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Effects of Stress Relief Annealing Time on Mechanical Properties and Operating Costs in Lamellar Graphite Cast Iron Engine Blocks

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Abstract: The study explores the impact of extended stress-relief heat treatment durations on the mechanical properties and residual stress levels of motor blocks made from EN GJL-250 lamellar graphite gray cast iron. Motor blocks, which are crucial for high standards of mechanical strength, thermal conductivity, and fatigue resistance, develop internal stresses during mass production due to non-uniform cooling. Two different stress-relief heat treatment cycles were applied to full-scale motor blocks, evaluating their effects on residual stresses, hardness, tensile strength, dimensional stability, microstructure, and operational costs. The results showed that increasing the annealing time reduced residual stresses by 50%-80% without significant changes in hardness, tensile strength, or microstructure. The cost increase associated with the extended cycle was marginal (0.4% per unit).

Keywords: Lamellar graphite cast iron, stress relief annealing, mechanical properties, residual stress, engine block.

Lamel Grafitli Dökme Demir Motor Bloklarında Gerilim Giderme Tavlama Süresinin Mekanik Özellikler ve İşletme Maliyeti Üzerinde Etkileri

Özet: Çalışmada, EN GJL-250 lameller grafit gri dökme demirden yapılmış motor bloklarının mekanik özellikleri ve kalıntı gerilim seviyeleri üzerinde genişletilmiş gerilim giderme ısıl işlem sürelerinin etkisi araştırılmıştır. Yüksek mekanik mukavemet, ısıl iletkenlik ve yorulma direnci standartları için hayati önem taşıyan motor blokları, seri üretim sırasında homojen olmayan soğutma nedeniyle iç gerilimler geliştirir. Tam ölçekli motor bloklarına iki farklı gerilim giderme ısıl işlem döngüsü uygulanarak kalıntı gerilimler, sertlik, çekme dayanımı, boyutsal kararlılık, mikro yapı ve işletme maliyetleri üzerindeki etkileri değerlendirilmiştir. Sonuçlar, tavlama süresinin artırılmasının, sertlik, çekme dayanımı veya mikro yapıda önemli bir değişiklik olmaksızın kalıntı gerilimleri %50-%80 oranında azalttığını göstermiştir. Genişletilmiş döngüyle ilişkili maliyet artışı marjinal olmuştur (%0,4 birim başına).

Anahtar Kelimeler: Lamel grafitli dökme demir, gerilim-giderme ısıl işlemi, mekanik özellikler, kalıntı gerilmesi, motor blok.

Article

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1.Introduction

Engine blocks are among the most critical components in internal combustion engines, housing essential elements such as the cylinders, coolant passages, and the crankshaft. Their mechanical durability, fatigue resistance, and thermal conductivity are vital for maintaining engine performance and reliability under severe operating conditions (Alagar et al., 2020; Abdelrahman & Elmahdy, 2018).

Lamellar graphite cast iron, especially EN GJL-250 (gray cast iron), remains widely used for engine block production due to its excellent thermal conductivity, superior vibration damping characteristics, and cost-effectiveness (Li et al.,2021; Song et al., 2020). Its flake-shaped graphite structure contributes to good compressive strength and machinability, making it a preferred material for high-volume automotive casting applications (Gao et al., 2019).

However, the casting process of gray cast iron, particularly in large and geometrically complex components like engine blocks, often leads to the development of residual stresses due to uneven cooling rates and solidification gradients. These stresses may adversely affect dimensional stability and fatigue life, and in some cases, can cause premature failure under service conditions (Yang et al., 2021; Zhao et al., 2020).

To address these issues, stress-relief heat treatment (annealing) is applied post-casting to minimize internal stresses without significantly modifying the microstructure or mechanical properties of the cast iron (Mishra & Shukla, 2019; Deng et al., 2022). Standard annealing protocols typically involve heating the component to sub-critical temperatures (approximately 550–650 °C), holding for a certain period, followed by controlled slow cooling to ambient temperature (Kim & Lee, 2020).

