Gazi Üniversitesi
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PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 11(2): 542-548 (2023)

Investigation of Microstructure and Mechanical Properties of Vermicular Graphite Cast Iron by Using Thermal Analysis

Merve Ulular[1] Veysel Durak[1] Cem Uluç[1] Hasan Hasırcı[2*]

[1]*Erkunt Industry, Inc., R&D Center, Ankara, Turkey*

[2]*Gazi University, Technology Faculty, Department of Metallrgycal and Materials, Ankara, Turkey*

Article Info

Research article
Received: 30/12/2022
Revision: 24/02/2023
Accepted: 29/04/2023

Keywords

Vermicular Graphitic Cast Iron (VGCI)
EURO6 standard
Thermal analysis
Microstructure
Mechanical properties

Makale Bilgisi

Araştırma makalesi
Başvuru: 30/12/2022
Düzeltme: 24/02/2023
Kabul: 29/04/2023

Anahtar Kelimeler

Vermiküler Grafitli Dökme Demir (VGCI)
EURO6 standardı
Termal analiz
Mikroyapı
Mekanik özellikler

Graphical/Tabular Abstract (Grafik Özet)

This work, made to predetermine the quality of the engine block produced from VGCI using thermal analysis during casting. The findings showed that successful and desired quality production could be made by examining the cooling curves obtained before the casting process. / Bu çalışma; döküm sırasında termal analiz kullanılarak VGDD'den üretilen motor bloğunun kalitesinin önceden belirlenmesi için yapılmıştır. Elde edilen bulgular, döküm işlemi öncesinde elde edilen soğuma eğrilerinin incelenmesiyle başarılı ve istenilen kalitede üretim yapılabileceğini göstermiştir.

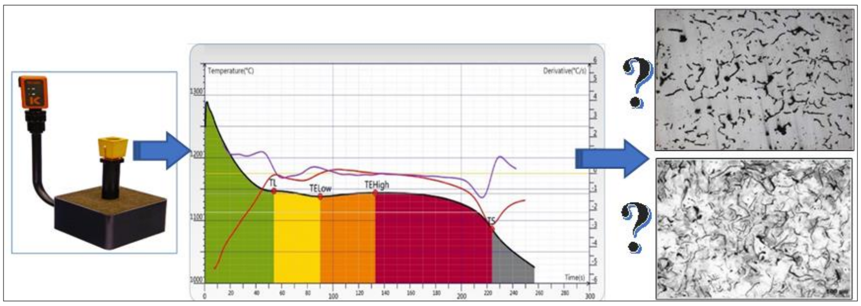

***Figure A**: Use of thermal analysis for structural prefixing in cast irons / **Şekil A:**.Dökme demirlerde yapısal ön tespit yapılması için termal analizin kullanımı*

Highlights (Önemli noktalar)

- *Thermal Analysis / Termal Analiz*
- *Compact Graphite Iron / Vermiküler Garfitli Dökme Demir*
- *Structural and Mechanical properties / Yapısal ve Mekanik Özellikler*

***Aim (Amaç):** This study was carried out to control material properties with thermal analysis applications during the production of engine block from VGCI material. / Bu çalışma, VGDD malzemeden motor bloğu üretimi sırasında termal analiz uygulamaları ile malzeme özelliklerinin kontrolü amacıyla yapılmıştır.*

***Originality (Özgünlük):** Predicting the mechanical properties of the VGCI material by controlling the structural properties of the material with thermal analysis is the original side of the study. / Termal analiz ile VGDD malzemenin yapısal özelliklerinin kontrol edilmesiyle mekanik özelliklerinin önceden tahmini çalışmanın özgün tarafıdır.*

***Results (Bulgular):** It was determined that the microstructure and mechanical properties can be ensured to comply with the targeted standards by using thermal analysis technique. / Yapı ve özelliklerin hedeflenen standartlara uygunluğu termal analiz kullanılarak sağlanabileceği tespit edilmiştir.*

***Conclusion (Sonuç):** The results of the study showed that the engine block produced conformed to the standards in terms of chemical composition, structure and mechanical properties. / İnceleme sonuçları; üretilen motor bloğunun kimyasal bileşim, yapı ve mekanik özellikler bakımından standarta uygun olduğunu göstermiştir.*

