Mathematical Modeling of RH-degasser Pipe Thermal Strain

A. V. Zabolotskiy, L. M. Akselrod, V. G. Ovsyannikov

The lifetime of a RH-degasser refractory lining was modeled mathematically using the latest calculation methods. Areas for the possible formation of thermal cracks and approximate installation lifetime for specified conditions of use were determined as a result of the calculations. The results obtained do not conflict with existing experimental data. Calculation algorithms can be used in the development and design of new refractory linings.

1 Introduction

The refractory lining of heating installations in the steelmaking industry is exposed to different factors that can cause its destruction during use. One of the destruction factors, termed thermal shock, takes effect on rapid temperature changes during heating or cooling of the installation. This is capable of destroying a refractory at the very beginning of its use. The destructive effect of thermal shock can be reduced with in-time repair of the lining and heating between melts, but for some installations (RH-degasser pipes, for example) effective between-melt heating is impossible. At the same time, prolonged between-melt period reduces the refractory lining lifetime (carbon burning of MgO-C bricks, for example). To explore the possibility of reducing the thermal destruction of refractories and lengthening their lifetime, a mathematical model of thermal shock is needed to optimize the conditions of use. The first stage of such a calculation is the determination of a dynamic temperature field – a matrix containing thermal data of any point of the object for any moment of time. Such calculations have recently been performed with the finite element method (FEM) or modifications on this [1].

It is expedient to conduct the second stage of calculation – temperature matrix transformation into a mechanical stress matrix – with the cellular automata method [2], which allows modeling of material properties as they change with the growth of destructive cracks [3, 4]. The advantage of this method is that the element condition is calculated as a function of neighboring area conditions, which can consist of tens of other elements, increasing the density of the method. Drawback of the method – necessity of a large number of simple mathematical operations, but this drawback is partly cancelled out thanks to the progress in computer technology.

This paper discusses the formation of thermal cracks in the RH-degasser pipe refractory lining, both during melt treatment and after-melt cooling. The investigation method was based on a calculation. Original software written by the authors of this paper was used as a calculation instrument. This software is based on the FEM and cellular automata methods.

2 Description of the object and calculation algorithm

The zone of the lining exposed to the most damage is the area between the degasser pipes, which is indicated by the oval in Fig. 1. This area was used as an object for 2D modeling of temperature fields and determining the coordinates of crack initiation under thermal shock. A typical indication of thermal destruction are horizontal cracks in the pipe lining at the level of cooling hole and lifting of the degasser bottom lining.

The calculations were conducted in two stages: object temperature field determination with FEM as the first stage, then mechanical strain and crack growth modeling with the cellular automata method, using the model of fatigue destruction [5].

For the working surface of the pipe lining, border conditions of the first type were used (the surface temperature was determined) and border conditions of the third type were used for surfaces that have heat exchange

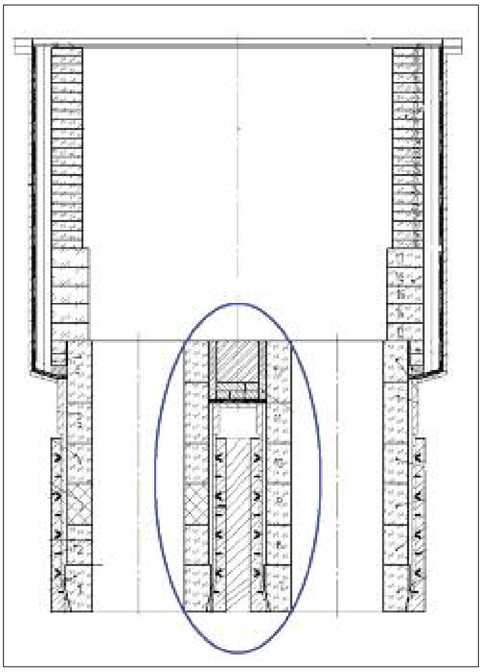

Fig. 1 Object schematic showing the RH-degasser pipe

A. V. Zabolotskiy, L. M. Akselrod,
V. G. Ovsyannikov
Magnezit Group Ltd.
119180 Moscow
Russia

Corresponding author: *L. M. Akselrod*
E-mail: lev@magnezit.com

Keywords: modeling, RH-degasser, thermal cracking, FEM

with surrounding air – inner cooling hole and bottom pipe surface (a law of heat exchange was proposed) [6].

