Study on the Effect of Vibratory Stress Relief on the Quality of Gravity Die Casting—Theory and Justifications

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Abstract. Experimental studies of improvement of the quality of gravity die casting by a low-frequency vibration treatment were carried out. The objective of the study was to establish in principle the possibilities of applying the method of vibration effect in the gravity die casting process for improving the production efficiency. Different testing methods established the advantage of the proposed method comparing to the basic one. The use of the technology of interest reduces a number of casting defects and can be recommended for use in conditions of large production capacities.

1. Introduction

At the current stage of development of the machine engineering, one of the most important and relevant tasks is to develop the resource-saving technologies for reducing the amount of waste in the manufacture of parts made of iron-carbon alloys, and especially of non-ferrous metals. In casthouse production it is of critical importance to reduce casting defects in billets and to obtain parts with minimal allowances for machining.

Foundry is the blank production base for mechanical engineering. Despite the long process of improving the production of castings, the technology of the manufacture thereof has many disadvantages reducing the quality of casting [1]. The analysis of foundries reveals that the casting production suffers significant losses from casting defects.

The number and types of casting defects can be judged on the defective casting storage sites. Here it is necessary to establish a kind of defects, since the correct determination of cause of their occurrence and elimination method depends on it. This is a rather difficult process, because the defect appears due to:

- Variations of process parameters (temperature, humidity, strength, gas permeability, mix gas-generation value etc., totally - more than two hundred parameters)
- Deficiencies in the casting production method
- Seasonal changes in air temperature and humidity
- Inadequate expertise of process staff in foundry shops.

There are some castings with defects formed due to violation of process discipline among the bulk of the sound castings. A distinction is made between casting defects of noncompliance with geometry (misrun, shift, variation in wall thickness, warpage, etc.) or shallow discontinuity (hot cracks, cold cracks, gas porosity, shrinkage cavity, shrinkage porosity, sand inclusions, etc.), noncompliance of casting metal with required structure (chilling, liqutation, etc.) and impurity (metallic/nonmetallic inclusions, etc.).

Defects are divided into two groups – non-repairable and repairable defects. Non-repairable defects (usually large ones) cannot be repaired or repair is uneconomical, so a casting with such defects is considered unfit for use (defective) and is sent for remelting. Repairable defects (usually small ones)
are eliminated in order to make the casting fit for further treatment and use. As the experience of many foundry shops producing shaped castings has shown the most common defects in castings are cavities and cracks. There are only 7 types of blow holes with specific characteristics. Usually two, at best three kinds of gas shells are mentioned. But it is even worse, when the defect is not detected in the billet immediately, but by non-destructive testing method in the already finished part after having passed all the stages of machining and treatment. This indicates that there is a real need to develop a method that helps to assist the foundrymen to reduce various defects and eliminate the causes thereof. As such a method, the use of vibro-impulse exposure is proposed. The main task of experimental studies on mechanical vibration is to determine its rational parameters and overall effectiveness of appliance of this technology for improving the quality of products and confirming the theoretical and laboratory research data of vibration effect in full-scale conditions.

2. Justification of the Need for Vibration Effect

Due to the uneven metal solidification, the phase transformations (during crystallization and cooling), related to the increase or decrease in the volume of individual grains, generate significant residual stresses in the casting process. Reference layers with different densities can be formed in the casting: a thin outer layer consisting of equiaxed crystals, followed by a zone of large elongated columnar crystals, and a central zone of large non-oriented crystals. When the ingot solidifies in its upper part a shrinkage cavity is formed. The near-surface layers solidify faster and create stresses that cause the tensile strain, and the inner layers generate compression stresses that balance the tensile stresses. For this reason and for a number of other reasons, there is a complex pattern of the strain-stress state in the finished product, which negatively affects the final shape of the billet. When calculating the strength of casting, according to the stress diagrams of the destructive forces, the outer layers of the casting experience the maximum stresses and displacements, and the median layers – the minimum stresses and displacements.

One of the most common casting processes, in which defective castings often occur, is the gravity die casting, namely, the casting using a permanent mold – f long-life mold with a melt filling by gravitational forces, and with natural or forced cooling [2]. In many cases, the permanent molds have nonmetallic parts, usually sand cores and inserts, but most of the surface of the casting is formed by the metal elements of the permanent mold, which significantly affects its quality. The disadvantages of gravity die casting, leading to casting defects, include:
- Rapid melt quenching when filling a metal mold, which makes it difficult to produce thin-walled castings, especially with extended walls
- Rigidity of permanent mold which can lead to the casting internal stresses, and as a result to warpage and even cracks
- Limited possibilities for air and gas exhaust from the cavity of the metal form.

To minimize the probability of forming these defects and to reduce the stress gradients, it is proposed to apply the mechanical vibration during metal solidification [3]. The method of low-frequency mechanical vibration is designed to reduce mechanical residual stresses in metal products with high requirements to their quality characteristics. When using the methodology, the natural frequency of the product is determined, after which the structure is subjected to mechanical vibration at a resonance frequency for 15-20 minutes, resulting in a redistribution of mechanical stresses.

3. Method Parameters and Determination of the Engineering Tools

The technology of vibration effect is based on the use of low-frequency vibrations generated by a special device - electric vibrator and it is characterized by absolute ecological purity, low energy costs and high efficiency.

In low-frequency vibration systems, it is most rational to use an eccentric actuator [4, 5]. This type of actuator is able to create large amplitude vibrations at low frequencies. Low-frequency machines also have less dynamic load on the actuator, which allows working with some detuning from the natural frequency of the vibration system, providing greater stability. When using variable speed motors, such as direct current motors or three-phase commutator motors, an actuator with a wide range
of frequency control can be obtained. Using rotary eccentrics, it is possible also to adjust the vibration amplitude.

