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Operational Aspects of Experiences in Vacuum Technology by Production of High Quality Stainless and Alloyed Steels

Praktične izkušnje pri uporabi vakuumske tehnologije pri izdelavi visoko kvalitetnih nerjavnih in legiranih jekel

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Highlights of the technological scheme of manufacturing quality steels as stainless steels in the vacuum by the duplex EAF (electrical arc furnace) + VOD (vacuum oxygen decarburization) process is presented here. Special attention is given to the stage of vacuum oxidation of carbon and chromium and to the use stage of degassing in vacuum. In short feature the VOD computer program is expalained, which enables the effective preparation of the complete technology for VOD - process from 15 to 100 tonnes.

Key words: production of high quality stainless steels by VOD process

Predstavitev tehnološke sheme izdelave kvalitetnih jekel v vakuumu kot so nerjavna jekla po duplex postopku EOP (elektro-obločna peč) + VOD (vakuumsko kisikovo žilavenje). Poseben poudarek je podan na procesno stopnjo vakuumske oksidacije ogljika in kroma ter izkušnje pri uporabi vakuuma. Na kratko bo predstavljen tudi računalniški program oziroma rezultati modeliranja, ki omogočajo hitro in učinkovito pripravo kompletne tehnologije VOD procesa za peči kapacitete 15 do 100 ton.

Ključne besede: izdelava kvalitetnih, nerjavnih jekel po VOD postopku

Introduction

The steel industry faces a number of problems related to an increasing demand for clean steel imposed by the consumer industry as well as increasing costs pressures. For these reasons, the steel industry is in the past reasoning its steelmaking techniques which resulted in a subdivision into two phases, namely:

- *metallurgy in the melter and,*
- *metallurgy in the ladle.*

Accordingly, most of the metallurgical work shifted from the melter to the ladle which became a metallurgical reactor. The great number of techniques developed in the secondary metallurgy is based on the application of complex vacuum systems. Before choosing among these techniques, the steelmaker must be perfectly aware of the objectives to be achieved and the requirements to be satisfied by the steel product and reasonable in price for the customer, while still generating a profit for the steelmaker.

The technology routes for secondary metallurgy are in no way a standardized task, even where the underlying basic processes are identical. The conditions differ too much from shop to shop. The state of technology by production of high quality stainless steels in Slovenia steelworks will be reported in this lexture, highlighting the vacuum processes using a typ case – stainless steel production as an example.

General overview of vacuum processes

The principles of secondary metallurgical processes used the vacuum can be brierfly described as following remarks:

1. Early in the 1950s, the vacuum degassing of molten steel was developed. The purpose was to reduce the hydrogen content in steel and particulary in forging ingots. The best results were achieved by stream degassing during ladle - to – ladle or ladle - to – ingot teeming[1].

2. In 1955 appeared almost simultaneously the **RH** and **DH** processes which led to the development of degassing facilities with much higher throughputs.

3. In 1956 the first argon injection trials were carried out – the method of stirring and heating whilst degassing – to enable large reaction volume necessary and the comparatively high temperature losses incurred led to the development of new advanced metallurgical techniques as: **ASEA-SKF, FINKL, VAD, VOD** combining new inductive stirring, new refracto-

