Scientific Journal of the Ternopil National Technical University
2026, vol. 122, no. 2, pp. 54–62,
ISSN: 2522-4433 Print, ISSN: 2522-4441 Online
https://doi.org/10.35784/ visnyk_tntu2026.02.054

Submitted: 2026-03-01 | Revised: 2026-05-09 | Accepted: 2026-05-26

Technological features of cast iron treatment

Vasiliy Kovbashyn[1,*], Igor Bochar[2]

[1]Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine, kovbashyn_v@ukr.net

[2]Ternopil Volodymyr Gnatyuk National Pedagogical University, Ternopil, Ukraine, igorbochar8414@ukr.net

*Corresponding author kovbashyn_v@ukr.net

Abstract: *The paper deals with the use of vibration technology, which is an effective means of reducing residual stresses in castings. Vibration can be used to achieve a stress relief sufficient to prevent further warping of castings due to the redistribution of residual stresses. In addition, it was shown that residual stresses in cast iron castings can be reduced without vibration by additional static loading with holding under load. The research resulted in obtaining the necessary data to assign vibration modes. It was established that the stress amplitude has a decisive influence on the magnitude of the reduction of residual stresses during vibration. The duration required for the complete stabilization of the stress relief process under vibratory action was determined. As a result of prolonged holding under load after vibration, processes may occur in the sample material that return it to the state before vibration. In other words, if the stress reduction process after vibration stops, it may be reactivated after a certain time. It has been established that for cast iron castings, in which residual stresses reach approximately 10 kg/mm², the stress amplitude during vibration should not exceed 3–4 kg/mm², otherwise there is a risk of cracks in the castings during vibration. The nature of the stress reduction during vibration is probably the same as during natural aging, only the speed of this process during vibration is much higher. After repeated vibration, observations of the samples continued for another four months. After this period, no changes in the magnitude of the stresses compared to the stresses remaining after vibration were detected. The results of this work give grounds to recommend conducting industrial tests of new methods of aging cast iron castings by vibration or static loading with the aim of their widespread introduction into industry.*

Keywords: *cast iron castings, vibration, residual stresses, warping, static loading.*

1. INTRODUCTION

In mechanical engineering, particularly in precision manufacturing, it is of critical importance that the geometric configuration and dimensions of base components – which dictate machine tool accuracy – remain stable throughout extended operational lifecycles.

It is well established that residual stresses within castings undergo redistribution over time, leading to dimensional instability and geometric distortion. Currently, there are no reliable methods to prevent the formation of residual stresses during the cooling phase within foundry molds. Consequently, cast iron components requiring long-term precision typically undergo natural or artificial aging prior to final machining to mitigate these residual stresses [1, 2, 3, 4].

2. METHODS

In recent years, novel vibratory methods for reducing residual stresses in castings have emerged within industrial manufacturing. According to existing data [5, 6], the primary advantage of this technique is the significant reduction in the time required for the aging process, combined with the relatively simple design of the equipment necessary for its implementation. However, it should be noted that published literature on this subject is sparse, and the available data are quite contradictory. Consequently, based on these sources [5, 6, 7, 8], it is impossible to draw definitive conclusions regarding the efficacy of these methods or their optimal parameters. In this regard, a study was conducted to establish the feasibility and extent of residual stress reduction in castings via vibratory treatment, to obtain the data required for determining vibration regimes, and to ascertain whether the stress reduction achieved through vibration is sufficient to prevent future distortion of the castings [9, 10].

The paper objective is to increase the efficiency of processing to reduce residual stresses in cast iron castings. In such products, vibration can be used to reduce stresses and prevent further warping by redistributing residual stresses.

3. RESULTS

The research was conducted using specimens designed as beams of uniform resistance to bending. Each specimen consisted of a rigid central section integrated with four cantilever beams, which served as the functional components of the sample. Stresses within the specimen were induced using calibrated rods inserted into the gaps between the ends of adjacent cantilevers. To ensure optimal loading, the lateral surfaces of the rods featured a specialized chamfer; this allowed the rod to be inserted freely with minimal clearance between the cantilever tips, after which a 90° rotation of the rod generated the required stresses. The selection of this specific specimen design was based on the fact that a bending-type specimen allows for the detection of even minor stress variations within the cantilever sections through simple and precise deflection measurements [11].