While the benefits of annealing are well-established, the optimal holding time and cooling rate can vary depending on component geometry, alloy composition, and manufacturing volume. Prolonged holding durations may lead to more effective stress relief but increase energy consumption and production costs. Conversely, insufficient annealing may leave high residual stresses, impacting performance and product reliability (Chen et al., 2023; Zhang et al., 2021).

Therefore, determining the optimal stress-relief annealing time is of both technical and economic importance. In this study, the effect of increasing the annealing duration (from 10 to 15 hours) on the mechanical properties, residual stresses, microstructure, and production cost of EN GJL-250 engine blocks was investigated. The objective is to provide a balance between mechanical performance and cost-effectiveness, contributing to more efficient manufacturing practices in the foundry industry.

2. Materials and Methods

2.1 Materials

The motor blocks used in this study are made of lamellar graphite gray cast iron EN GJL-250 material. The motor block production took place at the Döktaş Orhangazi factory. The raw materials used in the production include gray cast iron, automotive scrap, and recycled runners. The chemical composition of the engine block is shown in Table 1.

The cleaning and grinding processes of the produced motor blocks were carried out in the fettling department of Döktaş. Figure 1 shows the pattern and filter placement in the molding line during the production of the motor blocks. After casting, the blocks are left in the cooling tunnel for 3 hours and then allowed to cool in the atmospheric environment. During this process, internal stresses caused by uneven cooling are generated in the blocks. Therefore, after grinding and cleaning, the blocks underwent stress-relief heat treatment.

Table 1. Chemical composition of the engine block (EN GJL 250).
Tablo 1. Motor bloğunun kimyasal bileşimi (EN GJL 250).

Chemical Composition					
C	Si	S	Mo	Cr	Cu
3.100	2.137	0.77	0.022	0.268	0.663
Sn	Mn	Ti	Mg	P	Ni
0.073	0.857	0.020	0.001	0.026	0.024

Figure 1. Core and filter placement before molding of engine blocks.
Şekil 1. Motor bloklarının kalıplanmasından önce çekirdek ve filtre yerleşimi.

For the heat treatment, the motor blocks were subjected to stress-relief annealing in a System Teknik branded natural gas heated 6-burner trolley-type furnace. During the heat treatment, the stress-relief times and cooling rates of the blocks were considered as variable parameters. These variables were adjusted on the stress-relief heat treatment curve by setting holding times and cooling durations.

The 10-hours and 15-hours stress-relief heat treatment curves are shown in Figures 2 and 3. In the 10-hour heat treatment curve, the temperature reaches 600°C within 2 hours and is held at 600°C for 2 hours. Then, the blocks are cooled in the furnace at 75°C per hour until they reach 150°C, after which the furnace doors are opened. In the 15-hours heat treatment curve, the temperature also reaches 600°C within 2 hours, and the blocks are held at 600°C for 3 hours. Then, the cooling continues at a rate of 40°C per hour until the blocks reach 300°C. After 150°C, the cooling rate is 75°C per hour, and the furnace doors are opened.

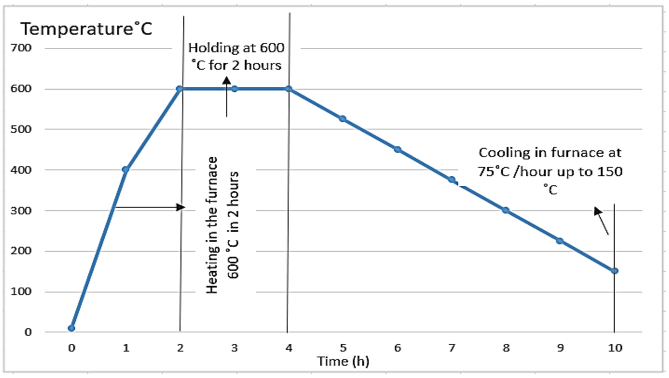

Figure 2. 10 hours stress relief chart.
Şekil 2. 10 saatlik gerilim giderme grafiği.

