The Action of an Electromagnetic Force on an Elongated Inclusion in an Electrically Conductive Liquid

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Abstract. The impact on the molten metal with electromagnetic forces makes it possible to create specific flows in the metal, which, in turn, are able to concentrate particles of inclusions in a given area, from where they can be removed mechanically. In this case, it is important to determine the shape of the inclusions, which will provide the best efficiency of impact on them with electromagnetic forces. The use of such an effect is possible in the process of crystallization (transfer of partially crystallized small regions of the metal), as well as during the separation of impurities from liquid metals using electromagnetic forces.

The work is devoted to a numerical study of the features of the effect of electromagnetic forces on inclusions (in shape that differs from spherical) in an electrically conductive medium.

1. Introduction
Metals and alloys with the best exploitation properties are especially popular nowadays. Such metals are widely used in nuclear power engineering, aerospace engineering, i.e. in such areas of industry where it is important to ensure the reliability and durability of structures. It is possible to increase the durability of metals, including their yield point, by cleaning the metal melt from particles of impurities and inclusions. The purified metal has increased corrosion resistance, strength, and other improved physical and mechanical characteristics. Impurities also significantly affect the properties of molten metal, which is used as a coolant at nuclear power plants on fast neutrons, in promising thermonuclear reactors.

There are many different technologies for the purification of liquid metals from impurities, inclusions [1-3]. The most famous of them are sedimentation, flotation, filtration. Such cleaning methods have several disadvantages. Their main disadvantage is the impossibility of organizing the simultaneous evacuation of impurities and flow-through mode. This requirement is key for modern industry, including nuclear.

One of the possible methods for solving this problem can be metal cleaning based on the principle of electromagnetic action [4-9]. A potential difference is applied to the system, an external magnetic field is applied. The crossed components of the vectors of the electric current density and the magnetic field will create a volumetric electromagnetic force. Since the particles of inclusions and liquid metal have different electrical conductivity, the electromagnetic force will act on them differently. Thus, the particles of inclusions can be concentrated in a given area.

An important issue is the shape of the particles of inclusions in the liquid metal. On the one hand, different electromagnetic forces will act on particles of different shapes. On the other hand, by chemical action, it is possible to create a special shape of inclusions, which will provide the best efficiency of the electromagnetic action. To do this, it is necessary to know in advance the shape of the particles of...
Inclusions that will be most affected by the electromagnetic force, i.e. will separate better than others from liquid metal.

To solve the problem of determining the shape of particles of inclusions, it is convenient to use the principles of mathematical modeling [10]. The mathematical model will make it possible to study the features of the effect of electromagnetic forces on particles of inclusions in liquid metal. In [11-14] studies were carried out for spherical and cylindrical particles, also the effect of the ratio of the electrical conductivity of an inclusion particle and a liquid metal (in the general case, an electrically conductive liquid) was studied. As part of this work, we will focus on elongated particles of inclusions, shaped like a cylinder with rounded ends. In this study, we will determine the dependence of the electromagnetic force acting on a particle on the aspect ratio of the particle, its orientation, and the ratio of electrical conductivities.

2. Mathematical statement

The proposed approach to constructing a mathematical model in many ways similar to the approach described in the articles [10, 13]. However, the proposed model has a number of features.

The mathematical model is based on the equation of electrodynamics. We consider a cell of liquid metal (representing a conductive fluid), which is composed of a Hx * Hy * Hz block. Inside the cell a pill-form electrically conductive particle having diameter D and a height H.

A potential difference is supplied to the system. The electric current of density j flows through the cell along the X axis. In order to suppress the own magnetic field of electric current (j = µ0σ0B0), an external magnetic field B0 is imposed to the cell along the Y axis. In this case f" = j × B0.

The equations (1-4) describe the electromagnetic part of the task.

\[ 4\varphi = 0 \]  
\[ f'' = j \times B \]  
\[ j = \sigma E = -\sigma \nabla \varphi \]  
\[ B = (0, B_0, 0) \]
Electrodynamic parameters: $\sigma_{\text{part}}$ – is particle conductivity, $\sigma_{\text{Me}}$ – is metal conductivity, $I$ – current strength, $B_0$ – magnetic induction of external field.

Boundary conditions for potential: $\varphi = \varphi_1$, $\varphi = \varphi_2$ – on opposite walls ($x = 0$, $x = H_x$). The problem is numerically solved in the Ansys Emag applications.

3. Results and discussion

We consider the cell with a single particle in the center (the scheme is shown in fig. 1). In the calculations, the cell size $H_x = H_y = H_z$ is fixed and is $H_x = 6.6D$ (it was chosen to be significantly larger than the particle diameter).

An electric current flows through the cell, with a density $j$. The current intensity is calculated as $I = j^* H_y^* H_z^*$. The calculations considered particle inclusions with excellent electrical conductivity from the environment. It is convenient to introduce the dimensionless coefficient $K$, which characterizes the ratio of the electrical conductivities of the inclusion and the liquid metal. $K = \sigma_{\text{part}}/\sigma_{\text{Me}}$. For $K > 1$, the electrical conductivity of the inclusion turns out to be higher than the electrical conductivity of the metal; for $K < 1$ - is vice versa.

For the convenience of determining the characteristic particle size in various calculations, we will use the concept of aspect ratio $\gamma$, i.e. the ratio of the particle height $H$ to its diameter $D$. In addition, in all numerical experiments, we will calculate the normalized electromagnetic force $F^*$. Force $F^* = F/F_{eq}$, where $F_{eq}$ is the force obtained in the calculation for $\sigma_{\text{part}} = \sigma_{\text{Me}}$. Thus, the normalization was performed for an identical calculation with equal conductivity of the particle and the metal. Only the Z-component of the electromagnetic force is considered in the calculations.