Gray cast iron of a specific grade was utilized for specimen fabrication, as it is the most common material for manufacturing base components of machine tools. The determination of initial stresses induced in the specimens, as well as the residual stresses remaining after vibratory treatment, was conducted by measuring the deflection of the free ends of the specimens using a specialized device equipped with a dial indicator (graduation scale of 0.001 mm). While stress levels can be calculated based on the deflection magnitude and the modulus of elasticity, it is well known that for cast iron, the elastic modulus varies with the applied load. Furthermore, the modulus of elasticity may fluctuate due to variations in chemical composition and cooling conditions of the castings, even within the same grade of cast iron. Therefore, to eliminate potential calculation errors, a significant number of specimens underwent calibration. The calibration of the specimens was performed using a specially designed fixture on a universal testing machine. Based on the calibration results, a correlation between the induced stresses and the deflection of the cantilevers was established. This relationship allowed for the selection of a calibrated rod diameter that would ensure the required initial stress levels in the cantilever sections during loading. The stress calculations during specimen loading were performed using standard formulas of the strength of materials, by dividing the bending moment by the corresponding section modulus [12, 13].

The stresses remaining in the specimen after relaxation were determined using a formula that assumes a trapezoidal distribution of relaxed stresses in the cross-section of the specimen.

It includes the initial maximum stress in the cantilever beam, the maximum stress remaining after relaxation, and the conditional maximum stress corresponding to the triangular law of stress distribution across the cross-section [14, 15].

The method of loading samples before testing was chosen based on the following considerations. It is known that due to the inclusion of graphite, plastic deformations in cast iron begin even under insignificant loads and this process is particularly intense in the first moments after loading. In production conditions, castings are usually sent for machining several days after removal from the mould. Accordingly, the plastic deformations that occur in castings during the formation of residual stresses are likely to be complete by the time they arrive for machining. According the magnitude of plastic deformation under load for the cast iron under study is approximately 9–11% of the total deformation. Therefore, in order to eliminate possible errors in assessing the effect of vibration on stress reduction in cast iron castings and to ensure sufficiently good repeatability of results, the following method of preparing samples for testing was adopted. The sample was preloaded with rods designed for the study and kept under load for 24 hours. Then the sample was unloaded, measured, and these dimensions were taken as initial values in the calculations of stresses arising both as a result of loading the samples and as a result of relaxation of the initial stresses.

Prior to the primary vibratory tests, specialized experiments were conducted to determine the impact of potential plastic deformations at the base of the cantilevers on the deflection magnitude. Such deformations could be induced by stress concentration at these points. These preliminary experiments demonstrated that plastic deformation at the cantilever base has virtually no influence on the overall magnitude of their deflection.

Vibration of the specimens was performed using both a resonance-based fatigue testing machine and conventional pneumatic vibrators typically employed in molding machinery. In both scenarios, the specimen mounting configuration remained identical. The calibrated rods used for loading were pivotally secured within two fixed, rigid supports, while an alternating load in the form of a concentrated force was applied to the massive central section of the specimen. Consequently, alternating stresses of a specific amplitude and frequency were superimposed onto the initial loads at the specimen edges. Regulation and monitoring of the vibration regime were conducted via strain gauges bonded to the cantilevered sections of the specimens; the resulting electrical signals were transmitted through an amplifier to an oscilloscope. In addition to continuous visual observation, the vibration parameters were recorded every 30 minutes. The following data were considered when selecting the initial stress magnitudes. It is well known that higher stress levels in metal accelerate the relaxation process. Accordingly, if vibration facilitates stress reduction, this effect should be most pronounced at relatively high stress levels. On the other hand, it has been established that in actual cast iron machine tool components, residual stresses can reach up to 10 kg/mm^2.

It was assumed that the most effective impact of vibration on the stress reduction process could be achieved with significant amplitudes of oscillation in the sample. However, the increase in the amplitude of oscillation is limited by the fatigue strength of cast iron, and excessive amplitude and sufficient duration of vibration can cause the sample to break.

The first series of vibratory tests was conducted to determine the impact of oscillation amplitude on the degree of stress reduction. The experiments were performed using a resonance machine with amplitudes ranging from 1.5 to 4.7 kg/mm^2, while maintaining a constant oscillation frequency of 3,000 cycles/min. The vibration duration varied from 0.5 to 6 hours. The test results are presented in Table 1.

Table 1. The initial stage of research.

Initial stress in the specimen, *kg/mm²*	Stress amplitude, *kg/mm²*	Vibration time, *h*	Reduction of stress during vibration, %
10,7	1,5	6	14
11,2	1,5	6	14
10,6	3,5	0,5	20
11,2	3,5	0,5	18
10,7	3,5	6	22
9,7	4,0	3	25
10,7	4,0	3	23
10,4	4,7	1	27

As observed, the reduction of stresses resulting from vibration is strongly dependent on the vibration amplitude: a higher amplitude leads to a more significant stress reduction. However, when the vibration amplitude exceeds 3.5–4 kg/mm² and initial stresses are approximately 10 kg/mm², the risk of specimen failure during vibration increases sharply. These tests also demonstrated that stress reduction occurs primarily within the first half-hour of the process. While further increasing the vibration duration does lead to additional stress decrease, the magnitude of this reduction is relatively minor.

