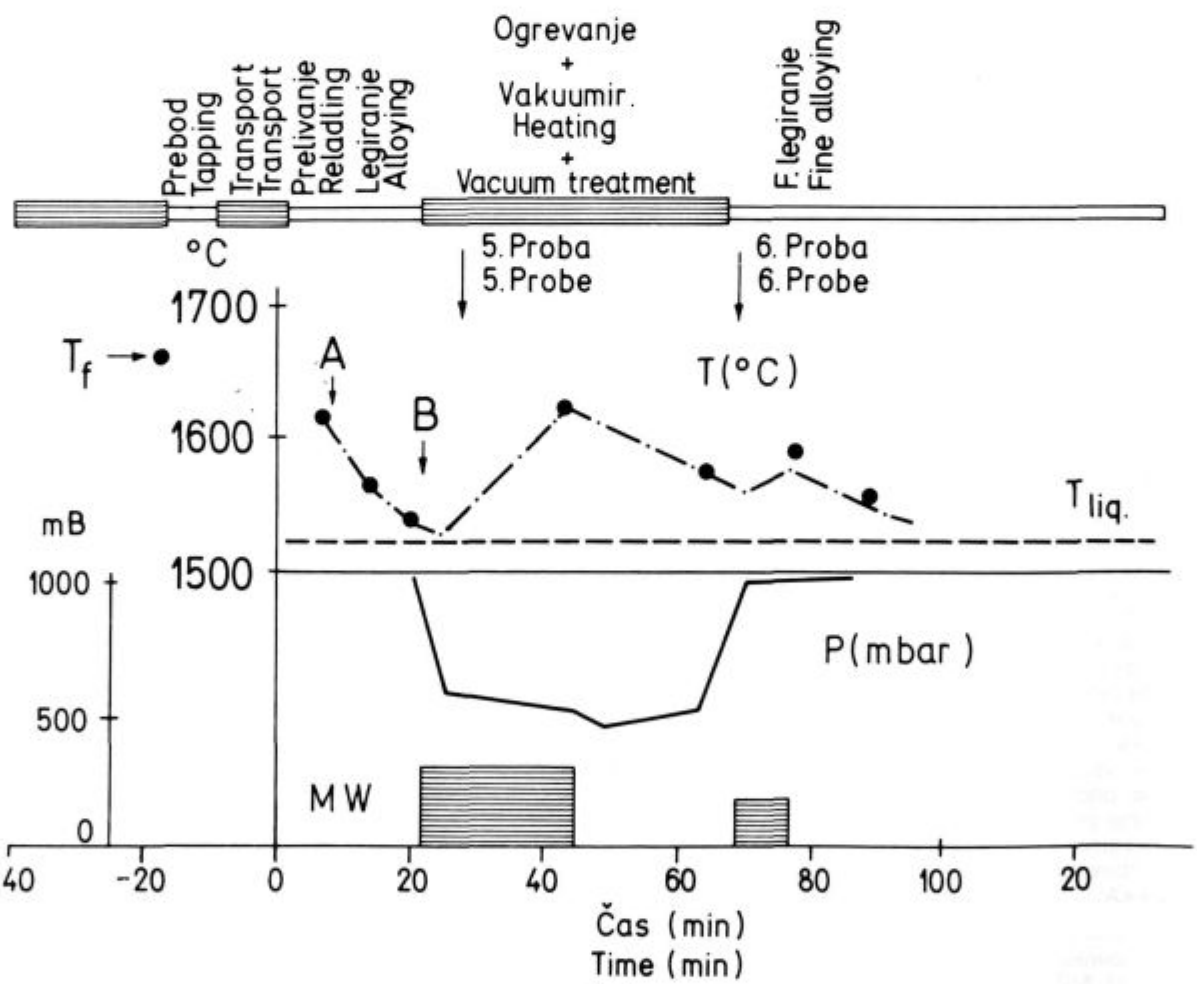
— temperature of melt T_f in furnace before tapping: 1660° C.

— after tapping the temperature drops by 44 ± 25° C depending on thermal state of ladle A which holds metal and furnace slag together.