The following heating and cooling conditions were used for the calculations:

1. Pre-heating of the working surface up to 1100 °C, which is done in several stages with isothermal periods at 300, 800 and 1100 °C respectively, in order to eliminate thermal strain. The duration of the whole process is 44 h or 158 400 s. The temperature increases as a result of heating from three sides of the inner degasser volume (two vertical and upper horizontal) during pre-heating. The lower horizontal side has contact with atmospheric air and is cooled as a result of natural convection. An inner hole is cooled with cold air under pressure. This stage is common for all heating and cooling conditions.
2. Thermal exchange with metal and during between-melt cooling was simulated with following approximate cyclic schemes:
   - 2.1. Heat treatment of the steel melt with a temperature of 1572 °C and for a duration of 25 min (1500 s), followed by 225 min (13 500 s) between-melt interval with a lining surface temperature of 1100 °C.
   - 2.2. Melting process with the same temperature and duration as 2.1., but the duration of the between-melt interval is 25 min (1500 s).
   - 2.3. Continuous melts with a duration of 25 min, without any intervals.

During melting, the object is heated from all four sides (the bottom surface is in contact with the metal melt), during the between-melt interval the heat exchange scheme is the same as for pre-heating.

The results of the calculation were presented as a matrix, containing all coordinates of the object points, time and temperatures at these points. This matrix was used as initial data for modeling with the cellular automata method.

The cellular automata model takes into consideration the following object properties and physical phenomena:

1. Temperature of all object elements.
2. Mechanical stress for all elements, calculated according to the thermal growth of the objects and growth of the surrounding elements. Stress calculations were performed, using the *Hook* equation [7].
3. Decrease in thermal stress, because of the relaxation effect [8, 9].
4. Reduction of the thermal stress growth rate because of the closing of the lining joints during pre-heating.

5. Mechanical stress reduction in the area surrounding the growing crack vertex [10, 11].
6. Microstructural data of the refractory material, such as average grain and pore sizes.

This calculation algorithm supposes that all mechanical stress that appears at some element could be concentrated at some point inside this element. Any grain that creates the structure of a material can become such a concentrator. Energy needed for grain destruction correlates with area of the appearing crack. It means that in the case that the small and big grains are of one chemical compound, small grains in the material matrix would be destroyed first. It means that any crack would go around the big grains. If the small and big grains are different in nature, the destruction pattern differs: for example, when big grains with low mechanical strength are distributed inside a high-strength matrix, cracks would be initiated inside the big grains and only after that would destruction of the matrix begin [14].

In this paper, the mechanical properties of the grains and matrix were considered the same (tensile strength, calculated with the heat displacement method, using tables [13], was found to be 2350 MPa). Average grain size was 1–5 mm and average matrix particle size was about 0,1 mm. The moment when mechanical stress in some element exceeds the value needed for one grain destruction was deemed the moment of the start of crack growth. Destruction of the full object was deemed to be when all grains had been destroyed at the maximum element section. Element destruction was simulated with the heat displacement method [12, 13], using data for a material porous structure, energy or mechanical strain needed for the destruction of one grain.

The present model describes a destruction process of one-type automata, which have their own inner structure, consisting of pores and grains. The destruction of such a system could be realized after cyclic strain accumulation. Another model [2] presupposes that the calculation system consists of several types of homogeneous automata.

Results and discussion

Mathematical modeling of the RH-degasser pre-heating and the first 15 melt cycles was performed for analysis of temperature fields and thermal mechanical strains inside its refractory lining. All calculations were performed assuming strict compliance with the pre-heating and melting schemes described above.

Calculation results are presented as object drawings superposed with a temperature field color scheme. Another color scheme for the possibility of crack growth was used for crack growth analysis.