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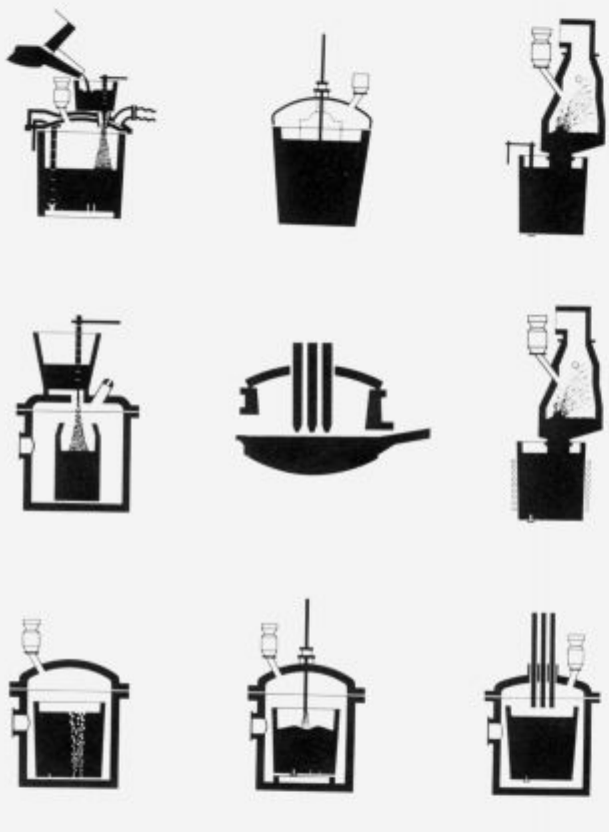

Figure 1: Processing units in the secondary metallurgy
Slika 1: Procesne naprave v ponovčni metalurgiji

ry lining materials, a sliding gate valve and oxygen lancing into the vacuum degassing unit[2-9].

With the industrial application of the above processes, especially vacuum steelmaking equipment passed through several stages of development, see **(Fig. 1)**.

The metallurgical possibilities of vacuum steelmaking have dramatically changed the role of the melting furnace. No longer is it necessary to use a particular type of furnace for the production of particular grades of steel. In other words, all furnace can produce nearly all steels if equiped with a secondary steelmaking facility.

Therefore, the demand for a high availability of the vacuum units is one of the essential factors and the modular concept has proved to be useful in the selection of suitable equipment for each application.

Steel production in Slovenia steelworks was based for more than 120 years on melting in hearth furnaces. During the 1960's and 1970's, the production moved progressively from open heart to electric arc furnace melting.

Vacuum refining began in Steelwork Ravne in 1970 with the installation of the vacuum degassing unit for the removal of hydrogen, particularly for the forging shop. The process did not find a wide application.

Vacuum refining in Ravne began in 1984 with the installation of two VAD/VOD units (20 and 50 tonnes) and some years later also in Jesenice with two 90 tonnes VOD-units with the aim to manufacture more sophisticated steel grades (very low S, O, H, C contents and higher contents in alloys – first of all stainless, dynamo, tool and other high alloyed steels)[10].

1 Some fundamental aspects of metallurgical processes in vacuum

An atmosphere at reduced pressure is one of the purest environments possible. Most of the metallurgical processes are made up of heterogeneous reactions, and the operation in vacuum increases the driving force for interphase mass transfer which is thereby accelerated.

Vacuum processing, compared to air handling, removes the difficulties due to the pick up of oxygen, nitrogen and hydrogen contained in the atmosphere. On the other hand, vacuum processes are concerned with the removal of hydrogen, oxygen, carbon and unwanted non-metallic inclusions from the melt. These benefits are often obtained at the price of same side effects as, for example, the difficulties caused by interaction between melt and refractory linings. Furthermore, just the development of new refractory lining led towards a successful application of vacuum treatment of the molten steel. With introduction of basic linings (magnesite or dolomite) into vacuum ladles began the era of vacuum metallurgical processes.

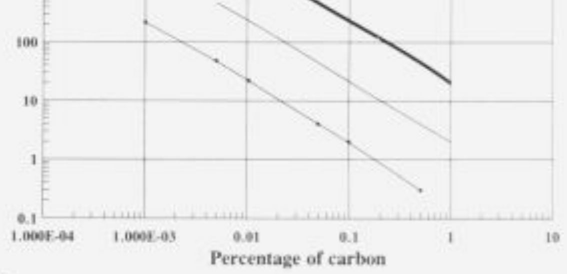

Figure 2: Deoxidation equilibria in liquid iron (1600°C)
Slika 2: Dezoksidacijsko ravnotežje v tekočem železu pri (1600°C)

2 Reactions with carbon and alloying elements

Carbon, probably the most important element in steel, under reduced pressure has a very high affinity towards oxygen, as demonstrated by the following considerations:

For instance, a CO pressure less then 100 Pa is a very effective reaction partner. The principal reaction governing the removal of oxygen by carbon is that producing carbon monoxide:

$$\underline{C} + \underline{O} = CO_g \quad (1)$$

where:

$\underline{C}$, $\underline{O}$ mean elements C and O are in the melt.