*Corresponding author, e-mail: hasirci@gazi.edu.tr
DOI: 10.29109/gujsc.1227029

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Abstract

In this study, the microstructural and mechanical properties of Vermicular Graphitic Cast Iron (VGCI) material complying with EURO6 standard during engine block production were evaluated using thermal analysis. The production of this engine block was carried out in Erkunt Industry company by pot metallurgy method with a new production approach suitable for mass production. Thermal analysis technique was used as a production control tool during production. Samples taken from the produced block material were examined to analyze the microstructural and mechanical properties. The results of the study showed that the engine block produced conformed to the standards in terms of chemical composition, structure and mechanical properties. It was determined that the microstructure and mechanical properties can be ensured to comply with the targeted standards by using thermal analysis technique. Some foreign (European countries) approvals have been obtained for the produced material.

Vermiküler Grafitli Dökme Demir Malzeme Üretiminde Termal Analiz Kullanımı İle Üretilen Mikroyapı Ve Mekanik Özelliklerinin İncelenmesi

Makale Bilgisi

Araştırma makalesi
Başvuru: 30/12/2022
Düzeltme: 24/02/2023
Kabul: 29/04/2023

Anahtar Kelimeler

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Mikroyapı
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Öz

Bu çalışmada; EURO6 standartına uygun Vermiküler Grafitli Dökme Demir (VGDD) malzemeden motor bloğu üretimi sırasında termal analiz kullanımı ile mikroyapı ve mekanik özelliklerin değerlendirilmesi yapılmıştır. Bu motor bloğunun üretimi Erkunt Sanayi firmasında seri imalata uygun yeni bir üretim yaklaşımla pota metalurjisi ile gerçekleştirilmiştir. Üretim sırasında termal analiz tekniği kullanılarak üretim kontrolü yapılmıştır. Üretilen blok malzemesi üzerinden alınan numunelerle mikro yapısal ve mekanik özellikler bakımından incelemeler yapılmıştır. İnceleme sonuçları; üretilen motor bloğunun kimyasal bileşim, yapı ve mekanik özellikler bakımından standarta uygun olduğunu göstermiştir. Yapı ve özelliklerin hedeflenen standartlara uygunluğu termal analiz kullanılarak sağlanabileceği tespit edilmiştir. Başarı ile üretilen malzeme için bir kısım yurt dışı (Avrupa ülkeleri) onayları da alınmıştır.

1. INTRODUCTION (GİRİŞ)

Vermicular Graphite Cast Iron (VGCI) materials are the latest addition to the family of ferrous alloys. VGCI's are better than Lamellar Graphite Cast Iron (LGCI) in terms of casting performance, high strength and toughness, and are better than Ductile Iron (DI) (or Spheroidal Graphite Cast Iron (SGCI) in terms of thermal fatigue performance and thermal conductivity. Therefore, as a new type of material, it has been widely used in cylinder blocks, cylinder heads, exhaust manifolds and brake discs in Turkey and abroad [1-3]. While classifying cast irons according to their graphite structure, the ratio of length to width is taken. This ratio is known to be between 2-20 in VGCI's, over 50 in LGCI's and around 1 in DI's [4]. Three-dimensional SEM microstructures of vermicular graphites were observed to be interconnected in eutectic cells (Fig.1). On the other hand, these graphites are not sharp/specular but have a round/circular tip structure. This graphite structure provides high

*Corresponding author, e-mail: hasirci@gazi.edu.tr DOI: 10.29109/gujsc.1227029

strength, ductility compared to LGCI and better thermal conductivity compared to DI [5]. In the study by Gorny et al. the main factors affecting the structure of VGCI castings are chemical composition, cooling rate, liquid treatment and heat treatment. It is known that the cooling rate of the casting depends on the section thickness, casting temperature and thermal conductivity of the mold material [6]. Different methods and materials are used in VGCI production [4,7-10]. Among these; extensive desulphurization, nitrogen addition, incomplete treatment, in-mold, overheating, CxHx gassing, and wire treatment techniques are the main ones. The success of these methods varies with relation to their controllability. Therefore, the wire treatment technique is accepted as the most prominent and preferred method currently. In this study, vermiculation process was performed with the "crucible technique" by using the spheroidization process method and tools and equipment used in DI production, but chemically treated with different material and VGCI material production was realized.