Fig. 2 shows the pre-heating process: development of temperature field (A) and field of destruction possibility (B). The numbers under the images indicated the time in [h] after the beginning of the process, numbers at the right of images indicate the temperature in [°C] for A and level of destruction in [%] for B respectively. Breaks of the figure at B correspond with the position of steel casing of the apparatus, which is more resistant to destruction and mechanical stress accumulation owing to the possibility of plastic deformation.

The results of the calculations allow the following suppositions:

- Total width of lining joints is more for the radial lining of degasser pipe, than for the bottom of the apparatus (the area between two pipes). Because closing of the joints reduces mechanical strain in the refractory lining – the bottom is subject to more mechanical stress and destruction than the lining of the pipes.
- A temperature difference of 50–100 °C between neighboring elements is sufficient for the formation of microcracks. This result corresponds with the typical values of heat resistance for refractory materials [15].
- Cooling of inner hole of degasser pipes enable reduction of the mechanical stress in materials around this hole during preheating of the apparatus.

Fig. 3 (A–C) shows a process of temperature field development during degasser usage. Version A corresponds to the usage scheme with the maximum between-meltv-interval (13 500 s), Version B to the intermediate value (1500 s) and version C to the scheme without between-melt cooling. Fig. 3, like Fig. 2, uses half sections of the object as a basis for drawing the images. The numbers under the drawings indicate the number of the melting cycles for which the results are presented. Zero-number corresponds with the end of the pre-heating process, so this field is the same for all versions. At the right part of the image a temperature scale is marked with small font.

The images demonstrate different isotherm configurations for the calculated versions: when the between-melt intervals were short (version B or C) the isotherms were closed, but when the interval was long (version A) the isotherms were not closed and begin at the corner of the authors` object.

The average temperature of the object increases with the melt number rising for all calculated versions. This is accompanied by an increase in the high-temperature section area and a respective decrease in of the low-temperature zone area. However, none of versions allows an equilibrium temperature field to become established during the first 15 melting cycles.

The creation of temperature field during one of the melts (Fig. 4.1–4.6) and its change during between-melt cooling (Fig. 4.7–4.12) are presented in Fig. 4. Images were made with the 300 s domain.

Fig. 4.1–4.6 show that during melting time (approximately 1500 s), the lining layers change their temperature: the middle area becomes hotter with 50 °C (for comparison: the working surface temperature inside the installation increases with 450 °C and the bottom layer temperature with 1400 °C).

While between-melt cooling of 1500 s is enough for the inner working layer temperature to return to its starting value, but the bottom surface cooling needs much more time (Fig. 4.7–4.12). This could be explained with a substantially different amplitude of temperature changing in these two zones.

Upper corners of the object stay hot longer than other parts because they are furthest away from heat exchange surfaces (Fig. 4.9 –4.11). So metal treatment and between-melt cooling are periods when the temperature of a large part of the objects section changes rapidly. This zone is exposed to thermal shock, crack formation and growth.

A field of crack formation possibility (level of material destruction) was determined with the cellular automata method for the degasser pipe lining refractory, whose matrix was presented with grains with a characteristic size of 0,1 mm. This model corresponds with real refractory material that has multi-size grains of the same physical and chemical nature. A destruction crack in this case would appear in matrix (zone of small grains) and it would grow mostly around big grains.

A measure of crack formation possibility, the amount of destroyed grains for each element is calculated and presented in [%] of the total element grains amount. A grain is deemed to be destroyed if the mechanical stress in the element has exceeded a certain critical level, calculated with the heat displacement method [12], considering the stress concentration.

Fig. 3 (D–F) shows the calculated possibility of destruction for three different heating schemes. The numbers under the images indicate the number of melts completed up to the illustrated state (zero-end of degasser pre-heating), the numbers at right of the image indicate the possibility of destruction.

It is obvious that the most comfortable treatment scheme for the lining is F, corresponding to continuous usage without between-melt cooling. In this case the working lining of the degasser bottom is exposed to the most stress. After 15 melts this area suffered around 25–28 % destruction, that corresponds to 1 % per melt (considering destruction received during preheating).

