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MECHANISM OF AN ACOUSTIC WAVE IMPACT ON STEEL DURING SOLIDIFICATION

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Acoustic steel processing in an ingot mould may be the final stage in the process of quality improvement of a steel ingot. The impact of radiation and cavitation pressure as well as the phenomena related to the acoustic wave being emitted and delivered to liquid steel affect various aspects including the internal structure fragmentation, rigidity or density of steel. The article provides an analysis of the mechanism of impac t of physical phenomena caused by an acoustic wave affecting the quality of a steel ingot.

Key words: steel, ultrasound, acoustic treatment, solidification

INTRODUCTION

In practice, steel ingots are not chemically homogeneous. This inhomogeneity, also known as segregation of elements, depends on the grade of steel being cast as well as numerous complex processes of liquation of the steel components during solidification. An increased content of the given component in the steel as compared with its average content determines the occurrence of positive (+) segregation of elements, whereas in the opposite case, negative (–) segregation takes place. The most extensive segregation of elements is observed in the areas which crystallised latest of all.

During the steel casting and solidification process in ingot moulds, no efforts are undertaken to reduce the segregation. However, one of the methods of reducing the extent of segregation of elements can be acoustic treatment of liquid steel in an ingot mould. The information comprising a description of an acoustic wave propagation in a specific medium that liquid steel present in an ingot mould is has not been provided in a comprehensive manner, and the results presented [1] enable efficiency forecasting for the ultrasonic processing of metals depending on the correlation between their overheating and the two-phase zone range between the liquidus and solidus temperatures. The acoustic wave propagation mechanisms described in various publications pertain to low-meting metals, although having entailed similar kinetics of the phenomena occurring in crystallising alloys of low-melting metals and iron, one may assume that the mechanisms of the acoustic wave impact in alloys are close to one another and they depend on such wave parameters as frequency and acoustic power.

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ACOUSTIC WAVE IMPACT IN LIQUID STEEL

The direct effects of the acoustic energy impact include the changes of structure of metals during solidification [2 - 5]. The vibrations caused by ultrasounds remove columnar structures and exert a positive influence on formation of equiaxed gains. This, in turn, influences the homogeneity of metals and reduces their heterogeneity. Structural changes in solidifying metals occur due to the processes taking place in the two-phase zone such as mixing and formation of crystal nuclei. All these changes are caused by the impact of acoustic (usually ultrasonic) waves of specific power and frequency. The propagation of waves also leads to such phenomena as cavitation, acoustic wind and radiation pressure.

Cavitation is a phenomenon enabling formation of small discontinuities and caverns in liquid causing their growth, pulsation and collapse. Caverns are formed as a result of the tensile stress caused by the acoustic wave in its weakening phase. After a cavern is formed, its further behaviour depends on both the liquid properties and the acoustic field characteristics. During cavitation, many caverns occur simultaneously in distances smaller than the wave length, thus creating a cavitation area characterised by high density of external energy and closeness of collapsing caverns. The velocity of the caverns' collapse can be so high that it causes emission of a high-pressure impact which, in turn, leads to formation of microstreams along the wave propagation route. These microstreams resulting from the impact of ultrasounds cause multiple phenomena to occur including structural changes in the crystallising metals and their alloys [3].

In accordance with the theory of cavitation impact on the nucleation velocity described in publication [2], it is commonly claimed that during cavitation, a pulsating cavitation bubble is formed in the liquid metal. During the growth half-period, the bubble suddenly increases its size and the liquid inside the bubble is evaporated. The evaporation and growth phenomena usually cause the bubble temperature to drop. The bubble temperature decrease below the equilibrium temperature leads to overcooling of the liquid metal on the bubble surface, and hence it is probable for the crystal nucleus to be formed on the bubble. During the successive stages of the bubble compression, due to the difference in the velocities of the solid and liquid phase, in the preliminary stage, the crystal separates from the bubble surface and the shock wave emerging while the bubble is collapsing leads to displacing the crystal nucleus to the liquid phase.

However, the available test results [6] imply that using ultrasounds leads to the structure break-up even when no cavitation occurs. Having analysed the influence of the lack of cavitation on the structure break-up, one may claim that a significant impact on this process is exerted by the radiation pressure delivered to the liquid steel as well as the dynamic forces caused by the acoustic currents. The phenomena taking place in liquid steel are beneficial for its mixing and breaking up of the "bridges" formed based on the expanding dendritic arms. These, in turn, can become the crystal nuclei which may lead to the structure break-up.

The specialist literary sources [1 - 6] contain information concerning the changes taking place due to the ultrasonic treatment of low-melting crystallising metals (Bi, Cd, In, Pb, Sn, Zn). The most apparent effect of such treatment being observed is the size reduction in the crystallised grain. This size reduction was applied as a feature determining the degree of acoustic treatability. On such a basis, it was found that metals and their alloys are characterised by different acoustic treatability which depends on various factors such as the strength of the acoustic wave introduced into the metal. One of the factors determining the dependencies studied was a comparison between the magnitude of the crystals break-up zone and the assumed sizes of the cavitation area. It was determined that in all metals tested the break-up zone was 1,5 - 2,5 times larger than the cavitation area.