It shows, for instance, that at P_{CO} pressure of 1000 Pa and based strictly on thermodynamic considerations, equilibrium oxygen activity is very low (for the C-content about 0,01 % an oxygen activity of about 20 ppm can be expected).

In the practice this level will be never reached because of the reactions between melt and refractory surface. As will be shown later, the vacuum way of producing stainless steel in VOD-process utilizes low partial pressure of carbon monoxide to the control selective carbon oxydation to prevent the imminent risk of the simultaneously chromium oxidation according to the reaction:

$$2\underline{Cr} + 3\underline{O} = (Cr_2O_3) \qquad (2)$$

where:

( ) means in the slag.

The formation of chromium oxide causes the slag to get crusty. Stirring with argon via the porous plug in the ladle bottom to break the slag layer and keep the metal exposed to vacuum is required.

The selective oxidation of carbon in the molten metal depends on the effective pressure P_{CO}. The fraction of oxygen reacting with carbon appears as CO and CO_2 and the rest as metal oxides (SiO_2, MnO, Cr_2O_3, FeO).

3 Use vacuum by production of the stainless steels

The production of stainless steel represents the specific problem of achieving a very low carbon content together with a high chromium content at the lowest cost. VOD-process **(Vacuum Oxygen Decarburization)** is nowdays the most favourable process for stainless steel production. The VOD – refining is carried out in the teeming ladle which has a basic wear lining and is sufficiently insulated to withstand the aggressive slag at high temperature (over 1700 °C) and long heat times (some hours). The conventional way is that the ladle itself with a refractory lined cover constitutes the vacuum chamber or tank degasser of the type VOD-unit (see **Fig. 3**).

Figure 3: Vacuum oxygen decarburization process (VOD)
Slika 3: Vakuumsko kisikovo žilavenje v VOD procesu

Oxygen is supplied at a controlled rate via a consumable refractory lance contained in a vacuum-tight housing on the top of the cover. A water-cooled lance with preferably a laval tuyere is also used. By using the laval tuyere the gas stream is kept concentrated and the distance from the lance tip to the steel surface can be increased to 1200 mm. The process is closely monitored using TV camera mounted on the vacuum cover.

4 Vacuum pumps

For creating vacuum mainly two different types of pumps are in use in the steel industry especially for large units. The most common type is a set of steam ejectors or alternatively a combination of steam ejectors and water ring pumps to save steam consumption, if the cooling water temperature is not too high (max. 32 °C). The suction capacity at low pressure, i.e. the shape of the pump curve is of special interest for the production engineer. **Fig. 4** shows the pump curve for a 30 tonnes ladle–lid system in Steelwork Metal Ravne. The shape of the curve is very important and had to be flat in the lower pressure regions to prevent the influence of small leakages on the working pressure. To prevent or minimize splashing, the chamber pressure must be kept at constant value for example 90 mbar.

