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Investigation of the Effects of Austenitizing Heat Treatment on Energy Consumption of Pipe Threading

Burak Öztürk*[1]

Abstract

Energy consumption is an important part of the production cost of mass production industrial enterprises. The casting, heat treatment and threading processes involved in the industrial production of fittings result in high energy consumption. In serial production, the threading of pipe fittings is carried out using high torque and low speed. The thin-walled designs of the fittings lead to rapid cooling, causing the formation of a high rate of pearlite microstructures and subsequent low or extremely hard machinability. Heat treatment with long austenitizing time in the furnace reduces the pearlite ratio, thus enabling a ferritic microstructure to be obtained. In this study, the ½-inch BSP threading process was applied to materials having both microstructures after casting and heat treatment. As in the mass production pipe threading process, fittings were threaded in a multi-threading process using a universal lathe and in a single threading process using a CNC mill. The Power Index (PI) was measured during the metal removal process and the energy consumption of the products was calculated via energy/power conversion equations. In addition, a new model was proposed that takes into consideration the energy consumption per product (ECPP) in the mass production machining process. As a result of combining the energy consumption and energy - power transformation theory with an experimental investigation, 39% optimization was achieved. That's a result of this experimental study resulted in energy savings of 8755 kWh annually.

Keywords: Austenitizing, cast iron, energy consumption, fittings, heat treatment

1. INTRODUCTION

Considering the current economy and competitive conditions, sustainability in energy consumption has become one of the most important research topics carried out in the manufacturing sector [1-3]. In order to obtain both semi-finished and completed products, energy consumption is required for the production processes. A significant increase in energy costs has emerged as a result of the continuous increase in energy consumption worldwide along with the inadequate supply of new energy resources. Moreover, due to rising production and energy consumption, the resulting increased environmental pollution has arisen as a causal factor for climate change [4,5]. Therefore, energy saving has emerged as a permanent issue for the global economy. One of the industrial areas where energy is consumed is that of the metal cutting sector. Sustainable production as a global concept encompasses important elements of many

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engineering areas and applications, especially in the processes of manufacturing [6,7]. The adoption of sustainable production practices allows companies to increase their economic as well as their environmental performance. Reduction of the energy consumption of machine tools and investigation of measures to be taken to realize clean production are of great importance in those production processes where a large amount of energy is consumed. In order to achieve this, it is necessary to calculate the energy consumption in the computerized numerically controlled (CNC) machine center [8,9]. The relationship between electrical energy consumption of the machine tool and the cutting process should be examined with the aim of achieving better energy efficiency associated with the production process.

2. ENERGY CONSUMPTION IN MACHINING APPLICATIONS

Chip removal using a CNC machine is a common process in the manufacturing industry. Based on this process, a number of studies have been published concerning the optimization of cutting parameters. In most of these studies, surface roughness, cutting force, power index (PI), tool life, and material removal rate (MRR) were used as optimization criteria. In particular, energy consumption during the machining process has previously been the subject of many types of research [10-18]. Mori et al. applied drilling and milling to S45 carbon steel using a CNC milling center. The effect of chip removal conditions on the PI was measured by attaching a clamp-type ammeter [10]. In addition, energy consumption in chip removal operations on different steels has also been investigated. The milling of ASSAB 760 steel was performed via CNC milling and the resulting forces were measured by a dynamometer. However, the power consumption was measured by a Power Meter and a new machining energy consumption model was presented in this study [11]. Negrete explored the hard turning of AISI 6061-T6 aluminum materials [12]. As a result, optimum cutting parameter values were obtained to minimize chip removal and achieve the best surface quality.

In the work carried out by Oda et al., the optimized angle of inclination of a 5-axis CNC milling machine was determined and consequently, reduced energy consumption was achieved [13]. Shokoohi et al. turned AISI1045 steel using a universal lathe and observed that the heat produced in the cutting zones during turning played an important role in the final quality of the workpiece and power consumption [14]. Neugebauer et al. drilled holes in gray cast iron and examined energy consumption changes [15]. Escalona et al. investigated the energy consumption of metal cutting on 303 stainless materials [16]. The PI was determined by an ammeter assembly during chip removal from a spheroidal workpiece and the machining process for two different cutting tools was optimized using Taguchi methodology in the study of Nas and Öztürk [17]. Liu et al. presented a new model for estimating the surface roughness of an aluminum alloy during milling. The model was developed using a hybrid approach combining analytical calculation of specific cutting energy consumption (SCEC) and experimental characterization of the correlation between surface roughness and SCEC [18].

