Introduction to Melting in Induction Furnace with Cold Crucible

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Abstract. The article describes the technology of melting using an induction furnace with a cold crucible. In the first part a brief introduction to the technology is indicated. The second part deals with the description of the induction furnace with the cold crucible, its geometry and explaining its functions. Its applications are discussed very briefly. The next part focuses on variants of modelling of the induction furnace with the cold crucible. The difference between 2D and 3D model is described here and the part contains some useful simplifications. Warnings for the limitations of these simplifications are also stated. Some possibilities for the further use of the described technology for research are outlined in the conclusion.

Keywords
Induction melting, electromagnetic field, thermal field, induction furnace with cold crucible.

1. Introduction

The induction furnace with the cold crucible (IFCC) is a technology offering a lot of possibilities of using for melting different materials. It is useful for melting the electrically conductive materials and non-conductive materials (oxides, glass, etc.). Of course it is not a universal device. Prior to the design of a new device it has to be absolutely clear what materials are going to be melted in it. From metallic materials TiAl alloys are worth mentioning. The technology of the cold crucible is widely used for their melting and material research [1].

Using the IFCC for melting the electrically non-conductive materials is also possible: for a vitrification of radioactive waste or for a simulation of a severe nuclear accident with core melting. But there are also many non-nuclear applications, for example melting oxides of metals with a high melting point [2]. For melting electrically non-conductive materials a starting phase of the melting process enters the melting. Electrically conductive material (for instance metallic zirconium) is added to the electrically non-conductive melted material. The additional material starts to melt and it leads to the melting of the electrically non-conductive material around. Thus the electrical conductivity of the required melted material is increased and the material can be melted. The melting of electrically non-conductive materials is not possible without the starting phase of the melting process.

The advantage of this technology is achieving high temperatures of melted material and obtaining highly pure melted product. The next indisputable advantage of this technology is the possibility to perform the melting process in a melting chamber which contains a different atmosphere or a vacuum. Therefore it is possible to melt also highly reactive materials inside.

2. Description of Induction Furnace with Cold Crucible

Generally, there are two IFCC arrangements. The first of them is a cold crucible with an integrated inductor. The second one is a segmented cold crucible.

Physical principle of the both types is the same however they have a different design. The following text will be devoted to the induction furnace with the segmented cold crucible.

In the Fig. 1 a basic geometrical arrangement of the induction furnace with the segmented cold crucible is shown. The red marked part is a two-turn inductor. Time-varying electric current flows through the inductor during the melting. The frequency of the electric current depends on the application. The inductor is water-cooled. The yellow part indicates the workpiece, it can be both electrically conductive and non-conductive as it was already mentioned in the introduction. The blue marked part represents the segments and the bottom of the cold crucible. The bottom and the segments are intensively water-cooled. It results in a fact that the temperature in the contact point between the segments and the workpiece lies around 100 °C. Therefore the material is not melted here. A protective layer is formed here and it prevents the melt from contacting the crucible wall. This
The protective layer is called a skull. It comes the situation that the material is melted in itself, so the high purity of the product can be achieved. The segments and the bottom are made of copper. In Fig.1 four segments were removed from the front part of the device for better illustration.

Fig. 1. Geometrical arrangement of the induction furnace with the cold crucible.

A photograph of the real IFCC equipment developed and used in St. Petersburg University LETI is presented in Fig.2. A similar device is located at the NRI Rež for simulating severe nuclear accidents with core melting under the name COMETA (Corium Melting Apparatus). It was designed and developed by prof. Petrov from St. Petersburg University LETI. Two other IFCC installations are being constructed in the Research Centre Rež at the time of the writing of this article. Output power of the new IFCC installations is 160 kW and 240 kW.

3. Ways of IFCC Using

The IFCC technology is ideal for simulations of severe nuclear accidents with core melting because it is possible to achieve the temperature up to 3 000 °C. The CORIUM melting point is lower than this value, CORIUM melting can be achieved and its behavior and material properties can be studied here, which can be useful for preventing or minimizing the damage during severe nuclear accidents with core melting in a real reactor [3]. It should be pointed out that unlike the real accident with core melting, where the temperature increases with the nuclear fission reaction, the physical principle in the IFCC is completely different. In this case the temperature rises with the Joule losses caused by an interaction of electromagnetic fields and matter. Therefore this is a safe way of creating a phenomenon which is interesting and it is very important to study it with regard to the safety of nuclear reactors.

Fig. 2. The Induction furnace with the cold crucible developed in St. Petersburg University LETI.

Fig. 3. Photograph of the melt during the experimental melting of CORIUM with the crust on the surface.

In the Fig.3 a photograph of the experiment progress with CORIUM melting in the IFCC Cometa is shown. The figure also shows the crust being formed on the surface of the melt, which was caused by the temperature decrease in the upper part of the workpiece.

This using of the technology includes also Fig.4, which contains a photograph of a severe nuclear accident simulation but the upper part of the melt is completely melted and the surface is visible.
Simulations of severe nuclear accidents are only one of many IFCC applications. Glass melting for both classical glass melting and glass melting in the process of vitrification is another possible use of the furnace [4]. The technology is also applicable to the study of a crystal growth [5], the melting of oxides and other materials with a high melting point.

Fig. 4. Photograph of the melt during experimental melting of CORIUM without the crust on the surface.

The aforementioned applications were dealing with the melting of materials with a low electrical conductivity. For the melting of metallic materials it is appropriate to mention the melting of titanium alloys, for example TiAl [6]. The IFCC technology is suitable for these applications because the melting point of titanium is higher than 1600 °C. This temperature can be achieved by using this technology. The main advantage of using this technology for melting titanium alloys is the purity of the melting product. The melt is not contaminated.