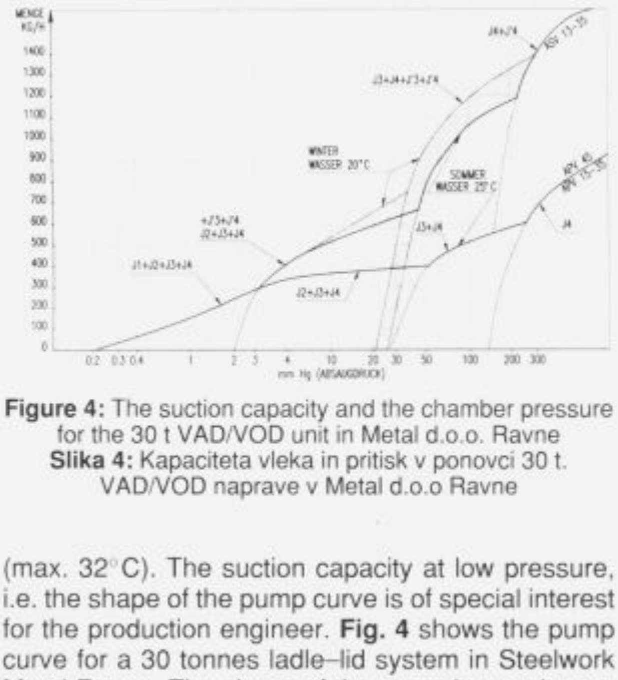

Figure 4: The suction capacity and the chamber pressure for the 30 t VAD/VOD unit in Metal d.o.o. Ravne
Slika 4: Kapaciteta vleka in pritisk v ponovci 30 t. VAD/VOD naprave v Metal d.o.o Ravne

For the heats at Metal Ravne, a 15 tonnes VOD-unit with the oxygen blowing rate about 6 Nm^3 O_2/min, the gas evolution of CO is about 900 kg/h if all oxygen is used for CO-production. For a oxygen yield of 50 % at "end-point" (begin of intensive Cr oxidation) and taking into account the presence of Ar, the *CO + Ar* production will be about 500 kg/h, giving a chamber pressure of 1500 Pa. From practical experiences it is known, that the chamber pressure is a very good

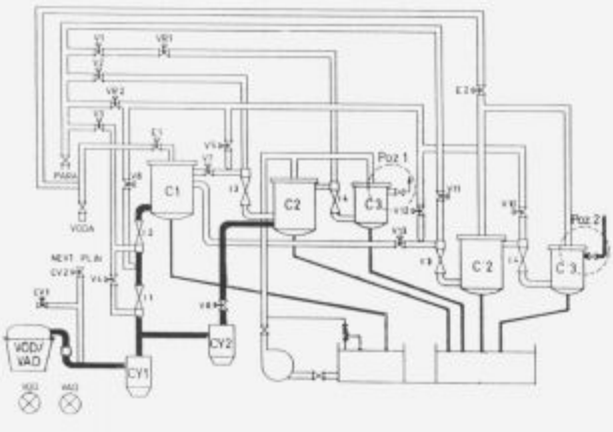

Figure 5: Arrangement of vacuum pump system for the 30 t. VAD/VOD unit
Slika 5: Sistem vakuumskih naprav za 30 t. VAD/VOD napravo

indicator of the boiling reactions and the control of "overboiling" melt which occurr normally at the beginning of the oxygen blowing. To obtain the low working pressures already mentioned the steam ejectors combined with water ring pumps (see example on the **Fig. 5**). As is seen, between the vacuum vessel and the vacuum pump, a gas cleaner/cooler is installed. The cooling is of special importance during the VOD treatment while the gas cleaning always is important for the increased availability of the pumps. The necessary cleaning of the ejectors must be frequent and is difficult.

5 Process control by the production of stainless steels

The vacuum refining process, especially production of stainless steel, present the specific problem of achieving a very high quality at the lowest price. However, from cost and productivity reasons, VOD-process is nowdays a standard way of producing stainless steels in the combination with EAF furnace. The costs of refining treatment, used in the economic assessment depends of the capacity of a unit and use rate, and many other variations of the input prices (the refractory linning, alloys, actual practice, steel grades). In **Table 1** are presented the average total costs for three different capacities of the VOD-units for the production of the steel grade AISI 316L (charge materials, energy consumption, refractory costs, the the vacuum refining treatment, alloys and oxygen + argon).