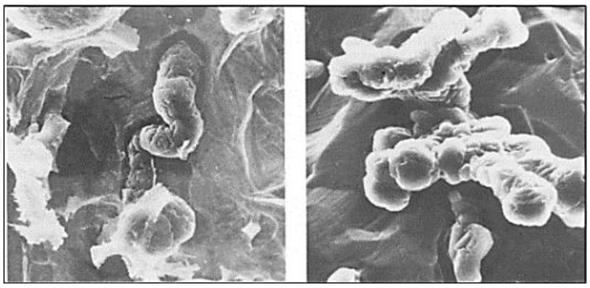


Figure 1. SEM image of two different photographs of VGCI (VGDD'in iki farklı SEM görüntü fotoğrafı) [5]

Thermal analysis method is widely used especially in cast iron casting processes. There are different thermal analysis methods and technologies [11-13]. However, basically, the behavior of materials during the transition from liquid to solid is observed to determine their structure, chemical composition, casting defects and material properties. This data is extremely useful in terms of showing how well the final casting material to be produced is suitable and accurate with the targeted structure and properties.

2. MATERIALS AND METHODS (MALZEMELER VE METOTLAR)

Dependence on foreign sources for the supply of technology and materials used in the manufacture of a product causes obstacles in production. This is because the techniques developed and the materials used have certain limitations. Therefore, these obstacles can be eliminated if there are opportunities to overcome the limitations of some properties of the materials in production. From this point of view, in this study; engine block production was carried out from VGCI material in accordance with EURO6 standard, which we specially developed and produced with laddle metallurgy technique suitable for mass production. Considering the necessity of preliminary evaluation and controls with the application of thermal analysis during production, the characterization of the produced part in terms of structural and mechanical properties is discussed. Casting processes were started by planning on the production of the engine block, which is routinely mass-produced in Erkunt Casting Industry. Melting processes were carried out in an induction furnace with a capacity of 8 tons. As the main charge input to the induction furnace, 50% ductile iron and 50% low carbon steel were used in the form of ingots. Additional alloying elements were added as ferroalloy as required. In this study, materials with 2 different compositions were produced and analyzed in terms of VGCI production. The chemical compositions of liquid cast iron obtained by OBLF brand spectrometer at the end of melting are given in Table 1. Casting processes were carried out between 1408-1414°C using liquid metal taken from the melting furnace. Vermiculation was performed in a 1 ton capacity spheroidizing crucible. A temperature range of 1280-1300 °C was preferred as the casting temperature. The material to be cast was subjected to inoculation with FeSi and FeSiMg material in two stages, during vermiculation and before casting. Vermicular solidification was guaranteed by thermal analysis of the liquid material in the ATAS device at the beginning, middle and end of casting. The experimental work started with the production of the engine block. Metallographic measurements of the matrix structure, graphite shape and distribution of the cast engine block were carried out on samples taken from different parts of the cast part after the completion of standard polishing processes (sanding with 80-1200 mesh and polishing at 6 microns). The number and shape of graphite per unit area were analyzed from un-etched and matrix structure were analyzed from the surface of the sample etched with 3% nital at x100 magnification from different regions using a Zeiss microscope and digital images obtained from the microscope's own image analysis. Grain size measurements were made according to EN ISO 945-1:2016 standard at x100 magnification. Specimens cut from engine blocks were prepared in the dimensions specified in DIN EN 1563 standard and tensile tests were carried out at room temperature in Zwick Roell brand device with 200 kN capacity. At least 6 specimens from the same series were tested and averaged in the results section. Hardness tests were measured as Brinell in "EMCO Test Duravision 2000" hardness tester. For this purpose, a steel ball tip with a diameter of 2.5 mm and a load of 147 N was applied. For each sample, 10 different measurements were made and the average is given in the results section. "The values shown with xxx in Table 1. are not given due to commercial reasons."

