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Analysis of the Effect of Temperature on the Ultimate Strength of Refractory Materials

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Abstract: The energy efficiency of high-temperature batch aggregates largely depends on the modes of their heating and cooling. The modes of heating and cooling of aggregates in which thermal stress does not exceed the critical values of the ultimate strength of the refractories make it possible to increase their service life. The increase in the service life of refractories will lead to a reduction in the number of lining repairs and a decrease in the specific consumption of refractory materials per ton of technological product. Shorter warm-up and cool-down times result in lower energy consumption. Reducing the time for variable modes for casting ladles increases their turnover (the number of melt discharges into the ladle per day). Increasing ladle turnover not only reduces the number of ladles but also improves the economic performance of the enterprise. The ultimate strength of the refractory material significantly affects the rate of temperature change during heating and cooling of the refractory masonry. The purpose of this research is to study the dependence of the ultimate compression and tensile strengths of chamotte materials of the ShKU brand on temperature. The determination of the compression and tensile strengths was carried out on new samples of refractory materials as well as on samples of refractories that were in operation until the intermediate repair. To determine the ultimate compression strength of chamotte refractories, the standard technique for axial compression of the test specimen until its destruction was used. To determine the ultimate tensile strength, a three-point bending test was used with additional control of the surface temperature of the test sample during the test. The ultimate compression strength of chamotte refractories of the ShKU-32 brand increased for the new refractories by a maximum of 44%. For refractories that were in operation until the intermediate repair, the ultimate compression strength increased by a maximum of 56%. The value of the ultimate tensile strength at elevated temperatures turned out to be higher than the value at a temperature of 20 °C. For new refractories, the maximum ultimate tensile strength is 25% higher than the ultimate tensile strength under normal conditions. For refractories that were in operation until the intermediate repair, the maximum ultimate tensile strength increased by 24%. The obtained results can be used to increase the rate of heating or cooling of linings.

Keywords: ultimate strength of refractory materials; lining; high temperature aggregates; thermal stresses; chamotte refractories

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1. Introduction (Problem Statement)

The energy efficiency of high-temperature aggregates is largely determined by the operation of the linings. For example, heat losses of aggregates to the environment during operation depend on the condition of the lining. In addition, the service life of the lining of some high-temperature aggregates (casting ladles and tundish ladles, arc and rotary furnaces, etc.) is a determining factor for the repair work.is a determining factor for the repair works.

The modes of heating and cooling of aggregates in which the thermal stress does not exceed the high values of the ultimate strength of refractories make it possible to increase their service life, reduce energy consumption, and increase the economic level of the enterprise.

The ultimate compression and tensile strength limits, to a large extent, affect the rate of temperature change during heating and cooling of the refractory masonry.

Passport data for molded refractory materials contains, as a rule, data on the ultimate compression strength of materials. The ultimate tensile strength of the material is not given in the passport data for refractory materials.

To determine this characteristic, it is proposed to use the dependence of the ultimate tensile strength on the ultimate compression strength. In the paper [1], the dependence of the ultimate tensile strength of refractories σ_{ten} on the ultimate compression strength is given as: $\sigma_{ten} \approx (0.16 \div 0.12) \cdot \sigma_{com}$.

The use of this ratio is incorrect. This fact is confirmed by the authors of the paper [2]. Researchers experimentally determined the ultimate compression and tensile strengths for periclase-carbon refractories. The results obtained show that the ratio of the ultimate compression strength to the ultimate tensile strength is 4.2 and 16.3 for the two types of refractories, respectively. Thus, the range specified in [1] has changed significantly for a number of refractory materials.

Production schedules for heating high-temperature aggregates do not always take into account the specifics of the technological process and the properties of the materials used. The rate of heating used is often the rate recommended by the manufacturer of refractory materials. This speed is an approximate value that does not take into account the lining thickness, the presence of thermal insulation layers, etc. Production schedules for lining heating may have periods when the heating rate exceeds critical values. Sometimes a low heat-up rate significantly increases the heat-up time. The absence or incorrect operation of control and measuring devices for measuring the temperature of the lining exacerbates the situation. As a result, some of the heating schedules for high-temperature aggregates are irrational in terms of heating time and thermal stress. For example, the heating curve of a 25-ton steel-casting ladle (with a total heating duration of 24 h) has sections where thermal stresses exceed the limit values. The total duration of these sections is 4 h 10 min [3]. The inner surface of the lining reaches its maximum temperature already after 16 h of heating. In the last 8 h of heating, only the maximum temperature of the lining is maintained.