Thus, a series of numerical calculations was carried out for a particle whose center coincides with the center of the cell. The aspect ratio $\gamma$ for a particle is $\gamma = H/D = 2$.

![Figure 2. Dependence of the force on the angle from the Z-axis.](image)

From Fig. 2 it can be seen that the greatest value of the force is observed at an angle of 90 degrees for a high-conductive particle. In this case, the smallest value of the force corresponds to an angle of 0 (and 180) degrees, i.e. the case when the particle is oriented across the direction of the current.

The symmetry of the dependence of the force on the angle is observed at angles of more than 90 degrees. In the case of a low-conductive particle (Fig. 2 on the right), the dependence of the force on the angle becomes opposite. In this case, the values of the normalized force turn out to be an order of magnitude smaller.
It is important to determine the shape of the particle on which the largest (and least) electromagnetic force will act. For example, the dependencies for particles with different aspect ratios: long and thin particle ($\gamma = 8$), as well as short and wide particle ($\gamma = 0.5$). In this case, the volume of the particle remains unchanged. A schematic representation of the particles is shown in Fig. 3.

It was found that for high-conductive particles with an equal volume, an elongated and a thin particle (Fig. 3 - a) is affected by a greater force than a short and wide one (Fig. 3 - c) for all orientations of particles, at all angles (Fig. 4).

The dependence of the force on the angle is identical to the graph above (see Fig. 2). For a low-conductive particle (Fig. 4 on the right), the dependence is inverse. Short particles of large diameter are exposed to the greatest influence from the side of electromagnetic forces, i.e. particles with a small aspect ratio.

Figure 4 shows that for a high-conductive particle the force is also greatest at an angle of 90 degrees between the cylinder axis and the Z-axis, i.e. when the particle is oriented along the current spreading (X-axis).

The features of the change in the electromagnetic force acting on the particle are studied, depending on the height and diameter of the particle separately. First of all, the study is carried out for a particle oriented along the Z-axis. Fig. 5 shows the dependence of the normalized force $F^*$ on the aspect ratio of the particle.

The left figure shows the results of calculations for a fixed particle height. On the right figure shows the results with a fixed particle diameter.
Figure 5. $K=10$. On the left - $H$ changes for a given $D$, on the right - $D$ changes for a given $H$.

Figure 5 shows that as the aspect ratio increases, the force $F^*$ acting on the particle decreases, which corresponds to the results above.

In the case of calculations with a low-conductive particle, the change in the force becomes opposite. With the growth of the aspect ratio, the force grows. At the same time, the force values decreased by an order of magnitude.

Figure 6. $K=0.1$. On the left - $H$ changes for a given $D$, on the right - $D$ changes for a given $H$.

It is important to note that for particles oriented along the X-axis, the character of the dependence of the normalized electromagnetic force on the aspect ratio is identical to the above results.

4. Conclusion

In this work, a mathematical model has built that makes it possible to study the features of the effect of electromagnetic forces on inclusions in an electrically conductive medium. The study of the dependence of the electromagnetic force on the aspect ratio of an inclusion particle in a liquid metal is carried out. The features of the location of the particle at different angles to the direction of spreading of the electric current have studied. Both low-conductive and high-conductive impurity particles are considered.

We have received the following. Elongated (with a high aspect ratio) high-conductive particles oriented along the direction of current spreading are subject to the greatest influence of electromagnetic forces. In the case of low-conductive particles, the best effect of electromagnetic forces will be on particles with a small (less than one) aspect ratio, the main axis of which is perpendicular to the direction of current spreading.

The change in the electromagnetic force essentially depends on the ratio of the electrical conductivity of the particle (inclusion) and the metal. For a high-conductive particle, the electromagnetic force decreases with the increasing aspect ratio of the particle. The opposite situation is observed for a low-
conductive particle. The strength increases with the growth of the aspect ratio. In this case, for a high-
conductive particle, the value of force turns out to be an order of magnitude higher.

The results obtained make it possible to proceed to the study of the representative volume of a cell
with a set of particles of different shapes and, in the future, to proceed to the formulation of the
constitutive relations. After that, it will become possible to formulate the constitutive relations for the
impurity particles that are in the liquid metal under the influence of electromagnetic forces.

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References
[1] Leenov D, Kolin A 1954 Journal of Chemical Physics 4 683-688.
[2] Zhang L et.al. 2014 Metallurgical and materials transactions B 49B 2153-2185.
[3] Xu Z, Li T, Zhou Y 2007 Metallurgical and Materials Transactions A 38 1104-1110.
[4] Makarov S, Ludwig R, Apelian D 2000 IEEE Transactions on Magnetics 36 2015-2021.
[5] Afshar M, Aboutalebi M, Guthrie R, Isac M 2010 International Journal of Mechanical Sciences 52
1107 1114.
[6] Han J, Xiao J, Qin W, Chen D, Liu W 2017 JOM 69 1563-1569.
[7] Tanaka Y, et.al. 1997 Magnetohydrodynamics 33 238-242.
[8] El-Kaddah N, Patel A, Natarajan T 1995 JOM 47 46-49.
[9] Taniguchi S, Brimacombe J 1994 ISIJ International 34 722-731.
[10] Kolesnichenko I 2013 Magnetohydrodynamics 1 217-222.
[11] Shu D, et.al. 2000 Metallurgical and Materials Transactions B 31B 1527-1533.
[12] Shu D, et.al. 2000 Metallurgical and Materials Transactions B 31B 1535-1540.
[13] Ozernykh V, Losev G, Kolesnichenko I 2020 IOP Conference Series: Materials Science and
Engineering 950 012008. DOI: 10.1088/1757-899x/950/1/012008
[14] Shu D, et.al. 2002 ISIJ international 42 1241-1250.