— transfer of ladle A which is placed above VAD ladle B and reladling the furnace slag remaining in ladle A. Temperature drops by 98 ± 32° C as seen from fig. 1. Necessary alloys are added to ladle B also. Sampling for sample Nr. 5 is followed by temperature measurement.

— Next step is the start of evacuation down to 450—500 mbars with simultaneous heating. The temperature is raised to desired level. After the heating is stopped melt temperature drops with 2° C/min rate on average.

— After removing the cover the sampling, temperature measurement, fine alloying (F. LEGI) and reheating by 10—20° C, if necessary i. e. in dependence on the



Slika 1
Potek osnovnih parametrov pri izdelavi jekla v VAD-napravi

Fig. 1
Change of basic parameters during VAD treatment

cijo se vzame tki. 5. vzorec in se pomeri tudi temperatura taline.

— Naslednja faza je začetek vakuumiranja taline v območju 450—550 mbarov ob istočasnem ogrevanju taline. Pri tem temperatura naraste na željeno vrednost in po izklopu napetosti transformatorja ponovno pada s povprečno hitrostjo ca. 2° C/min.

— Po odpiranju pokrova (zračna atmosfera) vzamemo vzorec taline, pomerimo temperaturo, glede na sestavo taline izvršimo fino legiranje (F. LEGI), in če je potrebno, ponovno ogrevamo za 10—20° C, v odvisnosti od količine potrebnih legur in termičnega stanja taline.

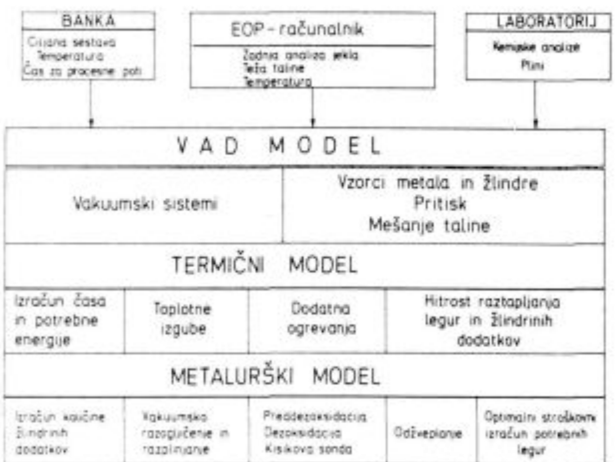
— V celotnem tehnološkem ciklusu je izpuščeno opisovanje faze priprave žlindre, preddezoksidacije, dezoksidacije in odžveplanja jekla, ker to obravnava opis modeliranja.

3. MODEL VAD-POSTOPKA

Zaradi sestavljenosti procesa VAD in vse bolj pogostega uvajanja osebnih računalniških sistemov za kontrolo industrijskih procesov je naša odločitev šla v smeri postopnega osvajanja matematičnih modelov[3].

Na **sliki 2** je prikazana shema strukture VAD-modela, ki sestoji iz:

— termičnega modela,
— metalurškega modela.



Slika 2
Shematska ponazoritev strukture VAD-modela

3.1. Termični model

Prva skupina programskih algoritmov zajema odnose in kontrolo termičnega stanja od preboda taline iz EOP-peči v ponovco A in nato vse do priprave taline za litje.

Termično stanje taline je pod vplivom številnih parametrov, kar je razvidno s **slike 3**.

Na **sliki 3** vidimo za 26 talin gibanje temperature taline v treh ključnih tehnoloških fazah:

T(pr) — temperatura taline tik pred prebodom iz EO-peči.
T(a) — temperatura taline, merjene v ponovci A (transportna ponovca) po končanem prebodu.
T(b) — temperatura taline, merjene v ponovci B, potem ko je dodano ca. 30 kg legur/tono in 8 kg dodatkov/tono za tvorbo nove žlindre.

Potrebno energijo Q_T za ogrevanje taline izračunamo iz toplotne bilance:

$$Q_T = Q_L + Q_S + Q_{TL} + Q_H, \qquad \ldots (1)$$

amount of added alloys and melt temperature, are carried out.