A higher value of the ultimate strength will increase the average calculated heating or cooling rates of the lining [4]. Knowing the dependence of the ultimate strength on temperature, it is possible to calculate the rates for heating or cooling. Heating or cooling the lining at a constant rate is not rational, as this will slow down the process. High rates of temperature change will lead to the destruction of the lining.

When developing rational schedules for heating or cooling the lining, the rate of change in the temperature of the lining can be higher if there is a margin of safety for refractories. Conversely, when the ultimate strength decreases below the standard values, lower rates of temperature change are required. The development of rational heating schedules consists of calculating the heating rates at the level of critical speeds without exceeding the limiting speeds [3]. This will make it possible to reduce the duration of heating or cooling operations on the lining and increase the productivity of high-temperature aggregates. In addition, the availability of data on the ultimate strength at elevated temperatures will not allow heating the lining at rates that are destructive to the lining. For the refractories that have been in operation until the intermediate repair, the dependence of the ultimate tensile strength on temperature will be important in the development of cooling schedules. An analysis of the literature data [1,3] shows that during cooling, the rate is limited by tensile thermal stresses.

But the large number of types of refractory materials used and the specific operation of high-temperature aggregates do not allow using the obtained data for other aggregates.

The high rate of heating of the linings of high-temperature aggregates leads to a significant temperature difference across the cross section of the lining [5]. The temperature difference is the cause of thermal stresses in the cross-section of the lining. When the value of thermal stresses exceeds the value of the ultimate strength of the material used, its destruction occurs. Thermal stresses arising in the refractory due to the expansion of some layers relative to others cannot be compensated by expansion joints.

The mechanisms of destruction of the lining under the action of tensile and compressive forces are different [6]. When compressed, the viscous behavior of the refractory material is observed, which contributes to the formation of microcracks. In tension, quasi-brittle destruction takes place under the action of much lower forces.

This article will consider thermal stresses that occur in the lining due to the uneven temperature profiles of individual masonry elements.

With the correct calculation of the necessary compensation for the thermal expansion of the lining, the destruction of the masonry will occur only when the thermal stresses exceed the ultimate compression or tensile strength of the material.

When heated, a compressive stress (σ_{com}) arises in the high-temperature section of the lining, and a tensile stress (σ_{ten}) arises in the low-temperature section. During cooling, the masonry layers on the hot side of the lining are subjected to tensile stresses. Ceteris paribus, fast cooling is more dangerous for the lining than fast heating. The danger of fast cooling of the lining is explained by the significant difference between the ultimate compression strength and the ultimate tensile strength of refractories [3].

The value of the ultimate tensile strength of refractory materials is important for calculating the operating modes of the lining at the following points in time:

- during the heating of the lining (when the layers are heated). The authors of the paper [7] note that during the heating of a steel-casting ladle, the formation of destructive thermal stresses is possible even at a temperature change rate of about 40 °C/h;
- during the period of downtime between fuses (for batch aggregates). According to the paper [8], the temperature of the inner surface of the lining after the first thermal cycle decreases from 1650 °C to 1250 °C within 1 h;
- in the process of equipment cooling before intermediate repairs with partial replacement of the lining. In the paper [9], calculations of the thermal stresses arising during the cooling of the lining at different rates were carried out. It was revealed that tensile stresses can become critically high and lead to the destruction of the lining material;
- during steady-state thermal conditions. As noted by the authors of the paper [9], tensile stresses during the steady-state thermal condition are on the cold side of the lining and are considered less critical since they are localized in its narrow region.