Table 1: Cost estimate in DM/MELT for the production of the stainless-steel AISI 316L by EAF + VOD route
Tabela 1: Ocena stroškov v DM/talino pri izdelavi nerjavnega jekla AISI 316L po postopku EOP + VOD

VOD-unit	15 tonnes	40 tonnes	90 tonnes
Total (DM)	35.700	90.600	193.950

Comparing the estimated costs reported in **Table 1**, it may be seen that by the production of the stainless-steels, the process control in the plant is of great importance. Technological decisions have to be tacken quickly and exactly since in many cases, for example, the temperature predictions by the smaller VOD-units is very short for manual calculations. The only way to arrive at a result within the time available is to use a computer model. The control of the VOD-process can be divided into two levels:

- Equipment control *(LEVEL 1)*: Including measuring and control of for example the vacuum station, the water-cooled oxygen lance position, alloy-system, etc..
- Process control *(LEVEL 2)*: Including model prediction for oxygen rate, melt temperature and chemical composition during VOD, VCD, slag reduction and finally calculations of alloy and slag additions.

However, from cost and production reasons, very important function has also a third level *(LEVEL 3)* for administration and production planning. A computer model simulation of the **level 2** will be shortly explained.

5.1 General view

The VOD-model for plant process control is developed to serve as an operator guide through the process, assuring an optimum and uniform refining of steel melt in VOD-unit. It will guide and advise the operator through all the different process stages by production of the routine steel grades or operate as an expert system by the introduction of new steel qualities or improvement of the know-how (for example: change oxygen consumable lance with an water cooled oxygen lance).

5.2 Data bank

The data bank contains all the information required for the model simulation for each steel grade according to plant specifications. It contains also all potentially useful data as physical-chemical data for the thermodynamic and kinetic calculations, alloy material characteristics, limited values and so on.

5.3 Process control system

Each steel grade is individually dedicated to a VOD-cycle composed of a number of process steps:

- Oxygen blowing during the VOD-stage,
- Vacuum decarburization,
- Slag reduction,
- Calculation of addition of alloying materials.

