The destruction model of cylindrical billet's hard shell during heating and melting by internal sources

Maxim Khatsayuk
Department of Electrotechnology and Electrotechnics
Siberian Federal University
Krasnoyarsk, Russia
maxhac@ya.ru

Viktor Demidovich
Russian Technologies of Induction Heating Ltd.
Saint-Petersburg, Russia
vbdemidovich@mail.ru

Viktor Timofeev
Department of Electrotechnology and Electrotechnics
Siberian Federal University
Krasnoyarsk, Russia
viktortim0807@mail.ru

***Abstract* — This article deals with the findings of researches and development of the theory for non-crucible induction melting of non-magnetic billets with due account of the MHD effect.**

***Keywords* — induction melting, magnetohydrodynamics, numerical simulation, mathematical modeling, MHD**

I. Introduction

This article deals with the findings of researches and development of the theory for non-crucible induction melting of non-magnetic billets with due account of the MHD effect. The prior experimental researches [1] of technology have provided basis for the assumption of significant impact of the natural MHD flows during the liquefaction and the necessity of their accounting at theory researches to the fullest extent possible. The computational process model has been developed therefore based on the created conjunction algorithm, such model inclusive of the related electromagnetic, thermal and hydrodynamic processes with due account of the turbulence as well as solidification and melting processes [2]. Convective q_α and radiation q_ε heat losses have been accounted for at nonlinear boundary conditions. Pre-evaluation of the process by similarity parameters has shown that the problem can be solved in non-inductive approximation, though the full-developed turbulence and free convection in the liquid phase should be expected. Fig. 1 provides the sketchy description of the process. The detailed description has been provided in earlier papers [3-5]. The essence of this technology lies in the fact that the liquid phase can be formed in the inner layers in case of the classical system of induction heating of the billets with a certain set of parameters and conditions.

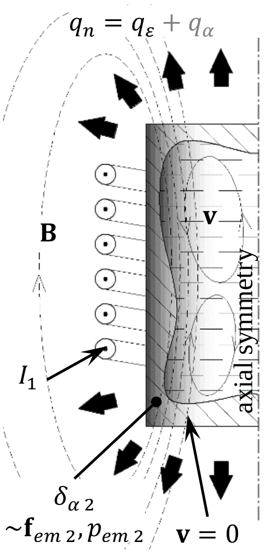

Fig. 1 – Non-crucible induction melting

II. Numerical modeling

A. Magnetohydrodynamics processes

The unsteady 3D numerical computation of the process (Fig. 2) has been performed based on the elaborated model and the available initial data corresponding to the executed experiments, such process consisting of three parts: preheating, melting and solidification. The computations have proved that MHD processes significantly affect the liquefaction pattern, such effect being, in the first place, evident as the liquid phase temperature field alignment which will inevitably change the thermal transfer conditions as well as the shape and volume of the liquid phase (Fig. 3). It was revealed that even slight circulation of melt will not allow its overheating in excess of the temperature T_{LIQ} without the surface being melt-through. This fact turns round the view of the process behavior and creates its own peculiarities. The process chart has been modified accordingly and the respective peculiarities and their accounting principles have been considered.

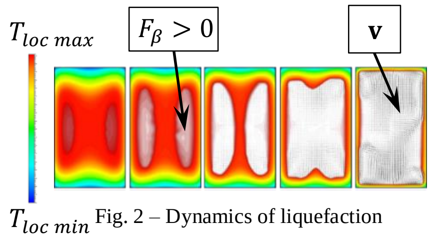

Fig. 2 – Dynamics of liquefaction

B. Mechanical problem

Also, one the technological peculiarities revealed besides the linear thermal expansion when preheating the billet is that phase transitions go along with the step change of the density and, respectively, the volume approximately by ρ_{SOL}/ρ_{LIQ} times. In this technology the produced liquid volume is confined in the solid tight shell of some thickness. The phase transition in the liquid volume is possible only when that shell is respectively expanded otherwise pressure starts increasing pro rata the heating until the shell is expanded or destroyed. This is evidently related, in the first place, to the shell thickness and requires the corresponding analysis to search for the stable modes. Problem of the stress-strain behavior (SSB) has been numerically solved to study the shell deformation. Therefore, the geometry of shell produced following the thermal hydrodynamic calculations has been approximately transposed to the numerical SSB solver ANSYS Mechanical – Static Structural. The problem reduces to calculation of the deformation vector u and equivalent stresses σ. Therewith the pressure problem is search solved until the required increase through deformation of the volume presented by the inner surface of the solid shell. As can be seen from the calculation results in Fig. 4, the most critical region is the angular belt on the billet inner surface. Also, regions of maximum stress and deformations are found at the centerline point on the face and in the center of a cylindrical billet. Thus, the billet destruction shall be expected with the face being broken away because of the tensile strength being exceeded. The predicted melt-through and destruction of the solid shell is one of the prerequisites of the technology as liquid phase shall be extracted for casting immediately after its liquefaction. Several solutions of the same kind are suggested in the Section. Fig. 5 provides one exemplary calculation of the

This research was carried out with financial support from Russian Foundation for Basic Research and Government of the Krasnoyarsk Territory as part of the Science Project No18-48-242013 on Research of the Influence of Spatial and Time-and-Frequency Distribution of Electromagnetic Forces in Melt on MHD process behavior in molten metal.

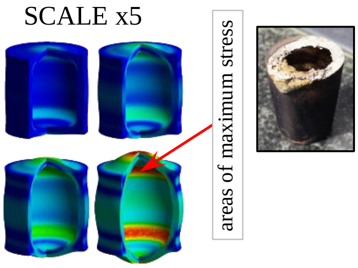

Fig. 4 – Scaled pattern of the billet deformation

deliberate bottom melt-through with the ingot being asymmetrically positioned.