An analysis of the above-mentioned periods of operation of the lining shows that the most significant influence on the destruction of the lining is exerted by thermal stresses that occur during heating and cooling. The rates of temperature change of the lining during heating and cooling are at their maximum. Even at low rates of temperature change, there is a possibility of thermal stresses that destroy the used refractories. It should be noted that the adjustment of heating schedules is associated with insignificant economic costs for reducing thermal stresses.

Considerable attention is paid to the rationalization of the heating process in the technical literature [10]. At the same time, the main emphasis in scientific developments is on thermal compressive stresses. Cooling processes have not been adequately presented in the literature. In practice, the process of cooling the lining of high-temperature aggregates is carried out without taking into account the properties of refractory materials, masonry geometry, etc. In the paper [11], a calculated schedule of uncontrolled cooling of the casting ladle after the metal is drained is given. The cooling of the lining from 1300 °C to 875 °C occurred at a rate of 318 °C per hour. With controlled cooling, it is recommended to keep the rate of temperature decrease at a much lower level. The authors of the paper [9] and the paper [12] recommend cooling the lining of a cement roasting rotary furnace at a rate of no more than 50 °C per hour. The presented results define a low cooling rate but cannot be recommended for other units due to the specifics of the furnace operation.

Cooling the lining at low speeds has a positive effect in terms of increasing the resistance of refractories. On the other hand, slow cooling of the lining before repair work reduces the technological performance of the high-temperature aggregate (productivity, equipment operation time, etc.). Therefore, in order to increase the efficiency and operational reliability of high-temperature aggregates, the processes of heating and cooling linings must be carried out according to special schedules developed for a particular aggregate. These schedules should be built on the basis of the properties of the refractories under compression and tension. It is worth noting the importance of determining the thermomechanical properties of refractories depending on temperature; otherwise, the result may be far from the actual operating conditions of the aggregates [13].

Knowing the dependence of the ultimate tensile strength of refractory materials on temperature, it is possible to achieve the maximum rate of change in the temperature of the lining of the aggregate. A number of works provide data on the determination of the ultimate tensile strength of refractory materials [14–17]. The value of the ultimate tensile strength of refractory materials must be determined for the temperature range from 20 °C to the operating temperature of the lining.

Studies [18,19] show that with increasing temperature, the ultimate compression strength can change by up to 20% for periclase-carbon and more than twice for diatomite.

It should also be taken into account that the thermophysical properties of refractories are affected by their impregnation with a working medium. In the paper [20], the authors conclude that the composition and physicochemical properties of new refractories and the refractories after operational activity differ significantly. Significant tensile stresses arise when the lining is cooled just after contact with the melt. Therefore, the use of reference values for the characteristics of refractory materials requires a cautious approach.

A review of the literature shows that the recommended rates of heating or cooling of the linings of high-temperature aggregates are of a particular nature in relation to a particular unit. The use of general recommendations for heating or cooling the lining can lead to its destruction even at low rates of temperature change.

The ultimate tensile strength of refractory materials largely depends on temperature. In some temperature ranges, the tensile strength of refractories is higher than its value under normal conditions. The use of these dependences will make it possible to carry out the processes of heating and cooling linings at high rates. Since passport data for refractory materials do not contain these dependencies and it is difficult to find these values for a specific material in the scientific literature, direct measurements in the laboratory are the only way to obtain dependences of ultimate tensile strength on temperature.

2. Materials and Methods

Below will be an assessment of the effect of the temperature difference in the lining on the destruction of the masonry elements of the casting ladle of the ferroalloy production.

Casting ladles for ferroalloy production are designed for draining the melt into them, transporting it to the casting site, and directly pouring the melt. The frame of the bucket is steel, welded, and 20 mm thick. The ladle has the shape of a truncated cone with a spherical bottom. The ladles have a drain spout on top, through which excess slag is discharged into slag bowls and the melt is drained into casting form.

A standard ShKU-32 chamotte brick (JSC "Borovichi Refractories Plant", Borovichi city, Novgorod Region, Russia,) is used as a refractory lining. The total thickness of the ladle lining is formed from two rows of bricks (protective refractory and working). The thickness of each row is 80 mm.