The publications concerning ultrasonic treatment of ferrous alloys also imply positive influence of an acoustic wave on the structure of such alloys. In studies [7 - 9] the subject of ultrasonic treatment was white cast iron. The results obtained showed fading of the cementite structure orientation and an increase in the size reduction among its precipitates. In the study discussed in paper [7], the sound amplification of liquid cast iron was conducted in a ladle, a chill and a sand mould. The treatment time was 40 - 150 seconds. It was found that, as a result of the processing, the porosity of casts decreased. In all cases, a broken-up structure was obtained and the directional orientation as well as the dendritic structure faded.

RESEARCH METHODOLOGY

The purpose of sound amplification tests conducted for liquid steel in an ingot mould of the weight of ca. 130 kg was to estimate the scope of acoustic wave impact through establishment of axial segregation of carbon, sulphur and phosphorus in carbon steel ingots. The tests were conducted in big-end-down ingots of round cross-section and the height of 600 mm. The test casts were prepared by application of a conventional technology as in the case of industrial casts in an electric induction furnace of the capacity of 300 kg. While preparing two casts, two ingots were formed the first of which was sound amplified and the second one treated as the benchmark. And during preparation of third cast, two ingots were formed with various sound amplification times, i.e. 90 and 300 seconds.

For the sake of the steel sound amplification, a thermally insulated piezoceramic head finished with a wave-guide and fed with a power generator was used [10 - 11]. The electromechanical resonance of a head immersed in liquid steel equalled 17 200 Hz whereas the same measure for water came to ca. 18 100 Hz. Changing the resonant frequency is caused by the difference in acoustic impedance which, in turn, depends on the liquid density and the acoustic wave propagation velocity in the medium. This experiment enabled determination of the most effective frequency of the head's operation that was then applied in the successive trials [11]. However, during the industrial tests conducted, it was found that changing the physical conditions of solidifying steel (temperature, density) as well as the head's load and the increase in temperature of both the piezoelectric ceramics as well as the passive and active part of the head cause that the resonant frequency changes within the range of ca. 17 000 - 18 500 Hz.

In order to prepare the test material, the crop end and the foot were cut out from each ingot, and then the ingots were cut into sections from which longitudinal and transverse disks were sampled. The arrangement of the areas in which samples were taken resulted from the assumptions made for the sake of the tests conducted and they made it possible to expect the most profound changes related to the acoustic wave impact on the crystallising steel in the ingot's upper half. According to the solidification process kinetics, it was assumed that external areas solidified in the first instance, therefore it was expected that the acoustic field had exerted the smallest impact on them.

The homogeneity tests for C, S and P were performed using the Q8 Magellan optical spark emission spectrometer manufactured by Bruker. The spectrometer operation stability was monitored by means of a pilot sample after each 20 measurements of the material being examined. The tests also covered the transverse disks, and five measurements were conducted for each of four levels between the axis and the ingot edge with uniform spacing of the measurement points. The test zones were divided into the ingot core zone (2 measurements) and the core-edge zone (3 measurements). The metallographic tests were conducted at the Institute for Ferrous Metallurgy in Gliwice.

TEST RESULTS

The tests of the ingots chemical homogeneity were performed in order to determine the percentage fraction as well as the positive (+) or negative (-) segregation of the elements showing the segregation inclination, i.e. carbon (C), phosphorus (P) and sulphur (S). The measurement results obtained were correlated with the average content of the individual elements in ingots, and then it was established whether positive or negative segregation occurred. The accumulated results for percentage portions of the individual areas characterised by positive or negative segregation were depicted in Figures 1 - 3, whereas the frequencies at which the individual segregation types occur were compared for the individual elements in the core (A) and core-edge (B) zones of both the sound amplified ingots and the benchmark ones.

With regard to all the elements in question, the results obtained imply considerable differences in terms of concentration of carbon, phosphorus and sulphur across the volume of sound amplified ingots as compared with the benchmark ones. A significant decrease of concentration of the individual elements was observed in the core zone of the sound amplified ingots with the simultaneous increase of their percentage fractions in the core-edge zone of ingots. The results obtained prove the efficiency of the acoustic wave impact inside the liquid core with the solidification front advancing from the ingot mould. The acoustic wave delivered to the liquid steel caused its stirring inside the ingot mould thus partly tearing the dendritic crystals being formed. The detached solid fraction was transported together with the rotary motions caused towards the ingot axis constituting a specific set of heterogeneous nuclei which initiated the formation of crystallisation centres inside the liquid ingot. The results discussed evidence that the hypothesis assuming the possibility of using an ultrasonic wave to influence the quality of a steel ingot cast in ingot moulds is correct. However, in order for this technology to be widely applied, more accurate physical examinations are required to be able to control the process in a manner enabling, for instance, a uniform chemical composition across the entire ingot volume to be obtained.