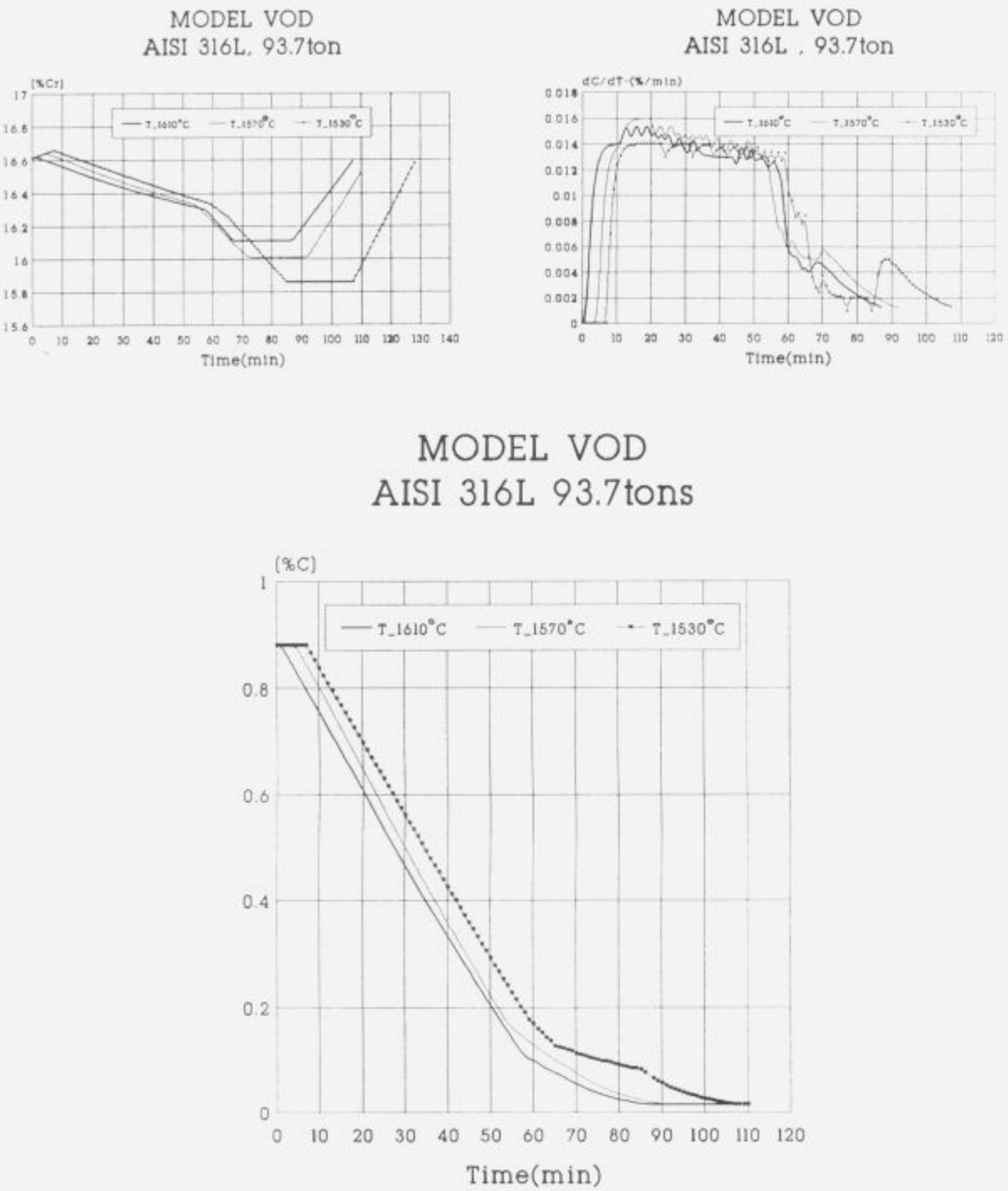

Figure 6: Influence of the initial melt temperature on VOD, VCD and slag reduction processes by the production AISI 316 stainless steel

Slika 6: Vpliv začetne temperature taline na VOD, VCD in redukcijo žlindre pri izdelavi nerjavnega jekla AISI 316

For each process step a number of the influenced input parameters was previously defined, such as: *initial temperature and chemical composition, process time prediction, thermal losses and energy absorbtion during the oxydation period and so on.* **Fig. 6** shows an example the complexity of the influence initial melt temperature on VOD, VCD and slag reduction by the production of the stainless steel AISI 316 in 90 t. VOD-unit.

During the oxygen blowing in VOD, carbon content in melt decreased linearly with the reaction time to about 0.1 % C. Below this carbon content, the oxi-