The duration of the working campaign of the linings of the casting ladles under consideration is from 4 to 10 melts and depends on the type of ferroalloys being smelted (ferrochromium, ferrosilicomanganese, and ferrosilicon). The low resistance of linings is due to a number of reasons, among which two main ones can be distinguished. Firstly, insufficient heating or lack of heating of the lining of the ladles before draining the melt into them from the furnace creates significant thermal stresses. Secondly, low-quality refractories are used for lining, for example, chamotte with low thermal strength characteristics. According to the Aksu Ferroalloy Plant (Aksu City, Pavlodar region, Kazakhstan), refractories of the ShKU-32 brand used for lining ladles have the following properties: the mass fraction of Al2O3 is at least 32%; the ultimate compression strength is at least 27 N/mm^2; the ultimate tensile strength is not specified. The value of the ultimate tensile strength for ShKU refractories, equal to 6 N/mm^2, is taken from the reference literature [1].

A visual assessment of the state of the masonry of casting ladles after the withdrawal for intermediate repair (after five fuses) shows that the destruction of refractory occurs evenly over the entire height of the ladle. In the region of the slag belt and drain spout, the greatest destruction of refractories is observed due to the additional impact of the alloy jet and the chemical impact of the slag (Figure 1).

Figure 1. The state of the masonry of casting ladle after five fuses.

The behavior of refractory materials under various cyclic loads can also be judged from the microstructure of refractories. In the works [21,22], the microstructure, characteristics, and properties of refractories (compressive strength, tensile strength, and crack resistance) were studied at various temperatures. The assessment of microstructural damage was carried out on refractory samples using a microscope METAM-32. In the articles, a significant effect of tensile load on the destruction of the structure of refractories is proven.

Figure 2 shows the state of a refractory brick taken from the working layer of the lining (at a distance of 40 mm from the contact surface with the melt). Numerous micro- and macrocracks with branches are visible. The reason for the formation of these cracks is the temperature effect. Similar results from studying the effect of temperature drops on the change in the structure of refractories are given in [23]. Cracks are intergrain, and, according to the gradation presented in [24], they can be attributed to operational ("hot") cracks.

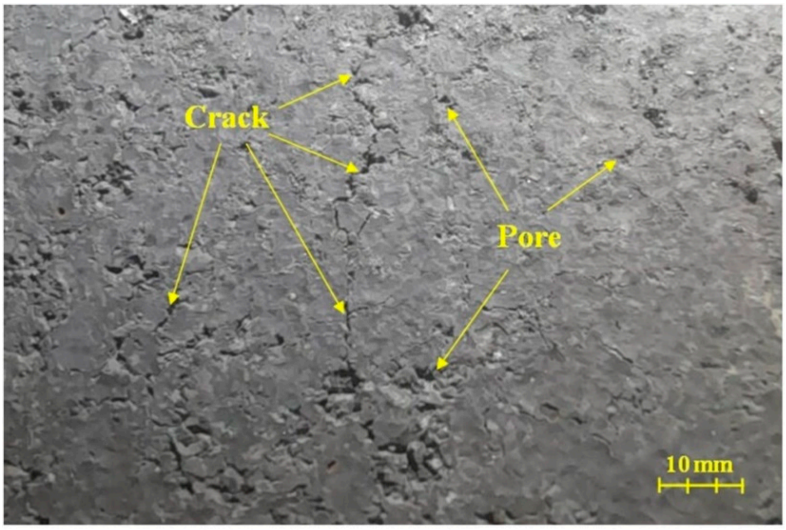


Figure 2. Condition of the refractory brick from the working layer of the lining.

An analysis of the destruction of refractory materials allows us to conclude that the presence of a significant temperature difference over the cross section of the lining in the processes of heating and cooling is one of the main reasons for the destruction of the masonry.

The determination of the ultimate compression strength is standardized [25]. The measurement results given in the technical literature have a fairly high accuracy [5,26].

In this work, the determination of the ultimate compression strength was carried out in accordance with [25] for samples in the form of a cube with a side length of 30 to 50 mm. After heating the samples in the furnace to the test temperature, they were subjected to unilateral loading until destruction. The maximum recorded pressure is the ultimate compression strength.