III. Analitical models

Any specific recommendations on selection of parameters of different billets are intricate if made only on the basis of computational simulation as this technology is multi-discipline and accommodates electromagnetic, thermodynamic, hydrodynamic and mechanic processes in the solid body. Behavior of processes is accordingly governed by the set of parameters related therewith which cannot be considered individually. The comprehensive analytical solution of the problem through the existing theories and procedures has been found therefore on the grounds of some assumptions which allowed significant simplifying of the problem and reduction of the most parameters to their generalized non-dimensional similarities. Therewith the thermoelectric part is considered jointly with the analytical solution of the problem concerning deformation of the shell surfaces. Expressions to calculate dynamics of the radial temperature distribution with application of S-functions known from the induction heating theory are presented. Nevertheless, the steady-state operating conditions with $\eta_т \to 0$ are of more concern for the technology. This allows significant simplification of the analytical expressions which are recorded with the set surface temperature of T_R (Fig. 6).

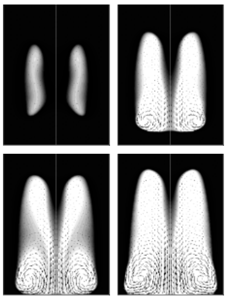

Fig. 5 – Asymmetrical bottom melt-through

Problem of the deformation of the cylindrical shell being formed and the respective mechanical stresses therein has been analytically solved to select the permissible wall thickness (safety margin k_{st}).

Thus, the second prerequisite of the process is keeping the integrity of the billet outer solid layer $\sigma_{MAX} < \sigma_u$ (or $k_{st} > 1$). Analysis of the received expressions shows that there are two process stability points (Fig. 7). The billet outer layer is destroyed and the liquid phase is bleeding-over in the range of $\beta_{w1} - \beta_{w2}$. Thus, keeping the hardness of the shell with the relative thickness of β_w depends on the shape H', ductility σ', relative deformation ν and the required expansion of the billet V'. Increase of the billet height leads to offset of the point β_{w1} and reduction of the respective working range of the wall thickness. Therewith, the possible range of parameters is expanded for more ductile materials with the minimum expansion at the phase transition and the processes become accordingly more stable when implementing this technology. The material deformation behavior (Poisson ratio) has almost no effect on the range typical for the maximum capacity. The range $\beta_{w2} - 1$ is of little interest as the required wall thickness is thick enough which complicates the liquid phase extraction and decreases the capacity.

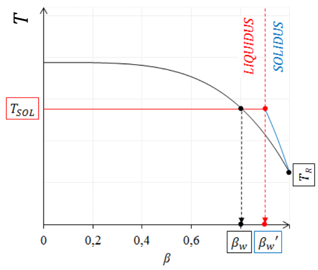

Fig. 6 – Determination of the shell thickness

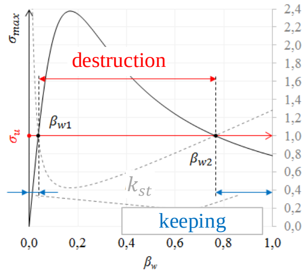

Fig. 7 – Analysis of the shell destruction

Conclusion

It has been established by the simulation of MHD-processes at non-crucible induction melting of non-magnetic billets that melt circulation prevents overheating of the inner layers in excess of the liquidus temperature without the surface being melt-through. The correction has been performed accordingly and the resultant peculiarities and technology restraints have been stated. It has also been established that the solid shell being formed is subject to deformation and mechanical stresses because of the required volume expansion of the liquid phase. Three critical areas have been theoretically found, therewith the maximum stress area is the angular belt on the inner surface.

Recommendation-based analytical expressions representative of thermoelectrical and mechanical processes have been set for selection of parameters of non-crucible induction melting. The procedure comes down to selection of sequential minimum wall thickness by the required volume of liquid phase of the original billet material, frequency and minimum power from the presented expressions and dependencies. It has been revealed that the system has two steady spots as regards the relative shell thickness which correspond to the ranges of maximum and minimum capacity. The thickness selected between these two spots will result in the billet destruction thus allowing the expected liquid phase extraction.

References

[1] V.B. Demidovich, P.A. Maslikov, “The role of MHD for producing a liquid phase in a titanium ingot during non-crucible melting in air,” Induction heating, vol. 2, 2013, pp. 33–36. (Роль МГД явлений для получения жидкой фазы в титановом слитке при безтигельной плавке на воздухе).

[2] V.B. Demidovich, M.Yu. Khatsayuk, V.N. Timofeev, A.A. Maksimov, I.I. Rastvorova, “Numerical simulation of non-crucible melting of titanium alloy in the alternating electromagnetic field,” Magnetohydrodynamics, Vol. 4, 2015, pp. 785-794.

[3] V.B. Demidovich, M.Yu. Khatsayuk, V.N. Timofeev, A.A. Maksimov, “Numerical modeling of crucibleless melting of titanium alloy in the electromagnetic field,” Metallurgy Engineering, Vol. 3, 2017, pp. 2-5. (Численное моделирование бестигельного плавления титанового сплава в переменном электромагнитном поле).

[4] V.B. Demidovich, I.I. Rastvorova, M.Yu. Khatsayuk, V.N. Timofeev, A.A. Maksimov, “Non-crucible induction melting of titanium,” Technology of light metals, Vol. 2, 2015, pp. 82-88. (Индукционная бестигельная плавка титана).

[5] V.B. Demidovich, M.Yu. Khatsayuk, V.N. Timofeev, A.A. Maksimov, I.I. Rastvorova, “Numerical simulation of MHD processes in the technology of non-crucible induction melting of titanium alloys,” 8th International Conference on Electromagnetic Processing of Materials EPM-2015, Cannes, 2015, 4 p.