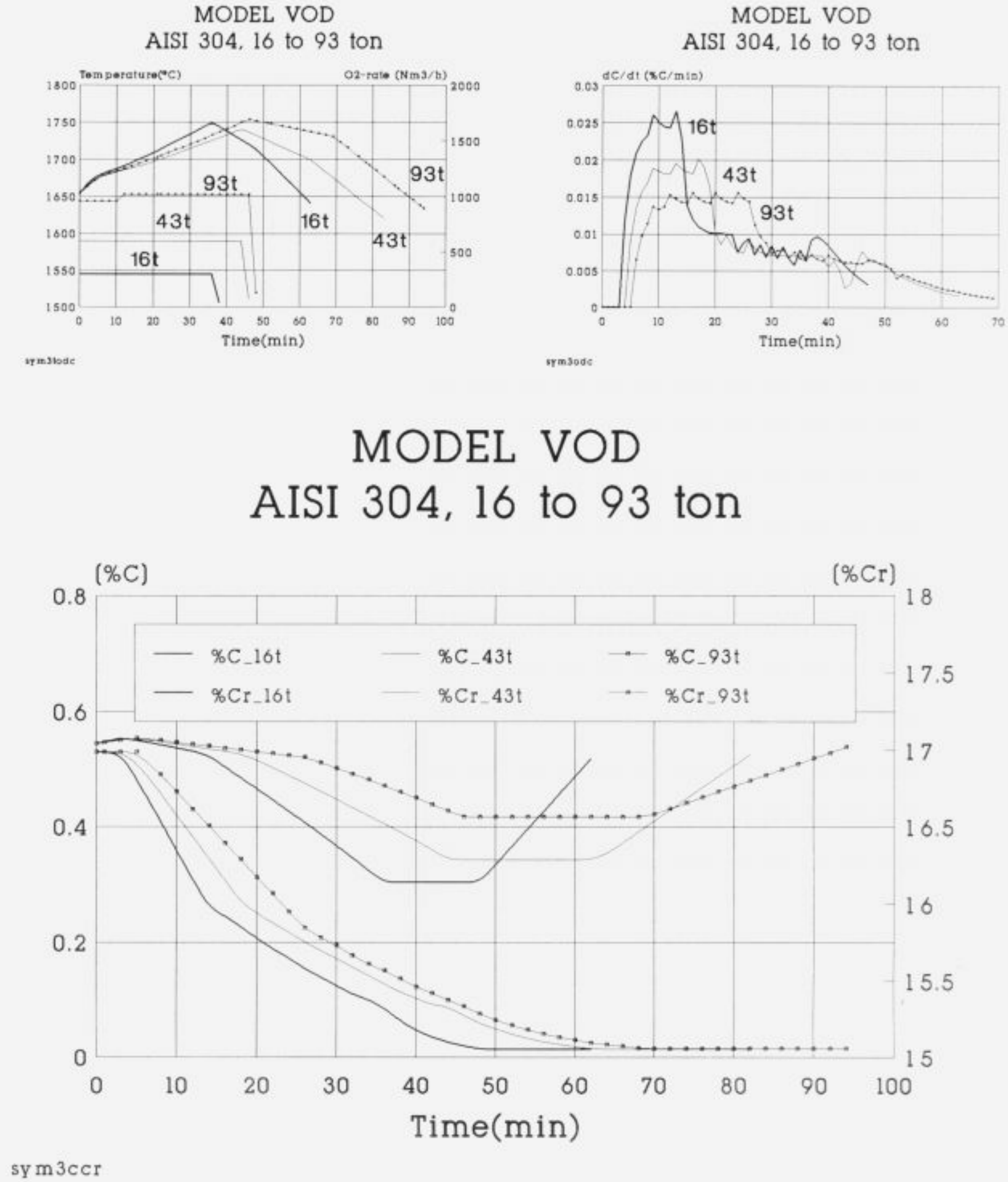

Figure 7: Carbon - Cr oxidation, temperature profile and decarburization rate in austenitic steel AISI 321 for 14.0 ton VOD-unit

Slika 7: Ogljik – krom oksidacija, temperaturni profil in hitrost razogljičenja pri izdelavi nerjavnega jekla AISI 316

dation of chromium was accelerated causes the formation of chromium oxide and slag getting in crusty. A varying starting temperature may have to be compensated by a change in starting analysis in order to reach a correct "carbon end point". Based on the analysis of a simulating model calculation taking into account the thermal losses in the VOD-ladle, an indicative calculation of the VOD-process is done according to principles reported from author[10,11] (see **Fig. 7**).