To determine the effect of vibration frequency on stress reduction, a second series of tests was conducted using pneumatic vibrators at frequencies of 7,600 and 12,000 cycles/min, with a nearly constant vibration amplitude ranging from ±2.8 to ±3.5 kg/mm². In all cases, the vibration duration was 6 hours. The results are presented in Table 2.

Table 2. Influence of vibration frequency on stress reduction.

Initial stress in the specimen, *kg/mm²*	Vibration amplitude, *kg/mm²*	Vibration frequency, *cycles/min*	Stress reduction, %
8,7	2,8	7600	18
11,7	3,0	7600	18
9,8	3,5	7600	23
8,5	3,0	12000	18
9,0	3,2	12000	20
11,5	3,5	12000	22

As can be observed, the stress reduction during vibration is of the same order of magnitude as in the first series of tests at similar vibration amplitudes. Thus, even a significant increase in the vibration frequency – from 3,000 to 12,000 *cycles/min* – has virtually no effect on the efficiency of vibratory stress reduction. These results provide a basis for proposing the following mechanism for stress reduction during vibration: If residual stresses exist within a casting, the additional loading induced by vibration triggers plastic deformations in the material. Once the vibration ceases and the additional load is removed, the magnitude of the residual stress becomes lower than the initial value due to these plastic deformations.

To test this hypothesis, experiments were conducted in which specimens were loaded to a stress level of approximately 10 *kg/mm²*, held under load for 24 hours, and then unloaded. Subsequently, they were reloaded to a stress level of approximately 13.5 *kg/mm²* to allow for a comparison with the vibration mode at a stress amplitude of ±3.5 *kg/mm²*. The specimens were held under this increased load for an additional 6 hours, after which the percentage of stress reduction relative to the initial 10 kg/mm² load was determined. The results of these experiments are presented in Table 3, which also includes comparative data for specimens subjected to vibration for 6 hours.

Comparing the magnitude of stress reduction resulting from additional static loading and vibration, it can be concluded that simple static loading can also reduce stresses in cast iron castings; however, this reduction is approximately 25–30% lower than that achieved through vibration. It is probable that vibration, by creating repeated additional loading cycles, leads to a more significant stress reduction than a single static load application.

The conducted experiments demonstrate that vibration is essentially an effective method for applying additional load to various sections of cast iron castings to reduce residual stresses. At the same time, residual stresses can also be reduced through simple static loading. To achieve the same percentage of stress reduction as that provided by vibration, higher levels of additional stress must be applied. This is easily attainable since static loading carries no risk of exceeding the material's fatigue limit, and the safety margin relative to the static ultimate strength is significantly larger.

Table 3. Additional static loading and vibration.

Specimen type	Initial stress, *kg/mm²*	Additional stress, *kg/mm²*	Stress relief, %
Vibratory	10,7	3,5	22
	9,8	3,5	23
	11,5	3,5	22
	9,7	4,0	25
	10,7	4,0	23
Non-vibrated	10,7	4,2	18
	11,0	3,9	18
	10,3	3,3	17
	10,4	3,3	17
	10,8	3,2	18

To determine the time required for the stress reduction process under vibration to reach completion, the following series of tests was conducted. Specimens were loaded to a stress level of approximately 10 kg/mm² and subsequently subjected to a vibration regime designed to ensure maximum stress reduction (vibration amplitude of ±3.5 kg/mm²). During the vibration process, the magnitude of the stresses in the specimens was measured at specific time intervals. The vibration process continued until no further changes in stress magnitude were observed (Fig. 1).

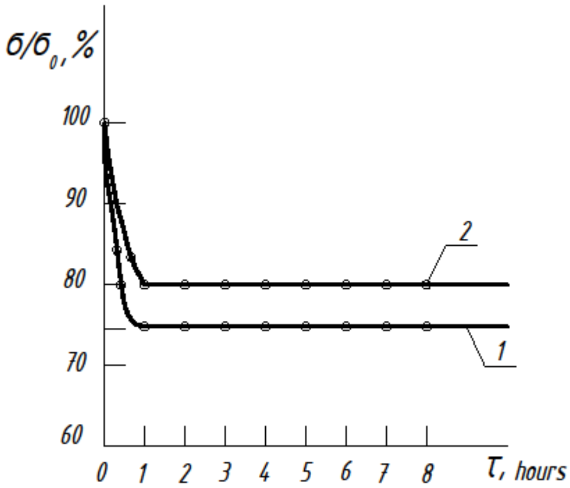

Figure 1. Stress change in specimens at the initial stage
1 – stress amplitude of *10 kg/mm²;* 2 – stress amplitude of 5 *kg/mm²*.