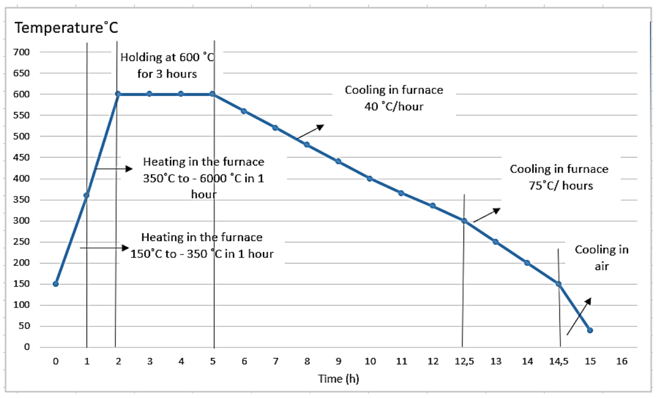

Figure 3. 15 hours stress relief chart.
Şekil 3. 15 saatlik gerilim giderme grafiği.

2.2 Experimental Parameters

In this study, the variable parameters included the holding time and cooling durations in the stress-relief heat treatment curve. Two different stress-relief heat treatment recipes of 10 hours and 15 hours were applied to the motor blocks, and mechanical properties were tested and analyzed after these heat treatments.

2.3 Equipment Used

Dimensional Measurement: Dimensional measurements of the motor blocks were performed using a Coord 3 CMM device.

- Tensile Test: Tensile tests were carried out using a Shimadzu brand device with a 250 kN capacity and an extensometer. The tests were conducted according to customer technical specifications.
- Hardness Measurement: Hardness measurements were taken using a Reicherter brand device with a 10 mm diameter probe and a 3-ton capacity. The hardness measurements were conducted on the head and crankcase surfaces in accordance with ASTM E10-96 standards.
- Chemical Analysis: Chemical analyses were performed using an ARL 4460 optical emission spectrometer. Sampling was done using a ladle sampling tool from the molten metal before casting.
- Microstructure Analysis: Microstructure analysis was carried out using a Nikon optical microscope. The analyses were conducted according to the instructions specified in the customer's technical specifications.
- Residual Stress Measurement: Residual stress measurements were performed using an IMC Chronosflex data collection system and 19 analog channels. The stress measurements were carried out with devices capable of data collection at a speed of 100 Hz.

2.4 Sample Preparation and Testing

Samples from the motor blocks were taken from areas suitable for tensile testing according to customer technical specifications and then machined to conform to DIN 50125 standards using a lathe. A visual of the sample is shown in Figure 4. In order to avoid incorrect results, the tensile test was performed on two pieces from both heat treatments. Hardness measurements were made on samples taken from the head and crankcase surfaces according to ASTM E10-96 standards. In the hardness test measurements were taken from four different pieces. For microstructure analysis, the samples were prepared according to the instructions specified in the customer's technical specifications. The chemical composition of the motor block was determined using the ARL 4460 optical emission spectrometer.

Figure 4. Tensile test sample prepared according to DIN 50125 Standarts.
Şekil 4. DIN 50125 standartlarına göre hazırlanmış çekme testi numunesi.

Strain gage locations for residual stress measurements were determined in accordance with customer requirement specification. The areas are usually the cap areas where the engine blocks are exposed to maximum stress under operating conditions. Each strain gage is of the linear type. The strain gages were oriented parallel to the direction of expected residual stresses (perpendicular to the evacuation cuts). Prior to installing the strain gages, the surface was prepared by applying 'M-Bond AE-10' adhesive to fill the cavities of the rough surface. After 24 hours of curing, the surface was smoothed and the strain gages were installed. Following the application, the motors were transported to the vertical machining center using an overhead crane. Then, the strain gages were connected to the data acquisition unit and energized to ensure optimal working conditions. Residual stress measurement process is shown in the Figure 5.