The difference between machines with a forced eccentric vibroactuator with a rigid connecting rod and machines with a kinematic eccentric vibroactuator is that the vibrations of their working member have an amplitude that does not depend on the dynamic parameters and load of the machine, but is only a function of the kinematic parameters of the actuator.

To select the type of the vibration effect device, it is necessary to calculate the diagram of the machine with an eccentric actuator.

Displacement of the movable operating element of vibration machine shall be according to the law [6-8]:

\[ x = A \sin \omega t \]

where \( A \) – is a displacement amplitude \((A = r)\); \( r \) – is a actuator eccentricity.

Substituting the values \( \frac{d^2x}{dt^2}, \frac{dx}{dt} \) and \( x \) into the equation of motion of the vibration machine, we obtain the following:

\[ mA\omega^2 \sin \omega t + cA\omega \cos \omega t + kA \sin \omega t = P \sin (\omega t + \varphi) \]

(2)

Hence the following amplitude value of the driving force:

\[ P = r \sqrt{(p^2 - \omega^2)^2 + 4n^2 \omega^2} \]

(3)

where \( n \) – is a viscous resistance coefficient, \( 2n = c/M \); \( p \) – is a natural frequency of vibrations of the product with mass \( M \); \( p^2 = k/M \).

The phase difference between the displacement of the working member and the driving force:

\[ \varphi = \arctg \frac{2n\omega}{p^2 - \omega^2} \]

(4)

The power supplied by the vibroactuator to overcome resistances in elastic constraints:

\[ N = m\omega^2 r^2 \]

(5)

Minimum driving force at \( \omega = p \).

In the steady state, under the eccentric vibroactuator operation, the elastic element – vibration mount is deformed, and the deformation depends not only on the parameters of the eccentric, but also on the law of motion of the working member. Due to the fact that the vibration system displaces \( x \) with the speed of \( \frac{dx}{dt} \), the elastic constraint of the actuator is deformed by \( x_0 - x \) with the speed of \( \frac{dx_0}{dt} - \frac{dx}{dt} \).

Here, \( x_0 \) and \( \frac{dx_0}{dt} \) are, respectively, the displacement and displacement velocity of the vibration mount. The dimensionless vibration amplitude \( \frac{A}{x_0} \) depending on the adjustment coefficient \( z = \frac{\omega}{p} \) for various damping coefficients of the elastic vibration mount \( v = \frac{n}{p} \) at different stiffness ratios and resistance coefficients of vibroactuator and vibration mount \( \chi = \frac{p^2}{p_0^2} = \frac{n_0}{n} \) is shown in figure 1.

Experimental studies on the maximum withstand load were carried out to select the type of vibration mounts. The vibration mounts were uniaxially loaded in terms of linear increasing strain. The P-50 pressing machine was used as the power unit, the stiffness of which was provided by elastic elements, extending the support plates of the loading device. As such elements, which compensate the response time of pressing machine, two hydraulic jacks fed from a high-pressure oil pumping station were used. In this case, with an increase in the load on the vibro-support to the ultimate strength, the increased stiffness of the testing machine redistribute the load between the hydraulic jacks and vibration mount, which allows to control the deformation process even beyond the limit of strength.
Mounted on the press displacement and force sensors were sending the signal to the computer through the analog-to-digital converter.

![Graph](image)

**Figure 1.** – Dimensionless vibration amplitude of vibration machine with eccentric vibroactuator — adjustment system coefficient at various damping coefficients curves.

Figure 2 shows the resulting stress-strain curve. Analyzing the curve, we see that the entire period of loading of the vibration mount can be conventionally divided into four stages:

1) – period of elastic strain;
2) – period of elasto-plastic strain;
3) – period of transition to the area of the ultimate strain;
4) – period of unloading.

![Graph](image)

**Figure 2.** – Vibration mount loading diagram
(Stains [mm] along the axis OX — load [kg] along the axis OY curve).

At the first stage (up to 10 tons) the vibration mount is compressed wherein smaller values of displacements in the lateral direction correspond to certain value of the relative displacement in the longitudinal direction, as the particles approach the total friction surface is increased. At this stage, the material becomes consolidated, increasing the differential modulus of elasticity caused by compaction, and as a result - by an increase in the slope of the time-load curve.

The transition from the first to the second stage is shown on the stress curve by changing the sign of curvature - from convexity to concavity, which leads to a decrease in the differential modulus of elasticity and gradual decrease in the slope of the time-load curve, [9].
The transition from the second to the third stage is marked by a maximum of strains (about 46 tons). In this case, the vibration mount is destroyed in the critical areas. After that, there is still some increase in the load up to 49 tons.

After unloading there is a transition to the fourth stage – the stage of the vibration mount shape recovery according to below curve.

Knowing the mass of the product $M$, the parameters of the vibration exposure can be selected, which minimize the casting defects and reduce maximally the residual mechanical stresses.

Based on the results of calculations, the main parameters of the complex of vibration exposure are the following:

- maximum shaking force [kN] 1.8
- synchronous speed [rpm] 1,500
- operating speed range [Hz] 1-200
- rated power [W] 120
- voltage applied to vibrator [V] 220

4. Conclusions

Vibration method widely manages operating effect parameters due to changes in the values of vibration velocity and vibration acceleration, more qualitatively and less costly equalizes the residual compressive and tensile stresses that arise in the billet during gravity die casting. The use of the test technology reduces a number of casting defects and can be recommended for use in large production capacities. The method of low-frequency vibration effect allows processing not only small-sized structures but also structures with a mass of up to 100 tons. In the serial production, the mechanical vibration can be automatically operated on a vibration exciter by a timer. Generally, the cumulative savings at each stage can provide tangible economic benefits as a whole.

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