3. CAST IRON FITTINGS

The process of manufacturing fittings consumes a great amount of energy due to the high temperature required for casting and subsequent long-term heat treatment in addition to the requirements for threading and coating, thus making sustainable production very difficult. In order to prevent water and gas leaks and other faults in the system, pipes must exhibit high mechanical properties [19]. In addition, secondary processing (e.g., heat treatment and galvanizing) is needed when cast iron fittings are to be used in plumbing. The cast iron fittings fabricated in Central Asian and Balkan countries are thin-walled, fragile and extremely vulnerable to corrosion. The chief problem of these fittings is due to their thin walls (5, 10, 15 and 20 mm), which are responsible for very high cooling rates (1.66 – 2.85 °C/s) [20] (Fig. 1.). The cooling rate following casting leads to ferrite, pearlite and bainite microstructure formation (Fig. 2.), which reduces the workability.

The hardness is increased as the fragility is reduced by austempering heat treatment application. Öktem et al. reported that processability was negatively affected by austempering heat treatment [21]. In serial production using a lathe, pipe threading is applied via multi-operation threading. However, this process is carried out with tap tools by a single operation on a CNC milling bench. There has been no exemplary study in the literature to date on this type of machining.

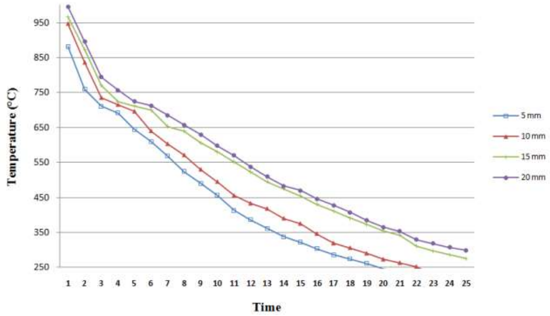

Figure 1. Microstructure changes due to the cooling rate of fittings [20]

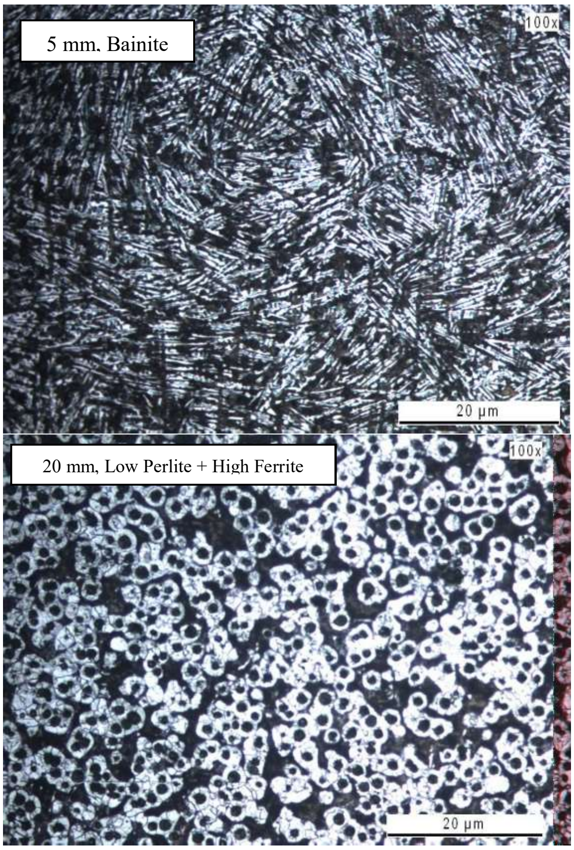

Figure 2. Hardness changes due to the cooling rate of fittings [20]

In this study, we examined the internal threading process of 15 mm-thick 1½ – ½ inch reduction products at a high cooling rate. In order to determine the machinability of these products under different production conditions, this study investigated the energy consumption of two different types of pipe threading processes used in mass production. Optimal conditions for energy conservation and sustainability were determined for the processing of fitting materials responsible for high energy consumption.