Table 1. Chemical composition ranges of produced alloys (Üretilen alaşımların kimyasal bileşim aralıkları)

Alloy Elements (%)	C	Si	Mn	S	P	Ti	Sn	Cu	Mg	Fe
Alloy 1	3.4-3.6	2.3-2.5	0.6-0.7	0.011-0.013	0.02-0.024	0.009-0.01	0.0012-0.002	0.8-0.9	0.18-0.22	Bal
Alloy 2	3.4-3.6	2.3-2.5	0.6-0.7	0.011-0.013	0.02-0.024	0.009-0.9	0.0012-0.02	0.8-0.9	0.18-0.22	Bal

3. EXPERIMENTAL RESULTS AND DISCUSSION (DENEYSEL SONUÇLAR VE TARTIŞMA)

3.1. Thermal Analysis Results (Termal Analiz Sonuçları)

Thermal analysis measurements are widely used during the casting of cast iron materials. With these measurements; gray and white solidification tendencies before casting, solidification start temperature determination (Ts), carbon equivalence (CE) measurement, solidification temperature / time ratio (Ts/ts), amount (ΔT) and duration (Δt) of undercooling during solidification, shrinkage and expansion rates and times during solidification, solid transition temperature (Tst), eutectic point (Te) and composition change etc. data can be determined. After these determinations, the successful completion of the casting process and the desired quality of the cast material are largely guaranteed.

Two different thermal analysis data (Fig. 2) and graphs (Fig. 3) obtained during this study are also given. When both data are analyzed (Fig 2); it will be seen that the data such as MQ, ACEL, TL, TES, TELow, TS are the same or very close. This is because the start and end of solidification in lamellar and vermicular graphite cast iron materials are similar mechanisms. In lamellar graphite cast iron, solidification starts with the formation of solid matrix (austenite phase) and is completed by the precipitation of graphite between austenite grains. However, in VGCI, spherical shaped graphites (up to 20%) are also formed. The formation of these graphites is different from lamellar and vermicular. Spherical graphites are formed by the precipitation of graphite in a spherical gas bubble at the beginning of solidification and the formation of austenite phase around it in the following process. Therefore, solidification and solid shrinkage and expansion occur differently in lamellar and vermicular graphite cast irons. When graphite is formed between the solid grains, its volume occupies more space than its proportion in the material, causing a decrease in solid shrinkage and solid shrinkage and even volumetric growth (negative shrinkage) in the produced parts. These data also allow for monitoring the amount of undercooling (T), reheating (recoalescence, R), shrinkage and expansion zones required for the formation of lamellar, vermicular and spherical graphite. Thermal analysis and cooling curves are therefore of great importance.

Looking at both data below, it is seen that they are materials with the same CE value (ACEL= 4.24 and 4.25). It will be seen that the dT/dt data in the liquid state are different in the data obtained from castings made at separate times with almost the same TL and TES temperatures. In the second data (b), it can be seen that a lower undercooling occurred, solidification occurred in a shorter time and the shrinkage during solidification was more easily met (S1). Accordingly, the amount of reheating (R) value has also decreased.

The situation will be better understood, especially when the meaning of the data mentioned in the cooling curves is expressed. Figure 3.a is obtained from cast iron with lamellar and b from cast iron with vermicular graphite. The most important differences in both curves are the undercooling (T), recalcitrance (R), the lowest (TElow) and highest (TEhigh) temperature values and the duration of the solidification process (t). The precipitation of lamellar graphite as a secondary phase during solidification is due to the formation of the first solids (austenite grains) in a shorter time. In vermicular, on the other hand, since both graphite and austenite are formed together, nucleation starts at a higher temperature (TL) and lasts for a longer time (B region) since both phases grow together.