Classically, the ultimate tensile strength is determined by axially stretching the sample until it breaks (when forces are applied to its end sections). In this case, the magnitude of the tensile strength is determined by direct measurement. But the use of this method has a number of disadvantages. First, these measurements take a long time (including sample preparation) [27]. Secondly, tensile tests are very sensitive to the eccentricity of the applied loads and the heterogeneity of the test material [28]. These factors can introduce a significant measurement error and make the results less valuable for use [29].

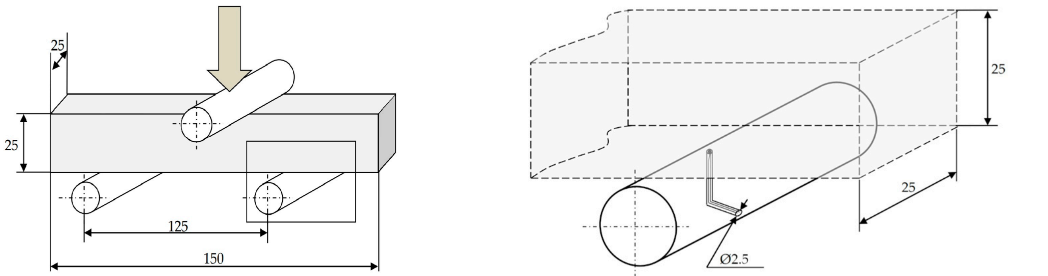
Currently, the method for determining the ultimate tensile strength by cleavage, as well as cleavage using a wedge, is widely used [30,31]. This method is technically simpler than the axial tension method, and it has a relatively high accuracy [32]. The accuracy of determining the ultimate tensile strength by cleavage is higher than that of a direct tensile test.

Based on experimental tests for cleavage or bending of wedges, only the destruction energy can be directly determined. The ultimate tensile strength and the shape of the softening curve are obtained by inverse analysis [31]. The results obtained do not always satisfy the specified accuracy of the research. For example, in [33] it is noted that the values obtained for the zones of extrema of load curves have a rather large error. Thus, it would be incorrect to talk about the universality of this method. Other researchers who have carried out work to determine the ultimate tensile strength also claim that they have obtained incorrect results [34]. The error in the results is explained by deviations in the destruction of refractories from the purely linear mechanics of elastic fracture (especially at elevated temperatures) and the presence of structural elements of different sizes (grains, etc.).

The application of the three-point bending test [35] assumes the use of only standard testing equipment (presses). This method is quite simple and less sensitive to eccentricity. The disadvantages of the method include the influence of the weight of the sample of the material under study as well as the contribution of friction forces to the measured external work. However, it is noted that these shortcomings can be minimized [33]. The results obtained by the authors [13,36] allow us to speak about the possibility of determining the mechanical strength of refractory materials using a three-point bending test with sufficient accuracy.

To improve the accuracy of process temperature measurement when determining the ultimate tensile strength, the three-point bending test procedure has been improved. The determination of the ultimate tensile strength was carried out as follows: The investigated sample of refractory material, with dimensions of 150 × 25 × 25 mm, was uniformly heated in a furnace to a predetermined temperature. The heating uniformity of the test sample was checked by heating it at a rate of 3 to 10 °C/min. This heating rate does not lead to the occurrence of significant thermal stresses that could damage the sample before testing. After reaching the specified temperature, the sample was removed from the furnace, placed on a hinged bearing, and subjected to loading by acting on the pressure rod. The hinged bearings were located at a distance of 125 mm from each other. The maximum loading pressure was used as a calculated value.

The temperature to which the samples are heated is used as the test temperature. The decrease in sample temperature after removing it from the furnace and during the test itself introduces an error in the measurement. To improve the accuracy of temperature determination, thermocouples were installed in the roller supports and the pressure rod. The hot junctions of the thermocouples must be at the same level as the side surfaces of the pivot bearings and the push rod (Figure 3). Thus, the hot junction of the thermocouple and the surface of the samples under study are in contact.