4. MATERIAL AND METHOD

4.1. Design of experiment (DOE)

Spherical graphite cast iron fittings are manufactured in the industry using two different types of machining: the multi-operation threading process using a lathe and the single operation threading process using a CNC machining center. In industrial serial production, the threading process is accelerated by the number of revolutions. With the lathe machine, the threading of the fittings starts with turning at the bottom of the teeth, followed by the threading process performed at depths of 0.5, 0.25 and 0.1 mm. As shown in Figure 3, different in-feed shapes can be applied in the multi-operation threading process, including radial, flank and alternate flank in-feed [22].

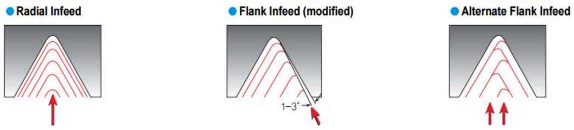

Figure 3. Multi-operation threading in-feed shapes

In this study, the radial type threading process was applied to fittings for a total of five operations. In addition, the single operation CNC milling process was carried out at low speed and high torque using a tap tool. The process of threading at 90, 125 and 180 RPM was selected for both of these machines. Turning was carried out for the first operation of the lathe at 500, 710 and 1000 RPM, respectively.

This experimental design is summarized in Table 1. All operations were applied under dry cutting conditions. The average flow indices (PI (A)) were calculated by repeating the experiment three times for each sample.

Table 1. Fitting pipe threading process design of experimental (DOE)

Trial No	Process type	Machine Type	Thread Turning Speed (RPM)
1	Casting	Lathe	90
2	Casting	Lathe	125
3	Casting	Lathe	180
4	Casting	CNC Mill	90
5	Casting	CNC Mill	125
6	Casting	CNC Mill	180
7	Austempering	Lathe	90
8	Austempering	Lathe	125
9	Austempering	Lathe	180
10	Austempering	CNC Mill	90
11	Austempering	CNC Mill	125
12	Austempering	CNC Mill	180

4.2. Production of experimental samples by casting process and austempering heat treatment

In this study, the reduction (¾ – ½”) product was designed according to TS 11 - EN 10242 standards. Table 3 shows the design features of the reduction fitting material. In addition, Table 4 shows the chemical analysis of the materials used in the experimental study measured after casting using the Oxford Foundry Master Pro spectrometer.

Table 3. Design features

Design Volume (mL)	Chip Volume (mL)	Internal Thread Chip Rate (%)	Pitch Diameter (mm)	Thread Length (mm)	Thread Size
10.097	0.302	3	1.814	20	1/2 " BSP

Table 4. Chemical analysis of fittings

Element	Fe	C	Si	Mn	P	S
After spheroidal (%)	93.3	3.58	2.64	0.14	0.03	0.015

The austempering heat treatment was carried out in the heat treatment furnace at 950 °C temperatures for 12 h and cooling was applied to the fitting products under ambient conditions. The object was to obtain a microstructure having a high ferrite content at the end of this heat treatment.

4.3. Threading of test samples and measurement of Power Index (PI (A))

The materials were divided into groups in order to repeat the experiment three times. A Wellcut tap tool was used for the pipe threading on the CNC milling center. As tool wear was not observed during the threading process in the 36 experiments, each test specimen was threaded with the same tap tool (Fig. 4).

Figure 4. Welcut ½ inch BSP tap tool

The tap tool used was 17.5 mm in diameter and 40 mm in length (L/D <3). Using the chuck assembly, the threading operation was carried out on the reduction materials attached to the CNC work bench. Table 5 presents the technical features of the Fanuc Microcut 1000 CNC vertical machining center used in the experimental study (Fig. 5) [23].

Figure 5. Fanuc Microcut 1000 CNC vertical machining center

Table 5 CNC milling machinery specifications

CNC Model	Motor Power	Machine Spindle Rotations (rpm)	Spindle Cos α	Spindle Voltage (V)	Maximum Torque (Nm)
Microcut 1000	15 kW	10.000	0.6	380	103

With the lathe, two different tools were used and a total of five operations were applied under dry cutting conditions. Figure 6 shows the Korloy DCMT-HMP NC 5330 turning tool and Figure 7 shows illustrations of the Korloy 14W IR 14 pipe threading insert.