— Slag preparation, predeoxidation, deoxidation and desulphurizing are omitted from the whole technologic cycle since these steps will be considered together with modelling.

3. MODEL OF VAD TREATMENT

Due to the complexity of VAD treatment and increasing introduction of personnel computers for industrial process control it has been decided to start with a gradual development of mathematical models[3].

*The structure of VAD model can be seen in **Fig. 2**. The model is composed of:*

— thermal model and
— metallurgical model.

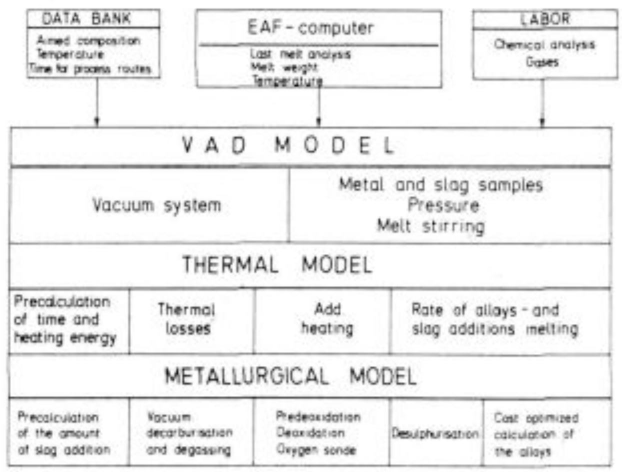


Fig. 2
Scheme of the structure of VAD process model

3.1. Thermal model

First group of algorithms deals with relevant relationships and control of thermal state from tapping from EAF into ladle A to final preparation of the heat for casting.

*Thermal state of melt is influenced by a number of parameters which can be seen from **Fig. 3**.*

Variations in melt temperature for three main technologic stages for 26 heats are seen in fig. 3.

T(pr) — temperature before tapping.

T(a) — temperature of melt measured in ladle A (transfer ladle) after tapping is finished.

T(b) — temperature of melt measured in ladle B after the addition of appr. 30 kg/t alloys and 8 kg/t fluxes for new slag.

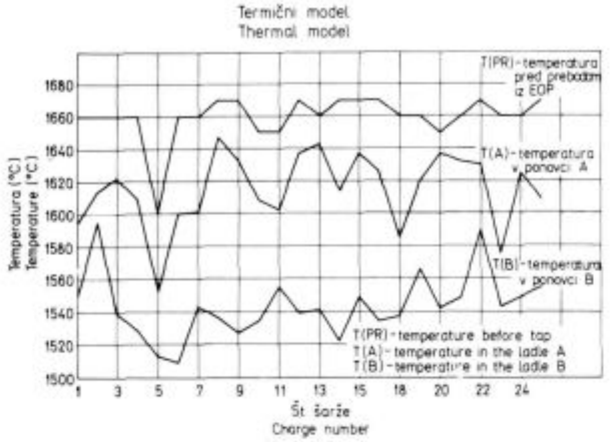
The energy Q_T required for reheating the melt is calculated from the heat balance:

$$Q_T = Q_L + Q_S + Q_{TL} + Q_H \qquad \ldots (1)$$

where:

Q_T — total energy necessary to attain aimed temperature,
Q_L — heat used up for melting aloys added to ladle,
Q_S — heat required for melting of fluxes
Q_{TL} — heat necessary to compensate for heat losses,
Q_H — heat required to raise the temperature from T(B) start to T(B) aim.