(**a**) (**b**)

Figure 3. Scheme of the method for determining the ultimate tensile strength (**a**) and the method of installing thermocouples in roller supports (**b**).

The thermocouples in the roller supports and the pressure rod are installed in channels, which are drilled with holes with a diameter of 2.5 mm. The drilled channels do not affect the research process or the overall strength of the roller supports and the pressure rod.

Based on the readings of the sensors, the average surface temperature of the studied refractory sample is calculated. After removing the test sample from the furnace, it is placed on roller supports. The calculation of the arithmetic mean surface temperature of the refractory sample T_{av} is carried out when the temperature on the surface changes by no more than 2 °C in 30 s. To ensure uniform temperature distribution on the sample, the readings of the thermocouples installed in the hinged supports and the pressure rod should differ by no more than 1%. The temperature inside the furnace T_t is taken as the test temperature.

When the difference between the average surface temperature of the test sample T_{av} and the temperature inside the furnace T_t is less than 5%, the sample is loaded until destruction. Otherwise, the sample is reheated and kept in the furnace until the average surface temperature of the sample T_{av} is equal to the temperature inside the furnace T_t (with a difference of no more than 5%) with further loading.

The ultimate tensile strength in bending of refractory materials is defined as the ratio of the maximum load at which the sample was destroyed to the cross-sectional area of the test sample at the site of failure.

The research setup for determining the ultimate tensile strength is shown in Figure 4.

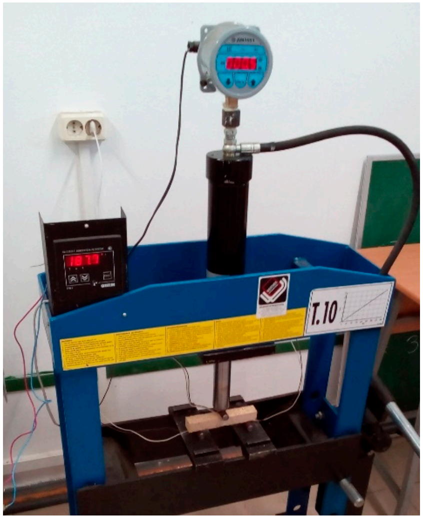


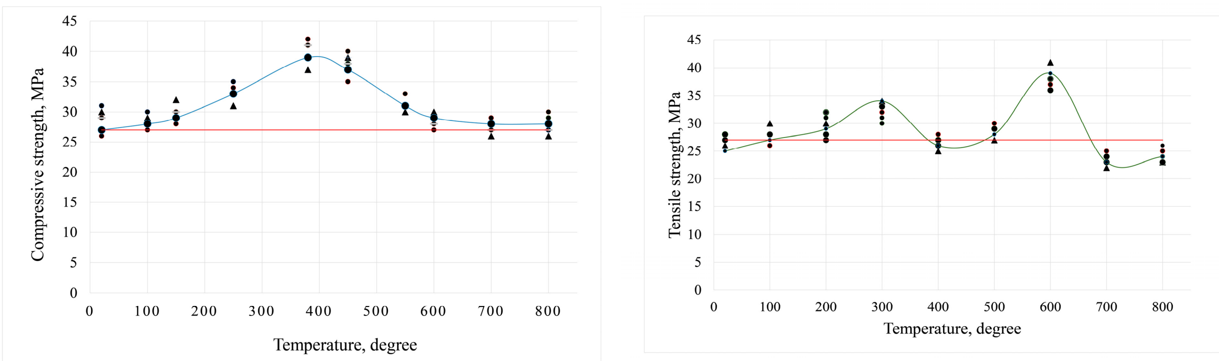
Figure 4. Research setup for determining the ultimate tensile strength.

3. Results and Discussion

Our studies, as well as a review of the literature, show that significant changes in the tensile strength of refractory materials are observed in the range of 100–800 °C [13,18,19,36]. Accordingly, the determination of the compressive and tensile strengths of chamotte refractories was carried out in the temperature range from 20 °C to 800 °C.