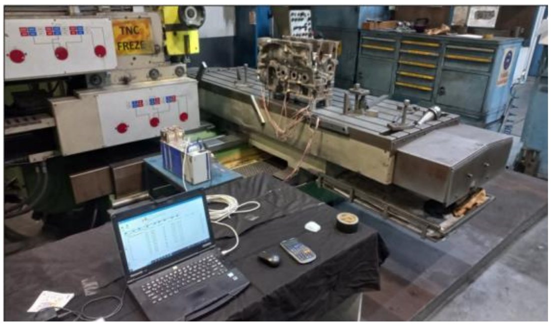

Figure 5. Residual stress measurement process.
Şekil 5. Artık gerilme ölçüm süreci.

Since residual stress tests can take several hours or even days and are associated with high costs, these tests were conducted on two separate specimens. According to the technical requirements, four strain gauge positions were identified as critical in the initial test application. These positions are SG 5.2, SG 5.3, SG 5.5, and SG 5.10. In the second test, strain gauges were applied only at these specific positions. These four locations were selected for the second test because they represent critical values in terms of technical adequacy, and the residual stress results obtained from these points were compared. Visual appearances are shown in Figure 6.

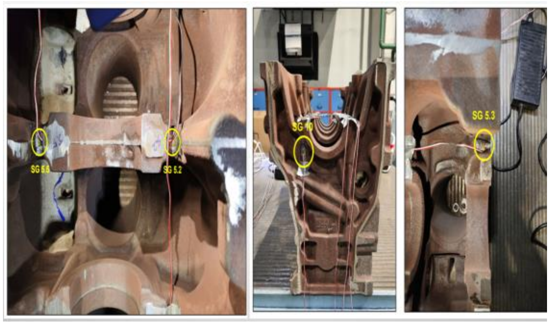

Figure 6. Residual stress measurement positions.
Şekil 6. Artık gerilme ölçüm konumları.

The evacuation process was carried out using a milling cutter operation. Material removal around the strain gauge location continued progressively until a satisfactory cutting depth was reached. This satisfactory depth is defined as the point at which the relieved strain values stabilize and no longer change significantly, even as the cutter proceeds deeper into the material. The stress–time history, derived from the strain data recorded at SG 5.2 during the evacuation process, is presented in Figure 7.

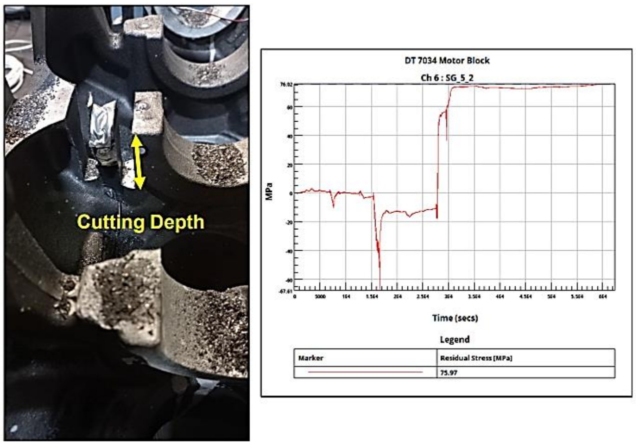

Figure 7. Residual strain measurement and depth of cut image.
Şekil 7. Artık gerinim ölçümü ve kesme derinliği görüntüsü.