*Since the model is very extensive, **Fig. 4** presents only results obtained by the algorithm for the calculation*

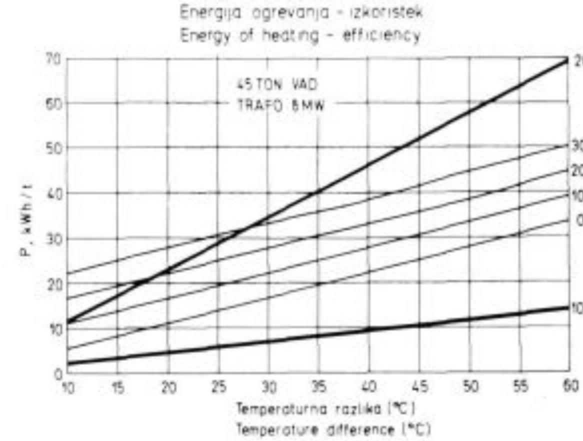


Slika 3

Gibanje temperature taline, in sicer: T(pr) — v EO peči tik pred prebodom, T(a) — v ponovci A po prebodu, T(b) — v ponovci B po prelivanju iz ponovce A in dodatku legur

Fig. 3

Variations in tap, ladle A and ladle B (after reladling and alloy addition) temperature for 24 heats



Slika 4

Algoritem za izračun potrebne energije za ogrevanje (xx/kg/T) = teža dodatkov v ponovco B pred začetkom ogrevanja

Fig. 4

Algorithm for the computation of energy required for reheating (xx/kg/t) = weight kg/ton of alloy added into ladle B before the start of heating

pri čemer pomeni:

Q_T = celotna energija, potrebna za doseganje načrtovane temperature

Q_L = toplota, potrebna za taljenje legur, dodanih v ponovco

Q_S = toplota, potrebna za taljenje žlindrnih dodatkov

Q_{TL} = toplota, potrebna za kompenzacijo toplotnih izgub

q_H = toplota, potrebna za dvig temperature od T(B)-start do T(B)-cilj

Zaradi obsežnosti celotnega modela podajamo le rezultate določevanja algoritma za dvig temperature taline za transformator s parametri: p = 8000 kW, U = 205 V (glej **sliko 4**). S slike je razvidno, da pri izračunavanju potrebne moči igra pomembno vlogo količina dodanih legur. Na podoben način je potrebno upoštevati tudi vpliv ostalih parametrov, kot je to razvidno iz enačbe 1.

3.2. Metalurški model

VAD-proces omogoča zaradi ugodnih pogojev (znižan tlak, mešanje taline, bazična ali nevtralna obloga, bazična žlindra, natančna kontrola kisikovega potenciala) izvajanje številnih reakcij.

Osnovna zahteva za doseg teh ciljev je popolna eliminacija vpliva pečne žlindre, ki ima visoko vsebnost oksidov, kot so $FeO + MnO + Cr_2O_3 + P_2O_5$.

Na **sliki 5** je prikazana primerjava kemične sestave žlindre v treh fazah VAD-procesa.

1. Pon-A: sestava žlindre (Chg. 75672, CK-45) v ponovci A.

2. Dodano: 200 kg CaO + 150 kg sinter-dolomita (približna sestava).

3. Pon-B: sestava žlindre (Chg. 75672, CK-45) v ponovci B po ogrevanju in pred 5. preizkusom).

Sestava žlindre v fazi vakuumske obdelave je izredno pomembna, ker direktno vpliva na obrabo obloge v coni žlindre.

Kemična analiza žlindre je po ogrevanju pokazala, da je največji del Al-dodanega za dezoksidacijo — reagiral s kisikom in ga zato najdemo v žlindri v obliki Al_2O_3. Vsebnost ostalih oksidov v žlindri iz ponovce B je zelo nizka: FeO = 0,48 %, Mn = 0,12, Cr_2O_3 = 0,05.