The D-scheme of treatment would have a slightly higher rate of damage, corresponding to long between-melt intervals. In this case, the lifetime of the bottom lining lifetime would be 50–60 cycles, the same for the inner pipe lining, but the concrete lining lifetime would be only 40 melts.

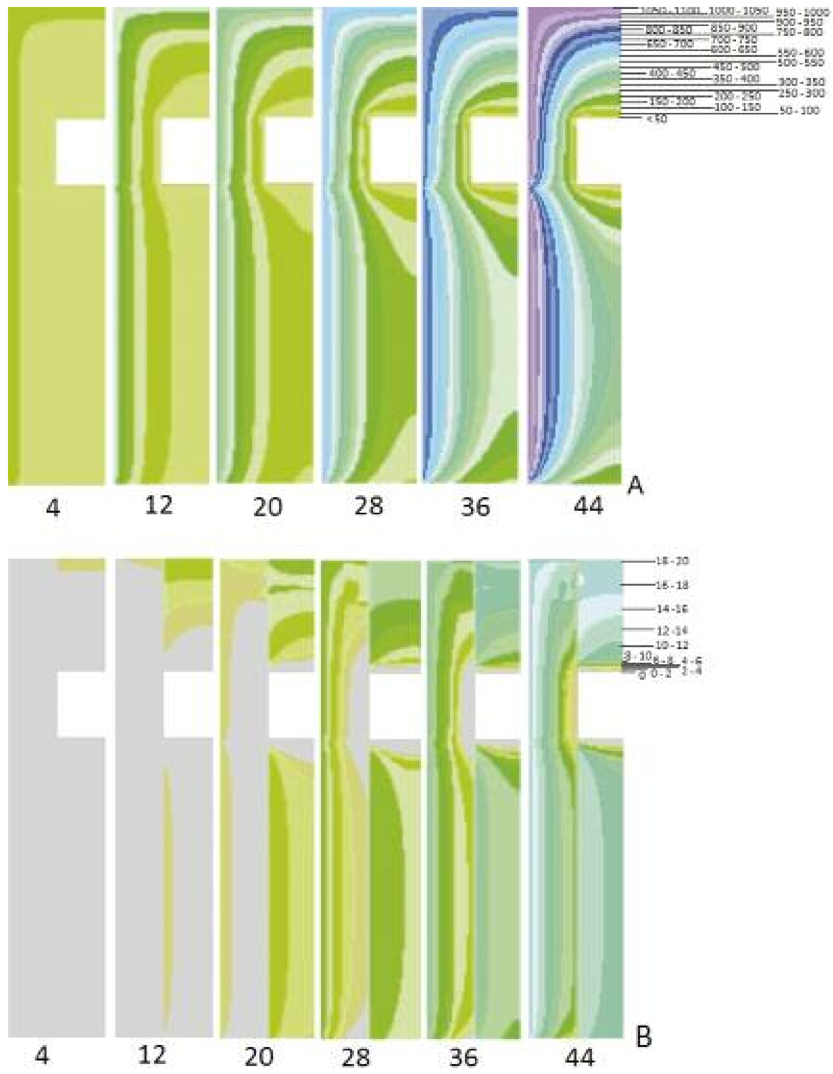

Fig. 2 Temperature field and damage during preheating

A less obvious result is the higher speed of destruction for the treatment scheme with short between-melt intervals (version E). A calculated forecast lifetime of bottom would not be more than 30–35 melts, 45–50 for the inner lining and about 40 melts for concrete. This result could be explained with consideration of thermal equilibrium establishment velocity in the studied object lining. During the between-melt interval, an equilibrium is established after 1500 s or more (Fig. 4), at the same time 1500 s is equal to the between-melt interval duration for the E-treatment version. That is why one needs to consider mechanical processes taking place in a pipe lining during melt and between-melt cooling. During the melting process, the temperature of the refractory lining rises, starting from the working surface. Heated areas begin to grow geometrically and have a mechanical impact on the surrounding areas. After-melt cooling also begins from the working surface, but at the same time heating and growing of the inner layers are continued. That is why, at some moment of between-melt cooling, maximum temperature of the lining could be found at some distance from the surface, inside the lining (Fig. 4). During the next heating cycle, the hot surface and non-cooled inner layers would mechanically influence the lining area between them. Thus, during cyclic thermal load, if the cooling phase is completed far away from thermal equilibrium, conditions for thermal mechanical stress growth have been observed. This explains the faster thermomechanical wear in the case E compared with case D, Fig. 3.