MQ = 50

ACEL = 4,25

Indicator	Min	Current	Max	Fingerprint
TL	0,0	1145,8	0,0	
TES	0,0	1142,9	0,0	
dT/dt TES	0,00	-0,46	0,00	
S1	0,0	18,3	0,0	
TELow	0,0	1138,8	0,0	
R	0,0	6,2	0,0	
GRF1	0	58	0	
GRF2	0	53	0	
dT/dt TS	0,00	-2,86	0,00	
TS	0,0	1084,5	0,0	

(a)

MQ = 50

ACEL = 4,24

Indicator	Min	Current	Max	Fingerprint
TL	0,0	1147,2	0,0	
TES	0,0	1142,6	0,0	
dT/dt TES	0,00	-0,38	0,00	
S1	0,0	21,5	0,0	
TELow	0,0	1138,4	0,0	
R	0,0	5,8	0,0	
GRF1	0	62	0	
GRF2	0	54	0	
dT/dt TS	0,00	-2,79	0,00	
TS	0,0	1086,7	0,0	

(b)

Figure 2. (a) Lamellar and (b) vermicular graphite solidified cast iron thermal analysis data ((a) Lameler ve b) vermiküler grafitli dökme demirin soğuma termal analiz verileri)

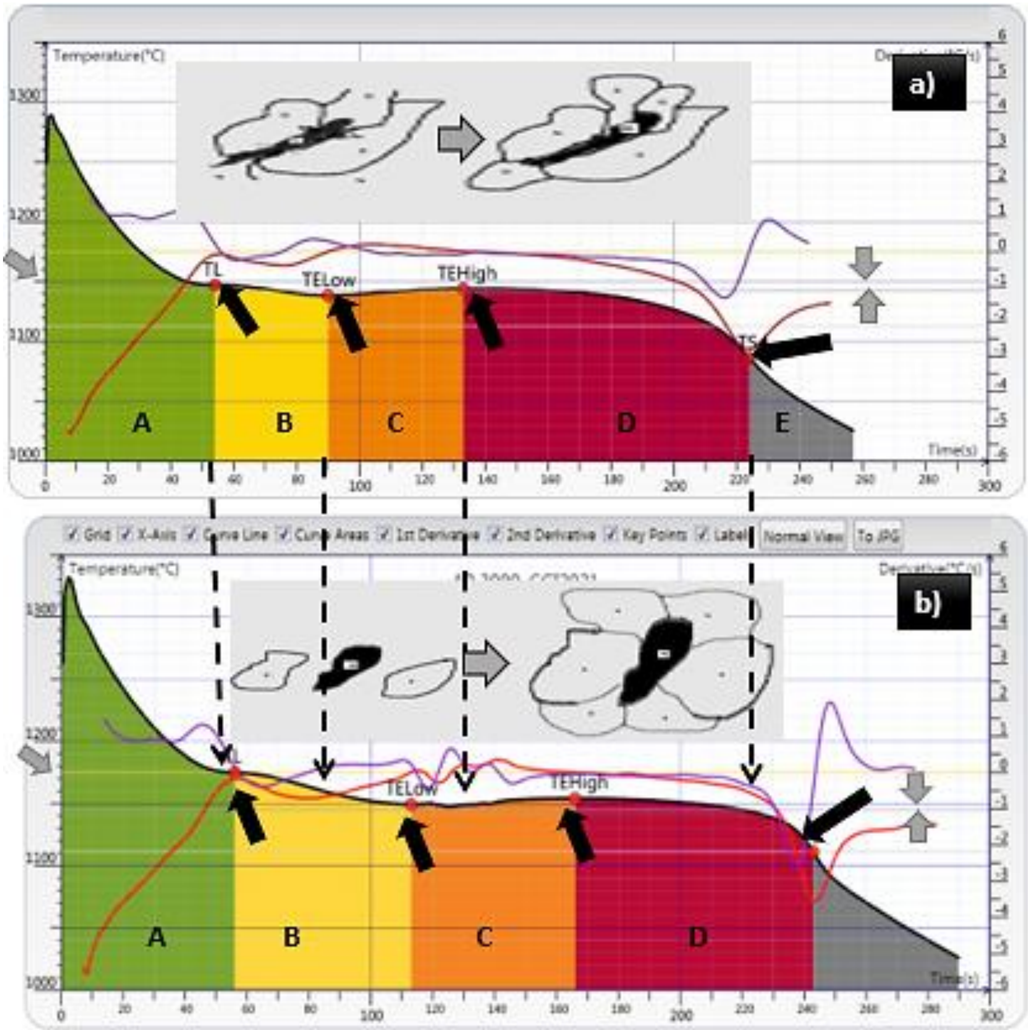


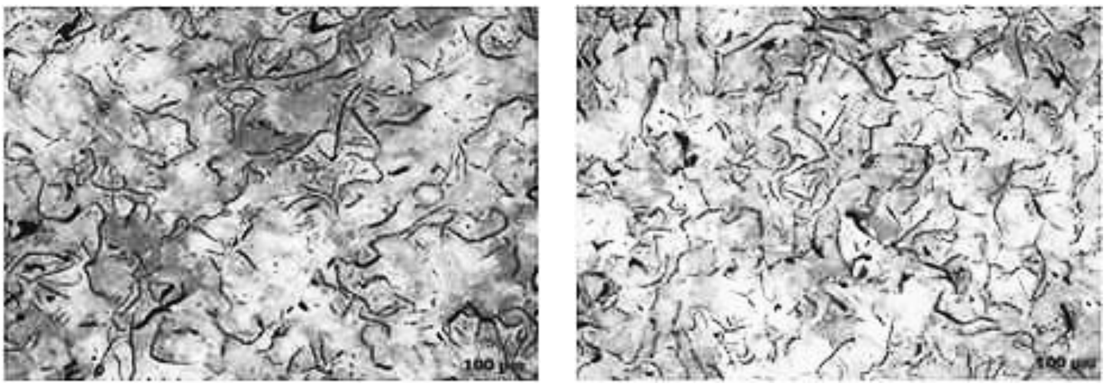
Figure 3. (a) Solidified cast iron cooling curves in the form of lamellar and (b) vermicular graphite ((a) Lameler ve b) vermiküler grafitli dökme demirin soğuma soğuma eğrileri)