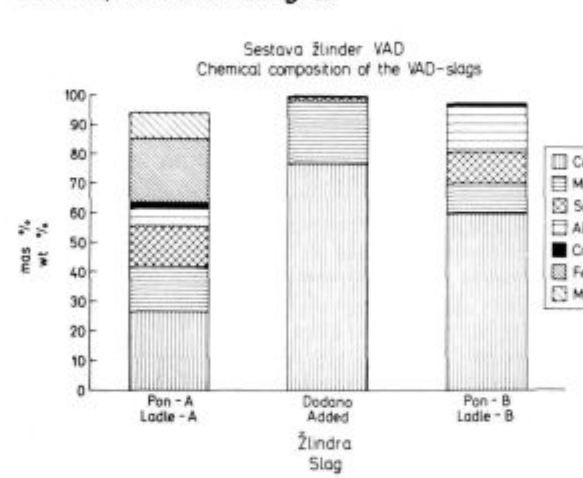
of power required in the case of transformer characteristics: P = 8000 kW, U = 205 V, (see fig. 4). It can be seen that the amount of added alloys plays an important role in the computation of required power. Similarly, the influence of other parameters have to be taken into account as seen from eq. (1).

3.2. Metallurgical model

Due to favorable conditions (lowered pressure, good stirring, basic or inert lining, basic slag, accurate control of oxygen potential) VAD process facilitate a number of reactions.

Basic conditions required for the achievement of these aims is complete removal of furnace slag with a high content of FeO, MnO, Cr_2O_3 and P_2O_3.

*Slag composition in the three stages of VAD treatment is presenteed in **Fig. 5.***



Slika 5

Gibanje sestave žlindre za tri ključne tehnološke faze Pon- A: v ponovci A, Dodano: v ponovco B, Pon- B: v ponovci B po končani obdelavi

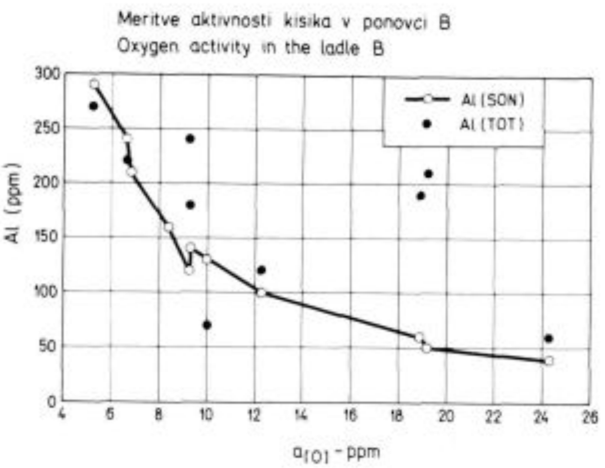
Fig. 5

Slag composition: Ladle A — slag from ladle A, Added — slag to ladle B, Ladle B — at the end of VAD treatment

3.2.1. Kontrola kisika v fazi obdelave taline

Analiza aktivnosti kisika v talini po obdelavi taline v vakuumu je pokazala, da je vsebnost kisika v celoti pod kontrolo vsebnosti Al v talini. Na **sliki 6** se lepo vidi, da lahko na osnovi meritev kisika v talini dokaj natančno kontroliramo vsebnost aluminija.

Analiza kemične sestave žlindre je pokazala, da je aktivnost kisika v talini daleč od ravnotežja z žlindro, kar je pomembno za študij odžveplanja, kot se bo to pokazalo v naslednjem poglavju.



Slika 6
Odvisnost vsebnosti Al(sonda) oz. Al(celotni) od aktivnosti kisika v talini

Fig. 6
Relationship between oxygen activity and Al as determined by EMF (Al son) and total Al content of melt in ladle B

3.2.2. Kontrola žvepla v fazi obdelave jekla

Kontrola žvepla postaja vse bolj pomembna zaradi dejstva, da se za številne kvalitete zahteva predpisana sestava žvepla. Vodenje procesa prenosa žvepla iz taline v žlindro ima torej ekonomski pomen, zato je napovedovanje končne vsebnosti žvepla pomembna naloga. Kinetiko odžveplanja lahko definiramo z enačbo:

$$\frac{dS}{dt} = -k_s (S - S_E) \qquad \ldots (2)$$

kjer pomeni:
k_S — konstanta odžveplanja (min^{-1})
S — trenutna vsebnost žvepla v talini
$\mathbf{S}_E$ — ravnotežna vsebnost žvepla (talina-žlindra)