The results discussed also conform with a previously published [2] theory of cavitation impact on the nucleation velocity assuming that during cavitation a pulsating cavitation bubble is formed in the liquid metal. Then the bubble abruptly increases its size and the liquid inside the bubble is evaporated which is accompanied by a temperature drop facilitating the creation of crystal nuclei on the cooled surface of the bubble. The impact wave emerging while the bubble collapses subsequently causes the crystal nucleus to be shifted to the liquid phase. However, one must bear in mind that a significant impact on the structure break-up and chemical uniformity is exerted by the radiation pressure delivered to the liquid steel as well as the dynamic forces caused by acoustic currents [2].

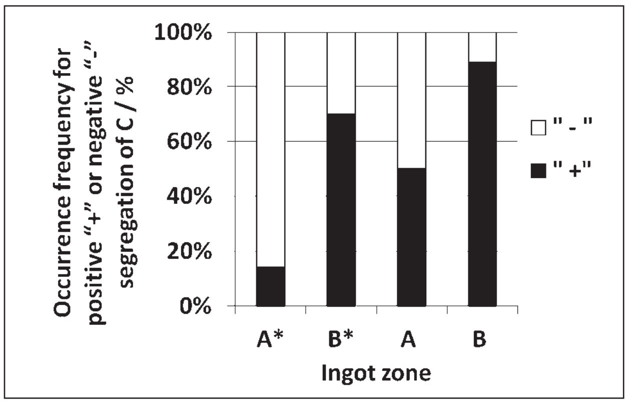

Figure 1 Occurrence frequency for segregation of carbon in ingots (* - sound amplified ingot)

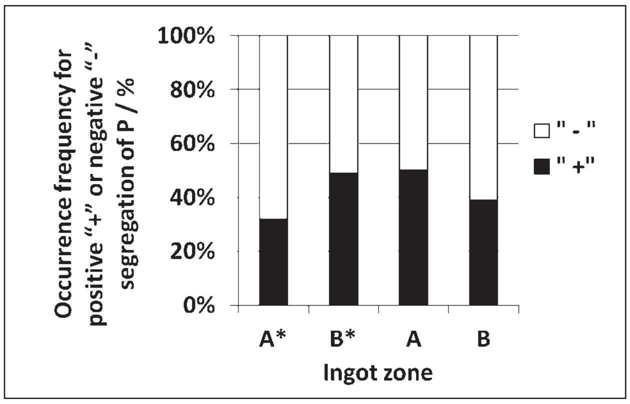

Figure 2 Occurrence frequency for segregation of phosphorus in ingots (* - sound amplified ingot)

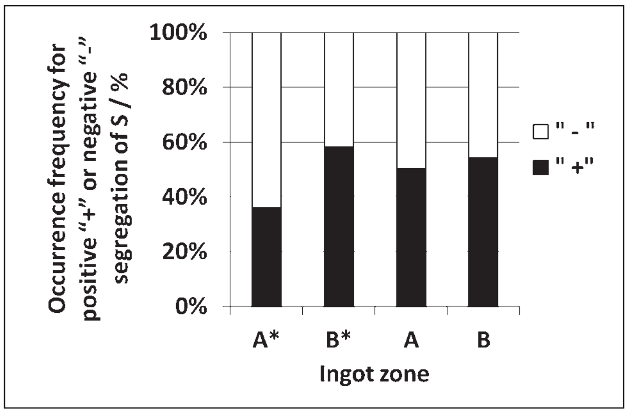

Figure 3 Occurrence frequency for segregation of sulphur in ingots (* - sound amplified ingot)

CONCLUSIONS

The mechanism of the impact exerted by an acoustic wave on steel during solidification is a phenomenon of complex nature as its depends on both the wave's acoustic properties as well as the physical and chemical properties of the medium subject to sound amplification. All the available mathematical models and physical simulations relate to uniform media, hence while conducting steel making examinations one must refer to theoretical descriptions of the phenomena occurring in liquid steel or apply the existing models created for low-melting metals.

So far, no comprehensive description of the acoustic wave propagation mechanism in a specific medium that liquid steel in an ingot mould has been developed, yet the test results discussed prove the possibility of using an ultrasonic wave to control the quality of steel in an ingot mould. In order to establish practical correlations between the impact exerted by the acoustic field generated by an ultrasonic wave in steel poured into an ingot mould and the steel ingot quality, it is required that a series of laboratory and industrial tests be undertaken. Results of such examinations may provide valuable grounds for development of numerical models to be used in the process control.

Based on the tests conducted and the results discussed in the paper, the following conclusions may be drawn:

Direct acoustic treatment of liquid steel poured into an ingot mould of the weight up to 130 kg is possible while using an acoustic head.

The axial segregation of steel in the solid phase caused by the diffusion of elements of lower crystallisation temperature (carbon, phosphorus, sulphur) can be reduced by applying acoustic treatment of the liquid steel in the ingot mould.

The acoustic wave propagating in the liquid steel causes tearing of the growing arms of dendritic crystals which may become the crystallisation nuclei after being transported to the liquid phase.

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Note: P. Nowak is responsible for English language, Katowice, Poland