Fig. 6 Korloy DCMT-HMP, NC 5330 internal hole turning diamond insert [22]

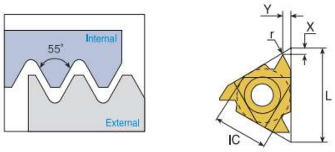

Fig. 7 Korloy 14W IR 55 ° internal threading diamond insert [22]

The multi-threading process was performed on the TOS SN 50 universal lathe machine. The PI was measured in the range 0.07–200 A (± 1 A) by connecting the Entes EPM 4C digital ammeter and the Entes CT-25 current transformer to each asynchronous motor in the lathe and the three-phase input of the motor drive in the CNC milling machine [24].

4.4. Machining process specific energy consumption model

There are many academic researches about energy in the literature [25-27]. Equation (1) presents the model of energy consumption P (Wh) for a machine tool during operation [10].

$$P = P1 \times (T1 + T2) + P2 \times T2 + P3 \times T3$$
(1)

In order to determine the energy required during chip removal ($P_{cutting}$), the power consumed when the chips are not being removed (P_{loss}) is deducted from the total power dissipated (P_{total}) (Eq. 2). The P includes the empty bearing power losses together with the power consumption of the spindle motor operating at the desired rpm [17].

$$P\ cutting = P\ total - P\ loss \tag{2}$$

During chip removal, the power index measurement (A) of the spindle servo motor driver was converted to kW using an ammeter via the 3 - phase motor power conversion as presented in Equation (3) [14]. The power factor value was that specified in the Microcut CNC Mill technical specification manual. Here, V = spindle motor voltage value (V, 0.38), I = energy load measured by ammeter (A), Cos $^{\sigma}$ = power factor (servo, 0.60; asynchronous motor, 0.85) [24].

$$P\ total = \sqrt{3}.V.I.Cos\ \sigma \tag{3}$$

Following a review of the literature, significant cutting parameters such as material removal rate (MRR), SCEC and material removal volume (Q) can be calculated using the energy power conversion equations and machining operations. The MRR is defined as the amount of chip (mm3) removed from the workpiece in one second and Q as the total amount of chip processed during manufacturing. The MRR is calculated using Equation (4) given below. The SCEC is the cutting energy used to remove 1 mm3 of material from the workpiece (Eq. 5) [18]. The SEC is the total amount of energy consumed to remove 1 mm^3 of chip and is calculated by the formula in Equation (6).

$$MRR = (ap * ae * F) / 1000 \tag{4}$$

$$SCEC\left(\frac{J}{mm^3}\right) = \frac{P\ cutting\ (W)}{MRR\left(\frac{mm^3}{s}\right)} \tag{5}$$

$$SEC\left(\frac{J}{mm^3}\right) = \frac{P\ total\ (W)}{MRR\left(\frac{mm^3}{s}\right)} \tag{6}$$

A number of studies in the literature deal with production conditions for metal cutting such as machine type and process parameters. For mass production, such as for pipe fittings, new definitions are needed for the energy consumption of short-time processing of materials. In this study, the amount of energy consumed is shown for the hourly production of a fitting material (Eq. 7). Thus, energy consumption for real-time production has been demonstrated. Moreover, energy consumed during the processing of different fittings can be examined and compared.

$$\boldsymbol{ECPP\ (Wh)} = \frac{P\ \text{total}\ \ (\text{W})\ (\text{inlet})}{\text{Numbers of Production (h)}} + \frac{P\ \ \text{idle (W)(outlet)}}{\text{Numbers of Production (h)}}$$

(7)

5. RESULTS AND DISCUSSION

5.1. Examination of microstructure and mechanical properties

Images of the microstructures after casting and austenitizing heat treatment were obtained using an optical microscope (Fig. 8). When these microstructures were examined, it was observed that a pearlitic microstructure was formed after casting. Although the graphite was not fully spheroidal in some regions, it can be said that the *spheroidization* was generally close to ideal. However, peak infusion caused a low incidence of vermicular structures. A high rate of α-Ferrite was observed after the heat treatment. However, while the graphite was often diffused within the parent matrix, the spherical structures had become distorted and lamella formation was observed. The reduction materials produced after casting and heat treatment were cut and tensile specimens were obtained. The mechanical properties of each product in terms of hardness changes are given in Table 6. The tensile strength results showed that after heat treatment, the hardness decreased, while there was an increase in the elongation % rate.