Pri analizi kinetike prenosa žvepla smo vpeljali pojem **»kapaciteta žvepla v žlindri«** in jo označili z oznako:

$$C_{SS} = \frac{(\%S)}{\%\mathbf{S}} \cdot (\%FeO) \qquad \ldots (3)$$

Za VAD-napravo smo uporabili kriterij prostih baz po Jacquemont[4]

$$PB = (CaO + MgO) - (SiO_2 + Al_2O_3), \qquad \ldots (4)$$

ki omogoča izpeljavo analitične funkcije za C_{SS}:

$$n = 11 \qquad r^2 = 99$$

$$C_{SS} = \frac{(\%S)}{\%\mathbf{S}} \cdot (\%FeO) = 0{,}99 \cdot \exp(0{,}1 \cdot PB) \qquad \ldots (5)$$

Naslednji korak je izpeljava algoritma za napoved ravnotežne vsebnosti žvepla:

1. Ladle A — Heat Nr. 75672, steel grade CK-45.
2. Added — CaO 200 kg, burned dolomite 150 kg (appr. composition).
3. Ladle B — slag composition in ladle B after reheating and before 5th sampling. Heat Nr. 75672, grade CK-45.

The composition of slag in degassing stage is very important since it directly influences the lining life in slag line.

Chemical composition of slag after reheating indicates that a major amount of aluminium added for deoxidation has reacted with oxygen. Therefore, it has been found in slag in the form of Al_2O_3.

The content of other oxides in slag of ladle B is very low: FeO 0,48 %, MnO 0,12 %, Cr_2O_3 0,05 %.

3.2.1 Oxygen control

*Analysis of the oxygen activity in the melt after degassing as seen from **Fig. 6** clearly shows that the oxygen is controlled by the aluminium content of melt. It can be seen that the measurement of oxygen activity may be used for determination of the aluminium content of melt.*

Based on chemical composition of the slag it can be concluded that the activity of oxygen in the melt is far from equilibrium with slag, which is important for the following study of desulphurization.

3.2.2. Sulphur control

The control of sulphur is becoming more important because of an increasing number of grades with very precisely specified sulphur content. The control of sulfur transfer from melt to slag has therefore economic significance. Consequently, the prediction of final sulfur content is an important task.

Kinetics of desulphurizing can be defined by equation:

$$\frac{dS}{dt} = -k_S (\mathbf{S} - \mathbf{S}_E) \qquad \ldots (2)$$

where:
k_S — kinetics constant for desulphurizing (min^{-1})
S *— sulphur content of melt*
$\mathbf{S}_E$ — equilibrium sulphur content (slag-melt equil.)

In the analysis of kinetics of desulphurizing we have introduced the term "sulphur capacity of slag" C_{SS}:

$$C_{SS} = \frac{(\%S)}{\%\mathbf{S}} \cdot (\%FeO) \qquad \ldots (3)$$

The criterion of free bases according to Jacquemont[4] has also been used for VAD:

$$PB = (CaO + MgO) - (SiO_2 + Al_2O_3), \qquad \ldots (4)$$

which makes it possible to derive analytic function for C_{SS}:

$$n = 11 \qquad r^2 = 99$$

$$C_{SS} = \frac{(\%S)}{\%\mathbf{S}} \cdot (\%FeO) = 0.99 \cdot \exp(0.1 \cdot PB) \qquad \ldots (5)$$

Next step is derivation of the algorithm for prediction of the equilibrium sulphur content:

$$\mathbf{S}_E = (\mathbf{S}^o + S_{a/10}) \cdot \left(1 + \frac{m_s}{m_l} \cdot \frac{C_{SS}}{\%FeO}\right)^{-1}, \qquad \ldots (6)$$

where:
$\mathbf{S}^o$ — initial sulfur content
$\mathbf{S}_{a/10}$ — sulphur brought by alloy and slag addition
m_S — weight of slag (kg)
m_l — weight of steel (kg)

$$\mathbf{S}_E = (\mathbf{S}^o + S_{a/10}) \cdot \left(1 + \frac{m_s}{m_j} \cdot \frac{C_{SS}}{\% \, FeO}\right)^{-1}, \quad \ldots (6)$$

kjer pomeni:

$\mathbf{S}^o$ — vsebnost žvepla v talini pred začetkom obdelave
$\mathbf{S}_{a/10}$ — vsebnost žvepla, ki ga prinese žlindra in zlitine
m_S — teža žlindre (kg)
m_j — teža taline (kg)

Na osnovi enačb (2), (3) in (6) lahko izpeljemo končno enačbo za napoved žvepla; katere rezultate vidimo na **sliki 7**.