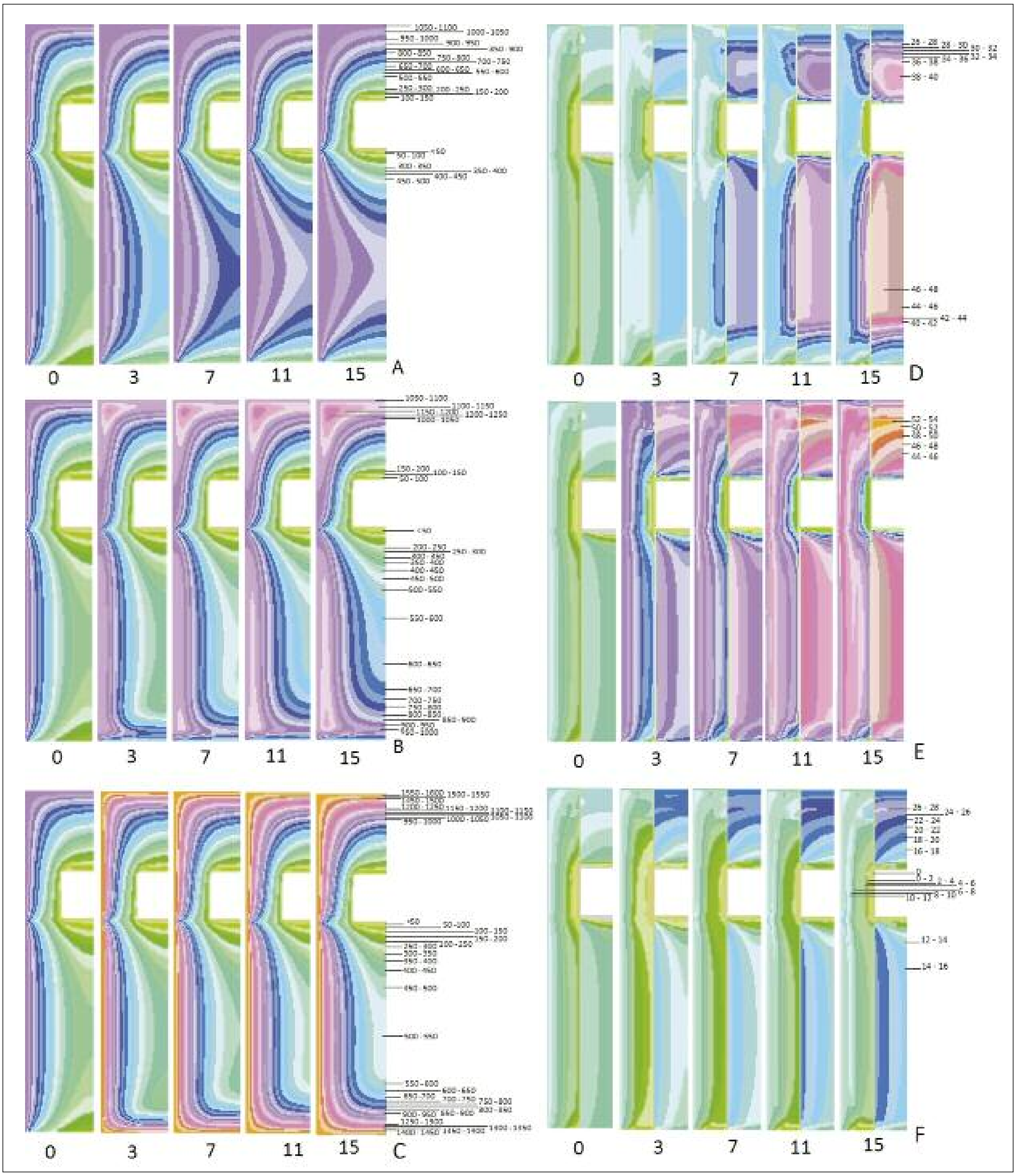

Fig. 3 **Temperature field of RH-degasser pipe development for the first 15 melts (A–C); pipe destruction possibility field for different versions (D–F)**

It is important to note that the refractory structure can in fact differ substantially from the suggested regular model and the growing crack can change the construction geometry, which in turn can also influence the destruction rate. Incidentally, the destruction level 100 % for some object areas does not mean full object destruction, but only means that the crack has gone through this zone. The possibility of using the installation further in this case can be assessed by means of visual crack investigation.

In the present paper, lining lifetime calculations were performed without consideration of chemical and mechanical wear of refractory.

Actually, the most damaged area is lining of degasser bottom. Fig. 5 shows a photo of the working lining bottom crack exit to the pipe vertical working lining. Such cracks appear after 25 melts or later.