Samples after three melts (with a residual brick thickness of 65–70 mm) were cut from the following parts: from the part in direct contact with the melt (0 mm to the hot surface); at a distance of 25 mm from the hot surface; and at a distance of 40 mm from the hot surface. In addition, measurements of the ultimate strength of samples from different rows of lining along the height were carried out. The difference in the obtained values of the ultimate strength of different samples did not exceed 7%. This paper presents the average data on the tensile strength of the samples.

The measurement results are shown in Figure 5 (a—for new refractories; b—for refractories after three fuses).



(**a**) (**b**)

Figure 5. Changes in the ultimate compression strength of chamotte refractories depend on temperature (blue line—obtained dependence; red line—tensile strength at a temperature of 20 degrees). (**a**)—for new refractories; (**b**)—for refractories after three fuses.

Analyzing the change in the ultimate compression strength of new chamotte refractories, it should be noted that the value of the ultimate strength at elevated temperatures is higher than the passport value. The ultimate compression strength at a temperature of 20 °C corresponds to the passport value and is 27 N/mm^2. With an increase in temperature (in the range of up to 400 °C), the ultimate strength has a tendency to increase. The ultimate compression strength reaches 39 N/mm^2. Further, the value of the ultimate strength begins to decrease, and at a temperature of 670 °C, it takes on a value of 27 N/mm^2, which does not change in the range up to 800 °C.

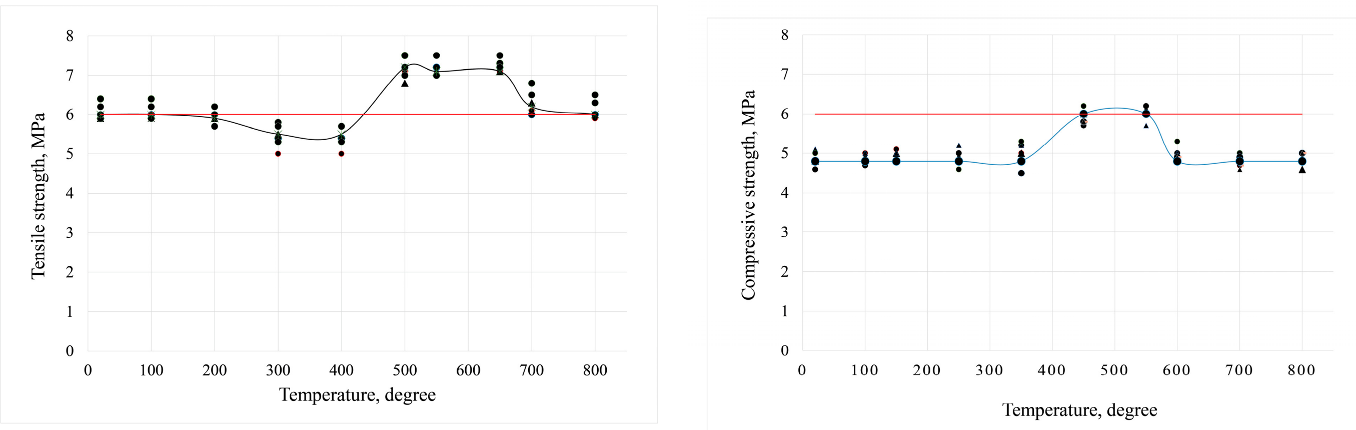
The study of the ultimate strength of refractory specimens after three fuses showed that the graph (Figure 5b) has two maxima (34 N/mm^2 and 39 N/mm^2 at 300 °C and 600 °C, respectively) and two minima (26 and 23 N/mm^2 at 400 °C and 600 °C, respectively). The value of the ultimate strength at a temperature of 20 °C decreased by 7.4%, which is explained by the presence of microcracks and the chemical effect of the melt. The increase in the ultimate compression strength of this sample over the passport value of the new refractory reaches 22% in the temperature range from 100 °C to 380 °C and 40% in the range from 480 °C to 680 °C.