Measured strain values for inverted to obtain the residual strains. The residual stresses are calculated with the Elastic Modulus via the given formula.

$$\sigma = E * \boldsymbol{\varepsilon} \qquad (1)$$

In this study, the residual strains of grey casting engine block were measured and the corresponding stresses were calculated. The mechanical properties obtained from the tensile test (Elastic Modulus and Poisson Ratio) were used to calculate the residual stresses of engine block.15 strain gage locations were examined for residual stress. The area around each gage location was evacuated and relieved strains were measured. Relieved strains were converted to residual stresses using the calculated Elastic modulus and Poisson's ratio. The mechanical properties obtained from the tensile test demonstrated that the material exhibits an Elastic modulus of 109.17 GPa and a Poisson's ratio of 0.195.

As a result of the investigations, the residual stress that occurred in the engine block during the time interval from the time the engine was connected and clamped to the milling machine to the time the data was interrupted was calculated [0 - 31114.11 sec.]. After the evacuation of Strain Gauge 5-1 (Test1), the corresponding location was completely destroyed in order to properly mill SG10 [0 – 41723.31 sec.]. All of the values provided for Test 2 are valid. The average of the last 20 seconds of deformation data from the engine block was evaluated in order to calculate the residual stresses. These studies were carried out with support from Bias Company.

3.Findings

This study examined the effects of stress-relief heat treatment times on the mechanical properties of EN GJL-250 lamellar graphite gray cast iron motor blocks. The results obtained after the 10-hours and 15-hours stress-relief heat treatments are presented in detail in Table 2.

In terms of residual stresses, as shown in Table 2, the residual stresses measured after the 10-hours stress- relief process were -75.97 MPa, -65.10 MPa, -108.14 MPa, and -4.97 MPa in the SG 5.2, SG 5.3, SG 5.5, and SG 10 regions, respectively. However, a significant reduction in these values was observed following the 15-hours stress-relief process. The residual stresses after the 15-hour process were measured as -40.47 MPa, -25.00 MPa, -20.38 MPa, and -2.98 MPa, indicating a reduction of approximately 50% to 80%.

Table 2. Results of mechanical tests after 10-hours and 15 hours stress relief heat treatment.
Tablo 2. 10 saatlik ve 15 saatlik gerilim giderme ısıl işlemlerinden sonraki mekanik test sonuçları.

Isıl işlem süresi	**10 saat Gerilim Giderme Isıl İşlem Sonrası**	**15 saat Gerilim Giderme Isıl İşlem Sonrası**
Kalıntı Gerilim [MPA] SG 5.2	-75.97	-40.47
Kalıntı Gerilim [MPA] SG 5.3	-65.10	-25.00
Kalıntı Gerilim [MPA] SG 5.5	-108.14	-20.38
Kalıntı Gerilim [MPA] SG 10.	-4.97	-2.98
Çekme Mukavemeti [N/mm2]	245	246
Ortalama sertlik değeri [Brinel]	212	208
Boyutsal ölçüm [mm]	480	480.2

Regarding tensile strength and hardness, no significant change was observed between the tests conducted after each heat treatment duration. After the 10-hours stress-relief process, the tensile strength was measured as 248 N/mm², and the average hardness was 210 Brinell. Following the 15-hour process, the tensile strength was 246 N/mm² and the average hardness was 208 Brinell. The difference between these values is minimal and considered negligible. This suggests that the hardness did not significantly decrease, which is essential for ensuring the motor block maintains high performance under demanding operating conditions.

The effect of heat treatment duration on dimensional stability was also investigated. After the 10-hours stress-relief process, the dimensional measurement was 480 mm, whereas after 15 hours it was 480.1 mm. This result indicates that there was no significant dimensional change in the motor block after either heat treatment duration and that it remained within acceptable tolerance limits.

Microstructural analysis was performed following both heat treatment durations. Microscopic examination revealed the presence of similar A-type graphite structures in both cases. Furthermore, the matrix structure was found to be 99% pearlitic in both samples. The unetched microstructure images of the samples annealed for 10 and 15 hours are shown in Figures 8 and 9, respectively.