The thermal destruction of the pipe consists of cracking and rising of upper bottom layer with 200–300 mm thickness and cracking of vertical lining surface with distance of 350–800 mm from horizontal bottom surface (Fig. 5). So, cracks appear at the vertical lining surface at the level of the bottom corner of the bottom working lining or top and bottom corner of the air-cooling hollow between pipes. These zones are areas of maximum thermal mechanical stresses, as was proved with calculations. So, the destroyed zones determined with calculations and observed visually are the same.

Conclusion

The level of destruction reached during one "heating – cooling" cycle of the refractory lining enabled forecast of the lifetime of a pipe up until crack formation. The calculated value of 30–100 melts, depending on usage scheme, does not conflict with experimental data.

The calculations showed that during cyclic usage of the installation with cooling and heating periods, the destruction influences not only rapid temperature change, but short cycle duration too. When this cycle is short, thermal mechanical stress grows because of insufficient cooling of the inner lining layers.

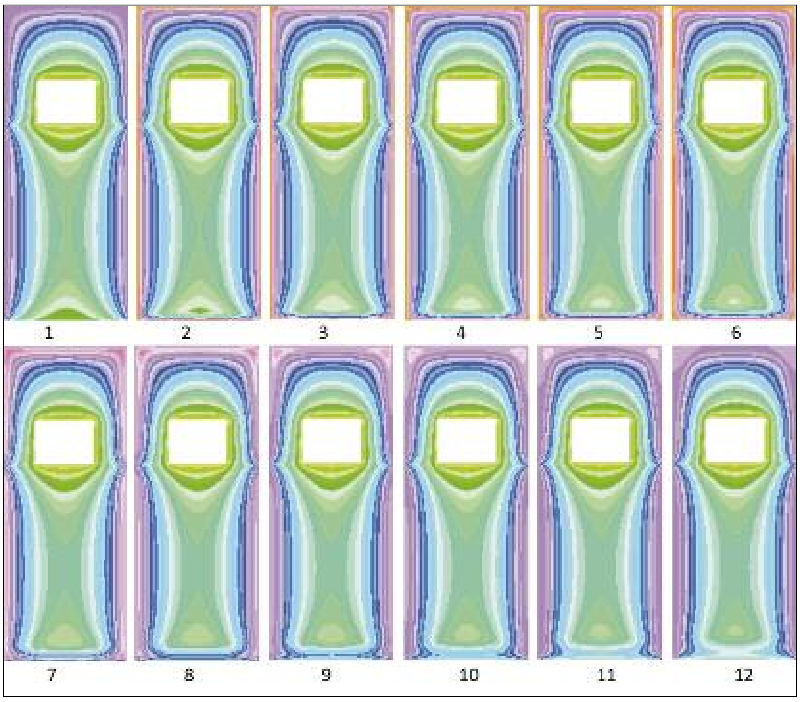

Fig. 4.1–4.12 **RH-degasser pipe temperature field change during melting and between-melt cooling**