4. Possibilities of IFCC Numerical Modelling

The melting process in the IFCC is a generally coupled problem because several fields interfere in the task. It depends on the particular example, what fields are modelled and what kind of coupling is used for the calculation. A physical field whose calculation the process should start with is the magnetic field. With the knowledge of the source currents, the geometry and the material properties it is possible to calculate the values of the magnetic field but also the quantity and distribution of Joule losses in the workpiece. If the temperature field should be solved, the distribution of Joule losses, the geometry and the material properties enter the calculation as the input data. Another physical field that can be solved in the calculation of the IFCC is the flow field. All fields mutually interact and their influence can be respected in the calculation by the coupling of the fields in the problem.

There is another possibility of the calculation. It is so called inverse problem where Joule losses in the workpiece are known, e.g. by a calorimetric measurement. These losses enter the calculation, the material parameters of the given material are the output of the calculation [7]-[8].

Generally, the problem of the IFCC is a 3D task. However there is the possibility that the 3D calculation is substituted by the 2D axisymmetric calculation. In this case it is necessary to use a significant simplification of the task.

4.1. 3D Model

There is a considerable amount of commercial software for the solution of 3D physical fields with coupling, for instance ANSYS, COMSOL Multiphysics and QuickField.

Each software uses different equations for the calculation, some of them use the equation for the magnetic vector potential $A$, the other use equations for individual components of the vector of the magnetic field strength $H$.

Basically, even the method of the solution may vary although all of above mentioned software use a finite element method. An algorithm of the calculation can be different. There can be a difference in an order of an approximation polynomial, in a shape of elements or in using some adaptive “accelerating” algorithms.

That is reason why a user should be informed about the method of the used software. The user should know how the chosen software works to be able to evaluate its suitability for the particular problem.

Fig. 5. Geometry of the smallest symmetrical part at the numerical calculation of the IFCC in 3D.

In Fig.5 the geometry of the IFCC with a two-turn inductor in 3D is shown. The blue colour marks the bottom and the segments, red and black mark turns of the inductor,
yellow colour marks the workpiece and a clamping ring is coloured green. The clamping ring is only a construction component and its task is to keep the cold crucible together. Since this article does not deal with any specific calculation results, dimensions of the IFCC are not presented because they are not important for the description of the calculation principle. For the substantial saving of degrees of freedom (DOFs) the task was limited to the smallest symmetrical part. On its border a suitable boundary condition was put.

\[ \nabla \mathbf{A} - j \gamma \omega \mathbf{A} = -\mu \mathbf{J}_{\text{ext}} \] (1)

For the solving of the magnetic field using equation (1) following boundary conditions were used: \( \mathbf{A} = 0 \) on the symmetry axis and the outer boundary, electric scalar potential \( \varphi = 0 \) is used as the boundary condition for both cross-sections in the XZ plane and electrical current flowing through the inductor is inserted into the cross-sections of the inductor.

Additionally the calculation can proceed with the thermal field. It will be described by the heat transfer equation or the flow field, which will be expressed by the Navier-Stokes equation or some of its modifications.

4.2. 2D Model

For the 2D axisymmetric model of the IFCC, simplifications are more significant than in the case of using the smallest symmetrical part of the furnace used in the 3D model. However the number of saved degrees of freedom is significantly higher than in the first case. In Fig.6 the geometry of the IFCC with the two-turn inductor in 2D is shown. The colour coding of the elements is identical with the 3D model case.

At this point it should be stated that the 2D and 3D calculation can be further simplified, e.g. by replacing individual hollow turns of the inductor with one turn of the equivalent area with the equivalent current density, which would have the same effect on the magnetic field as the individual turns. In this case it would not be possible to study the current density distribution over the cross section of the inductor.

For the calculation of the 2D IFCC model the segment is substituted by two equivalent areas of electrically conductive surfaces with an equivalent thickness \( \delta \). The two surfaces are applied with regard to the fact that the segment creates a short turn and the eddy currents will have the opposite direction in each area. It is necessary to keep the equivalent thickness of the surfaces \( \delta \) for the surfaces to have the same effect on the magnetic field as the real segment, i.e. to maintain the transparency of a magnetic material using the 2D model. It should be as similar as possible to the transparency of the real device, although as a result the distribution of the magnetic field will be different than in the 2D model.

Another possible simplification is the substitution of the two equivalent conductive surfaces for one area. Using a simplified 2D model for the task, which is generally three-dimensional, it is necessary to know how much the simplification does not affect the particular result. For example it is not appropriate to use a simplified 2D model specifically for the modelling of the IFCC, when the distribution of the magnetic field inside the cold crucible should be investigated etc.

5. Conclusion

The article was intended to provide basic information about the technology using the IFCC, possibilities of its use for research and industrial applications. The intention was also to bring a brief introduction of the IFCC applications in Research Centre Řež. And finally it was intended to describe generally the possibilities of the mathematical modelling of processes in the IFCC.

Opportunities for the further research in this area are immense, so it is possible to say that the technology is promising. There is a wide range of unsolved tasks in this field, for example the determination of the material properties of the skull, determination of the temperature dependence of certain material properties of materials with a high melting point, optimization of crystal growth and many others.
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References


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Jan HRBEK was born in Marienbad, Czech Republic, in 1988. He received bachelor’s and master’s degrees in electrical engineering with honors at the Faculty of Electrical Engineering, University of West Bohemia in Pilsen. Currently he is a Ph.D. student of the Electrical Power Engineering study program at the Faculty of Electrical Engineering, University of West Bohemia and he works in the Cold Crucible Laboratory in Research Centre Rež as a Junior Researcher.