In the microstructure annealed for 10 hours, the average graphite particle length was observed to be approximately 10–25 µm. The particles exhibit a shorter, thicker, and more convoluted or irregular morphology. In some areas, agglomeration of graphite particles (i.e., clustering) was detected. The graphite phase is distributed in a less homogeneous manner, with certain regions showing a dense concentration of graphite, while others exhibit noticeable voids or sparse distributions. This irregularity in shape, size, and distribution of graphite particles may lead to stress concentrations at the matrix–graphite interface. As a result, the structure could exhibit increased brittleness and a higher potential for crack initiation. These inconsistencies in the microstructure are likely due to insufficient annealing time, which may not allow enough atomic diffusion and matrix relaxation.

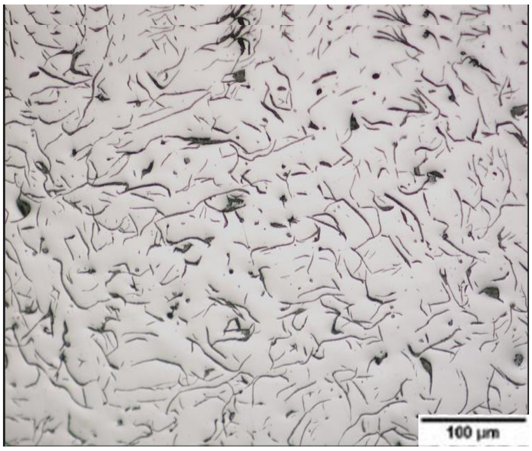

Figure 8. 10 hours annealed unetched microstructure.
Şekil 8. 10 saat tavlanmış, dağlanmamış mikro yapı.

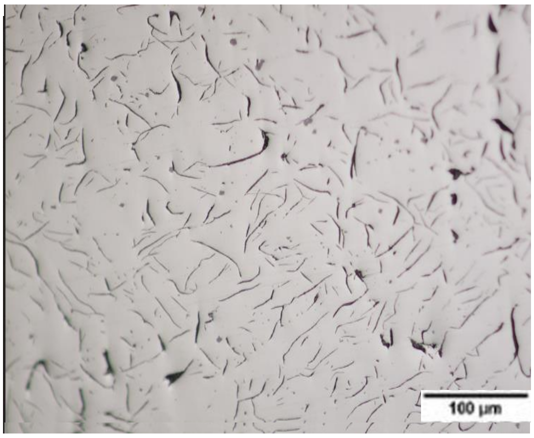

Figure 9. 15 hours annealed unetched microstructure.
Şekil 9. 15 saat tavlanmış, dağlanmamış mikro yapı.

In contrast, the microstructure annealed for 15 hours revealed more elongated and finer graphite particles. The average length was measured between 20–40 µm, and the particle thickness appeared more consistent. The graphite lamellae are more distinctly separated and approach a continuous flake-like morphology. Additionally, the graphite phase is distributed more uniformly and at regular intervals throughout the matrix. This suggests that the extended annealing time facilitated atomic diffusion and contributed to the development of a more stable microstructure.

Furthermore, the matrix appears to have undergone additional relaxation, likely allowing for greater carbon diffusion. As the graphite particles became better defined and more evenly distributed, the mechanical compatibility between the graphite and the matrix may have improved. This microstructural refinement is expected to enhance ductility and reduce the tendency for crack formation, indicating improved overall material performance after longer annealing durations.

The cost implications of extending the heat treatment duration were also analyzed, with the detailed breakdown presented in Table 3. The analysis indicates that prolonging the stress-relief heat treatment time leads to increased expenses in natural gas consumption, electricity usage, and labor costs. Assuming one annealing cycle is conducted per day, amounting to 280 cycles annually.