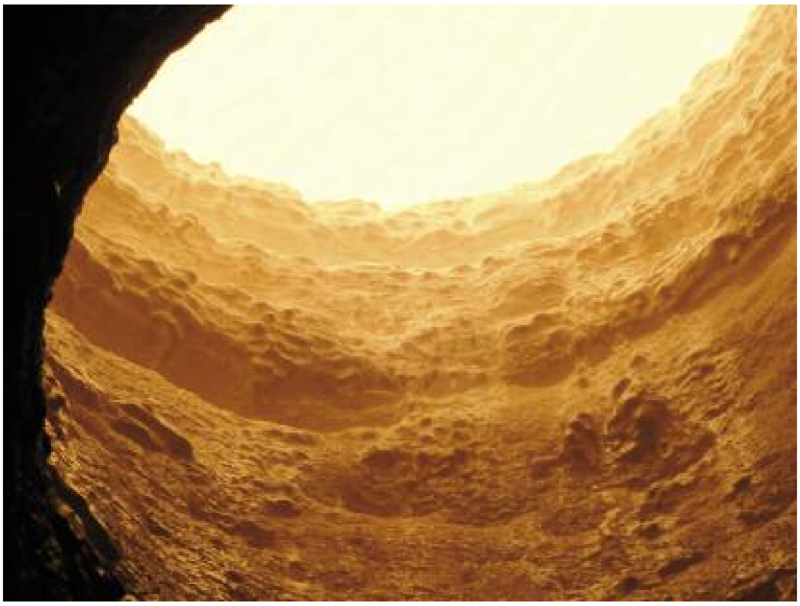

Fig. 5 **Crack location at the lining surface of a RH-degasser pipe**

This causes additional stress and damage to the refractory lining.

So, the mathematical methods based on calculations could be applied to obtain useful information that cannot be derived from direct measurement, e.g. the temperature at any point of the refractory lining at any moment in its usage. This information can be used in future for thermal mechanical stress calculations for refractory lining and for modeling of its destruction during usage or in the event of an emergency. The result of such modeling would be a forecast of installation lifetime or an analysis of lining failure during usage based on specific conditions.

References

[1] Segerlind, L.J.: Applied finite element analysis. New York, 1976

[2] von Neumann, J.: Theory of self reproducing automata. Urbana, IL, 1966

[3] Psakhe, S.G., et al.: About possibility of computer simulation of materials with high porosity and frame structure, using moving cellular automates. Letters to ZTP **24** (1998) [4]

[4] Beigelzimer, J.E.; et al.: Modeling of polycrystalline deformation with cellular automata method. J. of technical physics **68** (1998)

[5] Kazakov, D.A.; Kapustin, S.A.; Korotkikh, U.G.: Modeling of materials and constructions deformation and destruction processes. Nizhnii Novgorod, 1999

[6] Wong, H.Y.: Heat transfer for engineers. London, New York, 1979

[7] Timoshenko, S.P.; Gudier, J.: Theory of elasticity. Moscow, 1979

[8] Beliaev, N.M.: Material resistance. Moscow, 1976

[9] Mining encyclopedia: Chief editor Kozlovsky, E.A.. Moscow **5** (1984–1991)

[10] Sarafanov, G.F.; Perevezentsev, V.N.: Microcrack appearance in fragment structure. Nizhnii Novgorod University named Lobachevskiy N.I. **2** (2010) [5] 90–94

[11] Hirt, J.; Lote, I.: Dislocation theory. Moscow, 1972

[12] Cherepanov, G.P.: On crack propagation in solids. Int. J. Solids and structures **5** (1969) 863–871

[13] Physical Values. Handbook. Moscow, 1991

[14] Broutman, L.J.; Krock, R.H.: Fracture and Fatigue. New York 1974

[15] Kingery, W.D.: Introduction to Ceramics. New York, London, 1966