The nucleation and growth of these two phases together reduced the need for undercooling (TElow) and consequently the highest temperature required for solidification (TEhigh) was low [11-13]. Lamellar graphite needs higher temperature and time to form and grow between austenite grains. Therefore, graphite growth at higher temperature, high reheating temperature (TEhigh) and solidification completion time (D zone) occurred in the lamellar graphite material. In addition, the solidification end temperature (TS) is also higher in the vermicular graphite material due to the growth of both phases together and the completion of solidification.

3.2. Changes in Structural and Mechanical Properties (Yapısal ve Mekanik Özelliklerin Değişimi)

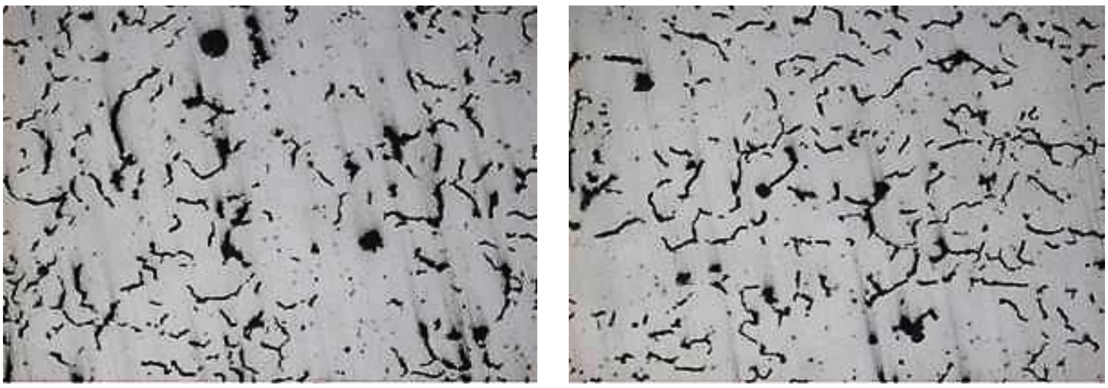
3.2.1. Structural Properties (Yapısal Özellikler)