Table 3. Effect of 15 hours stress relieving heat treatment on difference cost calculation and unit part cost calculation compared to 10 hours stress relieving treatment (The calculation is based on 28 000 pieces per year).
Tablo 3. 15 saatlik gerilim giderme ısıl işleminin, 10 saatlik gerilim giderme işlemine kıyasla maliyet farkı hesaplaması ve birim parça maliyeti hesaplaması üzerindeki etkisi (Hesaplama yıllık 28.000 adet parça üzerinden yapılmıştır).

Cost	Annual Cost (€)
Annual Natural Gas Cost Difference	€ 16.949
Annual Labor Cost Difference	€ 8.400
Annual Electricity Cost Difference	€ 924
Total Annual Cost Difference	€ 26.273
İmpact on Unit Part Cost	0,4%

Although the 15-hours stress-relief annealing process results in an additional annual cost of approximately € 26,273 compared to the 10-hour process, this cost translates to only € 0.94 per part, or approximately **0.4%** of the total unit cost.

According to typical foundry operations, production cost variations of ±1–2% are generally accepted as normal due to fluctuations in raw materials, energy prices, and labor efficiency. Therefore, the observed 0.4% increase is well within the expected cost variability range. Additionally, when considered in relation to production volume (28,000 parts/year), this cost increment results in a **Cohen's d** effect size of approximately 0.19, which indicates a *small and statistically insignificant* difference in practical terms. Based on this analysis, the increased cost associated with extended annealing time can be considered negligible in exchange for improved microstructural stability and reduced residual stresses.

The cooling rate during the 15-hours annealing process was reduced from 75 °C/h (used in the 10-hours process) to 40 °C/h, allowing more time for graphite particles to grow and reorganize. This significantly influenced the microstructural evolution, facilitating the development of longer, thinner, and more uniformly distributed lamellar graphite, as observed in the microstructure analysis. The slower cooling rate also minimized thermal gradients and contraction-induced stresses within the matrix, thereby reducing interfacial stress between the graphite and the metallic matrix.

From a metallurgical perspective, the reduced cooling rate promoted a more uniform and stable pearlitic matrix formation, while lowering the risk of cementite segregation and microstructural inconsistencies that often act as stress concentration sites and microcrack initiation points. This resulted in a more relaxed matrix and enhanced mechanical compatibility between graphite and the surrounding structure. Consequently, both the annealing duration and cooling rate are critical factors for achieving microstructural stability and effective residual stress relief in gray cast iron components.

In addition to macroscopic residual stress relief, the slower cooling rate also positively affected microcrack initiation potential. By reducing thermal gradients and contraction mismatches between graphite flakes and the pearlitic matrix—common causes of localized stress concentrations—the gradual cooling in the 15-hours cycle improved interface integrity. The observed increase in graphite uniformity and particle elongation further suggests more stable phase boundaries, less prone to cracking. Therefore, the reduced cooling rate not only helped in residual stress reduction but also contributed to lowering the risk of microcrack formation, enhancing the structural durability of the cast components.

4.Conclusion

In this study, motor blocks produced by sand casting using EN GJL-250 material were annealed with two different stress-relief heat treatment recipes, and their mechanical properties were examined. No significant change was observed in hardness, tensile strength, and dimensional measurements. The microstructures of both cases showed similar A-type graphites, and the matrix was found to be 99% pearlitic.

The most significant variability was observed in the residual stress measurements. By increasing the stress-relief annealing time and lowering the cooling temperature, the residual stresses in the motor blocks were reduced by 50% to 80%, remaining within the tolerance limits specified in the customer's technical specifications. These results are important for ensuring high performance when the motor is subjected to dynamic and static stresses during its service life. This study confirmed the optimal stress-relief heat treatment graph required to minimize internal stresses in lamellar graphite gray cast iron motor blocks produced by sand casting. The additional cost associated with increased heat treatment time is considered negligible when considering the motor's lifetime, performance, and potential quality issues.

5.Conflicts of Interest

The authors declare no conflict of interest.

6.References

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