The increase in the ultimate compression strength of the new refractory with increasing temperature is explained by the transition from brittle to ductile fracture. This is facilitated by the transition of aluminum oxide, Al_2O_3, acting as a binder, into a plastic state. For alumina-based refractories, the temperature range from 550 °C to 650 °C is decisive. Here, an increase in ultimate strength is observed. The decrease in ultimate compression strength with a further increase in temperature is associated with the formation of a liquid phase in the refractory and the weakening of interatomic bonds [37]. Similar results of changes in the thermal strength properties of materials based on Al_2O_3 in the temperature range from 550 °C to 650 °C were noted by the authors [38].

The presence of two extrema in Figure 5b can be explained by the effect of temperature and the chemical action of the melt and slag on the refractories during operation.

The maximum increase in the ultimate compression strength for chamotte refractories of the ShKU-32 brand is 44% for new refractories and 56% for refractories that were in operation before the intermediate repair.

The determination of the ultimate tensile strength of chamotte refractories was carried out in the same temperature range (from 20 °C to 800 °C). The measurement results are shown in Figure 6 (a—for new refractories; b—for refractories after three fuses).



(**a**) (**b**)

Figure 6. Changes in the ultimate tensile strength of chamotte refractories depend on temperature (blue line—obtained dependence; red line—tensile strength at a temperature of 20 degrees). (**a**)—for new refractories; (**b**)—for refractories after three fuses.

A relationship was obtained between the value of the ultimate tensile strength and the compressive strength at a temperature of 20 °C. The dependence has the following form: $\sigma_{ten} = 0.22 \cdot \sigma_{com}$.

Analyzing the graphs obtained, it can be argued that for new refractories and refractories that were in operation before the intermediate repair, the dependences under study are similar in nature. The ultimate strength in the temperature range from 20 °C to 350–400 °C almost does not change; only at a temperature of about 350 °C is a slight decrease observed. Further, the ultimate strength increases in both cases. In the range from 500 °C to 650 °C (for new refractories) and in the range from 450 °C to 550 °C (for refractories after three fuses), the ultimate tensile strength does not change significantly. Then the ultimate tensile strength decreases to the initial value (at 20 °C).

The ultimate tensile strength of refractories that were in operation before the intermediate repair decreased by 25% at a temperature of 20 °C. This can be explained by the effect of operating conditions on refractories. Relative to the initial value (at a temperature of 20 °C), the ultimate tensile strength increases by 27% at a temperature of 500 °C. In the range from 450 °C to 550 °C, the ultimate tensile strength of partially exploited refractories is higher than the reference value of new refractories by only 2%.

Thus, the ultimate compression strength of chamotte refractories of the ShKU-32 brand for new refractories is higher than the passport value at 20 °C over the entire temperature range from 20 °C to 800 °C. For partially exploited refractories, the ultimate compression strength is higher than the passport value of new refractories in the ranges from 100 °C to 380 °C and from 480 °C to 680 °C by 22% and 40%, respectively. The dependences obtained correspond to the data obtained by researchers for various refractory materials [18,19,39,40].

The value of ultimate tensile strength for new refractories turned out to be higher than the reference value by 25% in the range from 440 °C to 800 °C. The ultimate tensile strength of refractories that were in operation before the intermediate repair is higher than the value at a temperature of 20 °C by 24% in the range from 450 °C to 550 °C.

4. Conclusions and Future Research Direction

As a result of the research, the influence of temperature on the ultimate compression and tensile strengths of chamotte materials of the ShKU brand was evaluated. Studies were carried out for new refractory materials and for refractories that were in operation before the intermediate repair. At a temperature of 20 °C, the values of the ultimate compression and tensile strengths correspond to the passport values. For new chamotte refractories, the maximum increase in the ultimate compression strength in the operating temperature range was 44%. For refractories that were in operation before the intermediate repair, the maximum increase in the ultimate compression strength was 56%. For new refractories, the maximum increase in the ultimate tensile strength was 25% of the passport value. For partially exploited refractories, the maximum increase in the ultimate tensile strength relative to the initial value (at a temperature of 20 °C) was 24%. The authors plan to study the possibility of using the specified safety margin to increase the heating or cooling rates of the linings.

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