Na osnovi teh rezultatov lahko za izbrane pogoje (teža jekla, sestava žlindre, vsebnost FeO v žlindri) izračunamo potrebno količino žlindre, ki zagotavlja željeno vsebnost žvepla.

4. ZAKLJUČKI

VAD- postopek predstavlja danes ključni tehnološki postopek za ekonomično in tehnološko dognano proizvodnjo kvalitetnih jekel. V kombinaciji z visoko produktivnimi talilnimi agregati (konvertor, UHP-EBT ali UHP-OBT) predstavlja idealno tehnološko linijo[4].

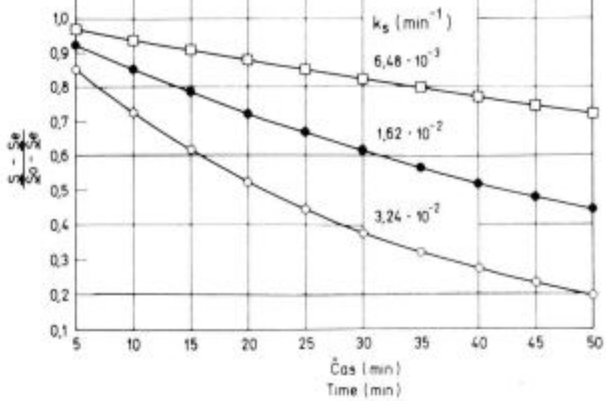
Toda, optimalne učinke je mogoče doseži le pri pravilni izbiri tehnoloških parametrov, pri čemer sta pomembna tako termični kot tudi metalurški model.

Ogrevanje taline mora biti izvedeno na najbolj ekonomičen način, zato je zelo pomembno poznavanje potrebne moči in časa ogrevanja, da bi se tako izognili večkratnim ponavljanjem ogrevanja in maks. izkoristili prednosti obločnega ogrevanja taline.

Zelo pomembna je pravilna izbira sestave žlindre, ki ima največji vpliv na obrabo obloge ponovce, s tem pa so direktno povezani proizvodni stroški.

Modeliranje posameznih tehnoloških faz se je pokazalo kot zelo uporabno orodje, ki omogoča poleg boljšega razumevanja procesa tudi zaokrožitev znanja v obliki uporabne programske opreme.

Na ta način postane lastno znanje uporaben know-how, kar je pogoj za procesno vodenje procesov.



Slika 7

Kinetika odstranjevanja žvepla v pogojih VAD-postopka

Fig. 7

Kinetics of desulphurizing in VAD treatment

*Final equation the results of which can be seen in **Fig. 7** is derived from (2), (3) and (6).*

In this way the amount of slag required to obtain aimed sulphur content can be calculated for selected conditions (weight of melt, slag composition, FeO content of slag).

4. CONCLUSIONS

VAD represents to day a key technologic process for economic and successful production of high grade steel. Combined with high productivity units such as convertor, UHP-EBT or UHP-OBT electric arc furnace it represents the ideal production line[4].

However, optimum results can be achieved only by selection of proper technologic parameters. Therefore the thermal as well as metallurgical model are important.

Reheating of melt has to be carried out in the most economic way which means that the power and heating time required must be known in order to make maxium utilization of vacuum arc reheating and to eliminate the need for additional reheating.

The selection of proper slag is very important in respect to lining life and associated production costs.

The modelling of particular technologic stages is very useful tool for better understanding of the process and for the transformation of knowledge into useful application software. In this way the available knowledge becomes a useful know-how which is precondition for successful process control.

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