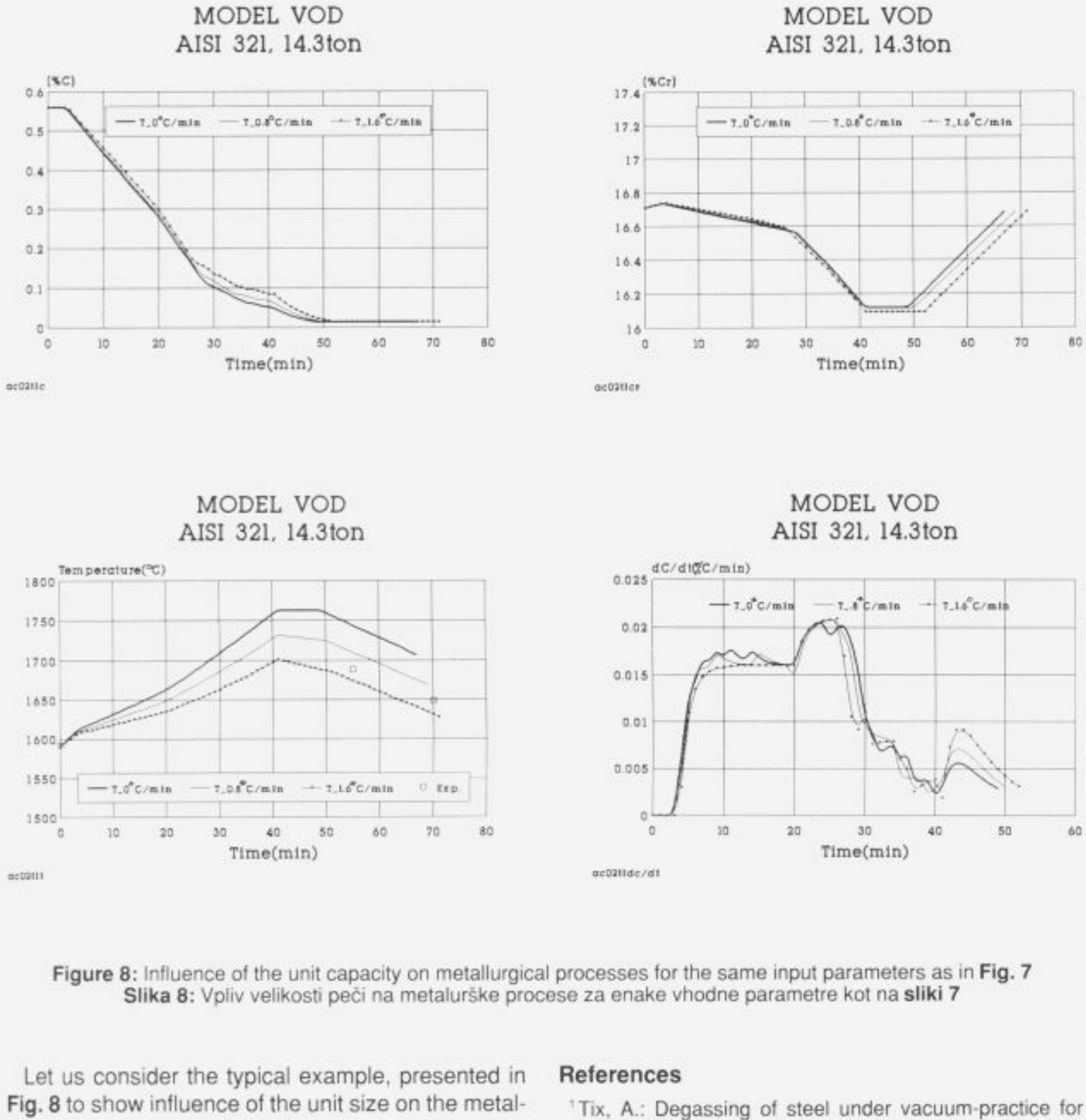

Figure 8: Influence of the unit capacity on metallurgical processes for the same input parameters as in **Fig. 7**
Slika 8: Vpliv velikosti peči na metalurške procese za enake vhodne parametre kot na **sliki 7**

Let us consider the typical example, presented in **Fig. 8** to show influence of the unit size on the metallurgical processes of VOD-technology, for the same input process parameters.

Presently the making of stainless steels and other alloyed steels with a short process time between the process steps is of great importance. As we learnt from this examples, the process modelling, combined with quick-reacting measuring devices helps to improve the vacuum process technology and it is the main purpose of our present and future work. The combination optimal of slag metallurgy and vacuum treatment is not yet accomplished.

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