Studies have shown that the stress reduction process occurs most intensively during the initial moments after the onset of vibration. Subsequently, the rate of stress reduction slows down; for initial stresses of approximately 10 *kg/mm²*, virtually no changes in stress magnitude are observed after the third hour of vibration. At lower initial stress levels of approximately 5 *kg/mm²*, the reduction process reaches completion sooner, with no significant changes detected as early as 1.5 hours after the start of vibration.

It was established that vibration can facilitate a reduction in stresses in cast iron castings by approximately 25% of their initial value. Consequently, in cases of high initial stresses, the stress levels remaining after vibration may still be quite substantial. In this regard, it was necessary to determine whether such a reduction is sufficient to prevent subsequent warping of the castings due to the redistribution of residual stresses. To address this issue, a series of tests was conducted in which specimens with initial stresses of 8–10 *kg/mm²* were subjected to vibration at an amplitude of 3.5 *kg/mm²* for 6 hours. Following the vibration, the magnitude of the residual stresses was determined, and the specimens were held under load for an extended period. Subsequent stress measurements were performed every 120 hours.

For an objective assessment of the vibration's effectiveness, a parallel observation was conducted on control specimens that had the same initial stresses but were not subjected to vibration. The research results showed that the vibrated specimens were characterized by a sharp reduction in stress during the first 6 hours, after which no further changes were observed. In contrast, the control specimens exhibited a gradual decrease in stress throughout the entire observation period (Fig. 2).

It was hypothesized that as a result of prolonged exposure to loading after vibration, processes could occur within the specimen material that return it to its pre-vibration state. In other words, even if the stress reduction process ceases after vibration, it might be reactivated after a certain period of time.

To verify this hypothesis, all specimens were subjected to repeated vibration after being held under load for one month. Simultaneously, the control specimens were also vibrated. The results of these experiments are presented in Table 4.

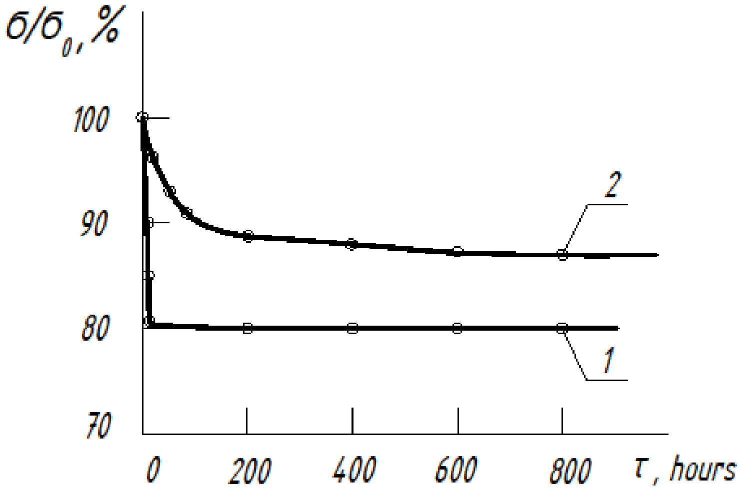

Figure 2. Dependence of specimen stress changes on the duration of the process
1 – test specimens; 2 – control specimens.

Table 4. Repeated vibration of specimens after prolonged exposure.

Specimen type	Initial stress, *kg/mm²*	Stress relief following the first vibration cycle%	Stress relief following the second vibration cycle
Vibratory	9,5	25	25
	9,0	18	18
	10	23	23
	8,0	23	23
	8,0	20	20
Control	10	—	—
(after a 1-month aging period)		10 (aging)	20 (post-aging vibration)
	8,5	13 (aging)	18 (post-aging vibration)
	10,5	13 (aging)	18 (post-aging vibration)
	9,0	10 (aging)	18 (post-aging vibration)
	8,5	10 (aging)	18 (post-aging vibration)

As seen from the table, repeated vibration of the specimens after prolonged holding did not lead to any changes in the magnitude of stresses. Vibration of the control specimens resulted in a reduction in stress; furthermore, the total stress reduction in these specimens – resulting from natural aging followed by vibration – was approximately the same as in the specimens subjected to vibration immediately. This suggests that the nature of stress reduction during vibration is likely the same as during natural aging, although the rate of this process is significantly higher under vibration.

Following the repeated vibration, observations of the specimens continued for an additional four months. After this period, no changes in stress magnitude were detected in comparison to the residual stresses remaining after the vibration treatment..

4. CONCLUSIONS

The conducted research demonstrated that vibration is an effective means of reducing residual stresses in castings. It was established that the vibration amplitude has a decisive influence on the magnitude of residual stress relief. Furthermore, the time required for the complete stabilization of the stress relief process under the influence of vibration was determined.

It was established that for gray cast iron castings with residual stresses of approximately 10 kg/mm^2, the vibration amplitude should not exceed 3–4 kg/mm^2. Exceeding this limit poses a risk of crack formation in the castings during the vibration process.

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