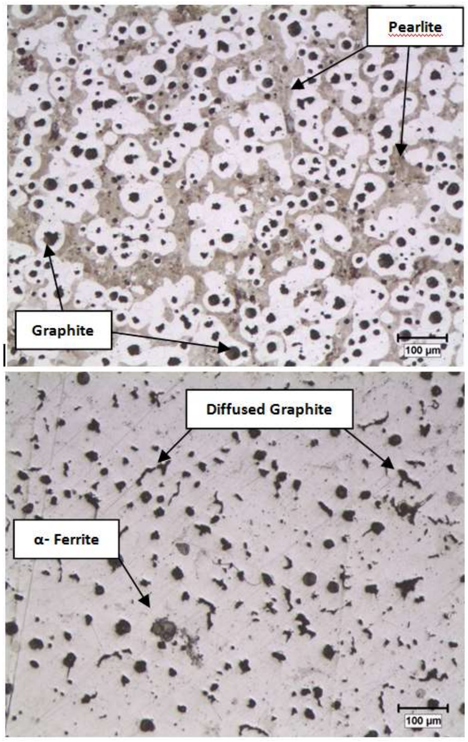

Figure 8. Microstructure: (down) after casting; (up) after heat treatment

Table 6. Tensile test results

	Max. Stress (N/mm²)	**Strain %**	**Energy (J)**	**Elongation (mm)**	**Hardness (HB)**
Casting	536.4	27.6	131.3	5.53	162
Heat Treatment	359.9	41.9	180.5	8.38	95

5.2. Energy consumption results

The threading process and PI were measured for the determined experimental design. Total power (P_{total}) was calculated by using the energy/power conversion equations. In addition to the P_{total}, the total chip removal rate and material removal rate (MRR) are given in Table 7. 3.80 to 3.93 kWh energy consumption in the range of the manufacturing process was performed on the universal lathe. However, 10.2 to 15.6 kWh energy consumption in the CNC milling machine thread cutting process is made. The amount of MRR of the universal lathe was 20.6 mm^3 on the other hand, CNC mills removed 82 mm^3 chip. The results of the instantaneous power measurement showed that the CNC milling machine consumed more energy. On the other hand, the MRR of CNC milling machine tools was more.

The ECPP and SEC results graph for these twelve different test samples is given in Figure 9. According to these results, although the energy required for the threading process on the CNC milling machine was much higher than the instantaneous energy consumption, the ECPP and SEC values were lower since the amount of chip removed is more and production time is shorter. In other words, the manual lathe consumes less P $_{total}$, but the production time and number of operations are much higher than the CNC mill.

Table 7. Main production data

No	P_{total} (kWh)	MRR (mm³/s)
1	3.86	10.30
2	3.91	14.30
3	3.93	20.60
4	13.3	41.08
5	14.8	57.08
6	15.6	82.06
7	3.8	10.30
8	3.9	14.30
9	3.9	20.60
10	10.26	41.08
11	10.33	57.08
12	10.49	82.06

Regarding the thread milling operations performed via CNC milling, the lowest values of ECPP after casting and heat treatment were calculated as 32 and 21.4 Wh.

According to this result, an energy saving of 49% was provided after the austempering process was applied to the fittings materials. In Table 7, P_{total} results showed similar results with ECPP values. According to these results, Energy consumption was reduced from 10.6 kW to 15.6 kW by the heat treatment applied. The most probable reason for this is that the perlitic microstructure can be converted into a ferritic structure, the hardness value decreases and the tensile strength can be decreased.

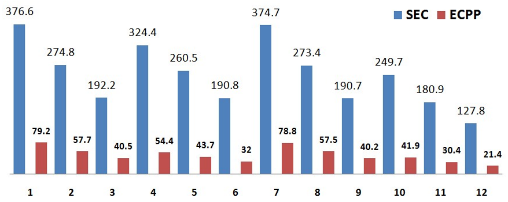

Figure 9. Changes of SEC and ECPP results

The SCEC and $P_{cutting}$ results (Table 8) provide information on the workability of the materials. The changes resulting from the applied heat treatment for these two parameters were examined. Accordingly, the results of measurements for 90, 125 and 180 RPM showed that workability was increased by 49%, 74% and 84%. According to these results, it was determined that the austenitizing heat treatment had a significant effect on the machinability. However, the effect increased as the number of revolutions increased.