Gray cast iron materials are generally composed of matrix + graphite structure. The matrix structure can generally be ferritic, ferrite + pearlitic, pearlite + pearlitic, pearlite + pearlitic, pearlitic in the case of casting. Apart from these, different carbides are also included. Graphite structure is spherical, lamellar and vermicular [14-17]. The graphite ratio in the structure generally varies between 9-11%. Figure 4 shows lamellar and Figure 5 shows vermicular graphite cast iron material structures. In both, the matrix is pearlite + ferritic (80 + 20% in the matrix) and the graphite volume fraction is 10.2%. Although there is very little difference in the chemical composition of these two materials, the graphite shapes are clearly different when looking at the images of both materials. Both materials were subjected to the vermiculation process, but one material had a lamellar and the other a vermicular graphite structure. When the chemical analysis of both materials is examined, it is seen that it depends on the changes in the ratios of elements such as Ti and Sn. In the previous section, it was explained in detail what thermal analysis can tell about the casting process before casting and what can be seen from the curves. Although the general composition is the same, it is clearly seen how a change in the amount of a few elements changes the cooling characteristics of the material and changes the structure (here graphite shape). In this respect, the application and interpretation of thermal analysis can predict the structures (matrix type and/or graphite shape, etc.) that will be formed before casting, which is beneficial in preventing incorrect casting processes.



(a) (b)

Figure 4. Lamellar graphite structure (a) and (b) (Lamel grafit yapıları, a ve b)



(a) (b)

Figure 5. Vermicular graphite structure (a) and (b) (Vermiküler grafit yapıları, a ve b)

3.2.2. Mechanical Properties (Mekanik Özellikler)

The results obtained from tensile, impact, fatigue and hardness tests of the cast alloys are given in Table 2. When the results are analyzed; it is seen that the properties of the cast iron materials with similar matrix, but produced by changing only the graphite shape (lamellar and vermicular), have changed to a great extent. The least change was seen in hardness, while the most change occurred in elongation. With the same basic chemical composition, the properties of the material produced by changing only the graphite structure can also change significantly [14-17]. It was observed that the properties of the two materials with lamellar and vermicular graphite structure produced with the chemical composition prepared for the production of GJV 400 material were also different. It is a known fact that properties change with the change of graphite structure. There are many researches and applications related to this. However, what is important in this study is to determine this structural change by thermal analysis before casting and to plan and perform production accordingly. Therefore, when the thermal analysis results are read correctly; the structure and properties that can be obtained after casting can be determined to a great extent.

Table 2. Changes in mechanical properties of cast iron due to lamellar and vermicular shaped graphites (Lamel ve vermiküler şekilli grafitlerden dolayı dökme demirin mekanik özelliklerindeki değişimler)

	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Impact Resistance (J)	Fatigue Resistance (MPa)	Hardness (HB)
Lamellar graphite structure material	200,5 ±5	183,2 ±4	0,5 ±0.7	1,1±1	82±5	220,3±6
Vermicular graphite structure material	440,3 ±8	342 ±8	2,5 ±0.7	4,5±1	103±5	234,5±5
% Change	***120***	***87***	***400***	***309***	***25***	***6***

4. CONCLUSIONS (SONUÇLAR)

As a result of this study, the change of graphite shape and the change of mechanical properties accordingly were investigated by using thermal analysis method;

- As a result of a very small difference in chemical composition, although the casting conditions are similar, different graphite structures can be produced in different (lamellar or vermicular) shapes,
- With thermal analysis applications, differences that may occur in similar materials before casting (graphite structure, shrinkage amount, freckle formation) can be easily detected and faulty casting processes can be prevented,
- With the application of thermal analysis, the desired quality of cast iron production can be achieved,
- It has been determined that very large changes in mechanical properties can be obtained by changing only the graphite structure.

ACKNOWLEDGMENTS (TEŞEKKÜR)

This study was supported with the project "CGI engine block production and optimization" under the R&D program of ERKUNT Casting Company.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Merve ULULAR*:** She is responsible for the follow-up of the studies, the execution and writing of the experiments.

Çalışmaların takibinden, deneylerin yürütülmesinden ve yazılmasından sorumludur.

***Veysel DURAK*:** He is worked in the coordination of the study.

Çalışmanın koordinasyonunda çalışmıştır.

***Cem ULUÇ*:** He is worked in the production and coordination of the study.

Çalışmanın üretimi ve koordinasyonunda görev almıştır.

***Hasan HASIRCI*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapar, sonuçları analiz eder ve yazma işlemini gerçekleştirir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study. / Bu çalışmada çıkar çatışması yoktur.

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