Table 8. Machining results in CNC milling

Trial No	$P_{cutting}$ (kW)	MRR	SCEC
4	9.35	41.08	227.60
5	10.65	57.08	186.58
6	11.28	82.06	137.46
10	6.27	41.08	152.63
11	6.11	57.08	107.04
12	6.11	82.06	74.46

The ECPP results were determined by surface plots generated using RPM, production method, MRR and SEC values (Fig. 10). When these results are examined, it can be said that both the ECPP and the SEC values increased in parallel with the MRR values. At the same time, the energy consumption decreased as the number of revolutions increased.

No proportional change was observed between production time and energy consumption. The intensity of the effect of each production parameter determined in the experimental design on the SEC and ECPP results is shown in Tables 9 and 10. According to these findings, the tap tool affected SEC results at the rate of 63%. In addition, the type of machine affected the ECPP results by 58%.

Table 9 Analysis of variance for SEC using adjusted SS for tests

Source	DF	Seq SS	Adj SS	F	F%	*P*
Production Method	1	4110	4110	5.27	11	0.055
Machine Type	1	10110	10110	12.96	26	0.009
Cycles	2	48771	48771	31.26	63	0.000
Error	7	5460	5460			
Total	11	68451				

Table 10 Analysis of variance for ECPP using adjusted SS for tests

Source	DF	Seq SS	Adj SS	F	F%	*P*
Production Method	1	115.94	115.94	3.16	5	0.119
Machine Type	1	1410.50	1410.50	38.45	58	0.000
Cycles	2	1810.01	905	24.67	37	0.001
Error	7	256.80	36.69			
Total	11	3593.25				

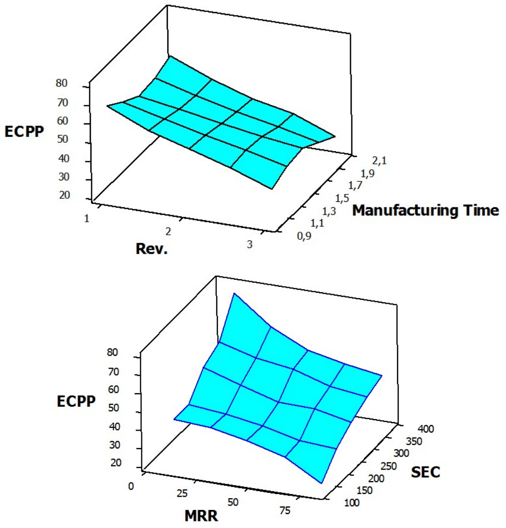

Figure 10. ECPP surface plot results

6. CONCLUSION

The amount of research into energy consumption has increased in recent years along with the rising energy production costs and growing inadequacy of available energy resources [9-18]. As the serial production conditions for reduction fittings involve different microstructure and hardness values, two different internal threading process methods were examined in this study. The threading process is applied in many manufacturing areas, including the aviation, automotive, and machine production industries, while sustainability and energy saving constitute important topics in these sectors.

This study may therefore serve as an important reference source for energy consumption surveys and pipe threading in metal cutting processes. Escalona et al. observed a maximum of 1.8 kWh of energy consumption when machining 304 grade stainless steel 16. In their studies, Neugebauer et al. measured 6 kWh of power consumption in the drilling of EN-GJL-250 gray cast iron 15. When three different types of treatment methods were examined by Negrete in the turning of 6061 aluminum, the maximum energy expenditure of 5.8 kWh was observed in hole drilling 12. In addition, Öktem et al. researched the threading processes of cast and austempered fitting materials and observed that a total power consumption of 16.5 kWh was needed for the threading of cast iron fittings 21. The process of threading the cast material was carried out at 170 RPM on the same CNC milling machine using a ¾ inch tap tool with an instantaneous power consumption of 13.3 – 15.6 kW.

As a result of the austenitizing heat treatment applied in the current study, the threading process was performed with a ½-inch tap tool at expended energy in the range of 10.26–10.49 kW, making it possible to optimize energy consumption by an average of 39%. After casting, a pearlitic microstructure was observed, and following the heat treatment, the ferritic structure was transformed into α-ferrite.

However, it was determined that the spheroidized graphite was mostly diffused in the main matrix. The tensile strength and hardness decreased after the heat treatment, whereas an increase in the elongation percentage rate was observed. When the P_{total} results were examined, these changes in the microstructural and mechanical features resulted in energy savings of 3040 Wh using the CNC milling machine, which amount to an annual savings of 8755 kWh. Thus, by improving the material properties, high energy savings can be achieved in production, while at the same time yielding products which exhibit superior engineering properties.

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