Hıdır Sercan Çubuk*
Dokuz Eylül University, Graduate School of Natural and Applied Sciences
Construction and Manufacturing Program
İzmir, Türkiye

İnal Kızılca
İzmir Demokrasi University, Graduate School of Natural and Applied Sciences,
Mechanical Engineering Program
İzmir, Türkiye

Alper Mutlu
Dokuz Eylül University, İzmir Multidiciplinary Vocational School Electronical Automation Biomedical Equipmant Technology
İzmir, Türkiye

Uğur Çavdar
İzmir Demokrasi University,
Faculty of Engineering
Mechanical Engineering Department
İzmir, Türkiye

Makale Bilgisi:
Araştırma Makalesi
Gönderilme: 12 Aralık 2024
Kabul: 19 Eylül 2025

*Sorumlu yazar: Hıdır Sercan Çubuk
E-mail: hsercancubuk@gmail.com

DOI: https://doi.org/10.56193/matim.159940

Investigation of Mechanical and Internal Structure Properties of 1040 Steel After Heat Treatments

This study aims to compare two heat treatment techniques—high-frequency induction and conventional furnace heating—applied to AISI 1040 medium-carbon steel. The effects on surface hardness, microstructure, and energy efficiency were evaluated under controlled thermal conditions at 950 °C followed by water quenching. A total of six samples were examined, varying in heating durations from 2 to 10 minutes for induction and 60 minutes for furnace treatment. A 4-minute induction process was found to be the most efficient, providing the highest surface hardness (647 HV), optimal martensitic depth (172.75 µm), and 33% lower energy consumption compared to the furnace-treated sample (613 HV). Microstructural analysis revealed a dense martensitic layer near the surface for induction-treated samples, while furnace-treated specimens exhibited a uniform ferrite–pearlite structure. This makes short-duration induction hardening a cost-effective and technically superior surface treatment strategy for medium-carbon steels.

Keywords: Steel 1040; induction; heat treatment; penetration; hardness

1. INTRODUCTION

Steel, an alloy primarily composed of iron with varying carbon and alloying element content, exhibits mechanical properties that are strongly influenced by its composition and internal structure. Its abundance, affordability, and compatibility with various manufacturing techniques—such as rolling, casting, and welding—make it a widely used material across multiple industries [1,2]. Through thermal treatments, key mechanical characteristics such as hardness, strength, and ductility can be adjusted by modifying grain size and phase composition, thereby enhancing steel's functional range [2]. As a result, heat treatment stands out as a vital method for adapting steel properties to industrial requirements [1–3].

AISI 1040, a medium-carbon steel containing approximately 0.4 wt.% carbon, undergoes hardness enhancement through cementite phase formation during thermal processing [4,5]. This steel possesses a body-centered cubic (BCC) structure at room temperature, which transforms into austenite at approximately 910 °C due to reduced atomic spacing within the lattice [4,6–9]. The thermal response during heating is determined by factors such as chemical composition, part geometry, and application-specific performance needs. In particular, the heating rate is inversely proportional to thermal conductivity and directly influenced by component dimensions [8–14].

High-frequency induction hardening has emerged as an effective heat treatment technique for improving both fatigue performance and wear resistance in engineering applications. The success of this method is dependent on material properties such as electrical resistivity (ρ), magnetic permeability (μ), and operating frequency (f). Induction-treated AISI

1040 steels often show greater surface hardness and toughness than those subjected to conventional furnace treatments, offering advantages in performance-critical scenarios [15–17].

Furnace heat treatments can also enhance the mechanical behavior of medium-carbon steels like AISI 1040. Pangestu and Rosidah (2024) [18] demonstrated that austenitizing at 950 °C for 60 minutes followed by water quenching increased surface hardness to around 590 HV, confirming the effectiveness of furnace-based approaches. However, the achieved hardness tends to be lower and more uniformly distributed compared to induction methods. Onan et al. (2012) [19] found that longer induction durations elevated surface hardness while maintaining core ductility, with microstructural analysis revealing a martensitic outer layer and a ferrite–pearlite core, validating induction's ability to improve mechanic properties. Likewise, Alrashdan et al. (2021) [20] reported that optimized austenitizing followed by rapid quenching significantly enhanced surface hardness, tensile strength, and ductility. These findings support the view that while furnace treatments contribute to surface hardening, their performance remains limited compared to induction methods applied under similar thermal conditions.

Although numerous studies have individually addressed induction and furnace heat treatments for carbon steels such as AISI 1040 [15–22], a systematic comparison of both methods under thermally equivalent parameters remains scarce. Particularly, few studies provide an integrated assessment of mechanical behavior, structural development, and energy performance. The present study addresses this gap by offering a side-by-side evaluation of high-frequency induction and furnace treatments applied to AISI 1040 steel under matched thermal conditions [18–22].

In contrast to earlier studies that often focused on isolated parameters like surface hardness or microstructure, this research adopts a multidimensional approach, analyzing hardness distribution, penetration depth, and specific energy consumption per unit mass within the same framework [15–22]. This allows for a more comprehensive understanding of the balance between energy efficiency and material performance—especially crucial in industrial environments where both reliability and cost are paramount [15,17,19,20]. Induction hardening, in this respect, offers precise surface property optimization without altering chemical composition [15–17]. Through controlled application of process parameters such as heating time and power level, targeted hardness values and depth gradients can be achieved. Consequently, an optimized hardened layer can be generated, enhancing overall surface performance [15,16, 19–22].

Accordingly, the main objective of this study is to evaluate the hardening behavior of AISI 1040 steel—a cost-effective and industrially significant medium-carbon alloy—following water quenching after high-frequency induction and conventional furnace heat treatments. The investigation emphasizes a comparative analysis of these processes in terms of their effects on mechanical properties, microstructural evolution, and energy efficiency. By implementing both treatments under thermally equivalent conditions, this study provides a novel and holistic evaluation that addresses the fragmented nature of previous findings.

2. EXPERIMENTAL WORK

In this study, six cylindrical specimens of AISI 1040 medium-carbon steel were used to comparatively investigate the effects of high-frequency induction and conventional furnace heat treatments. Each sample was machined to identical dimensions—18.31 mm in diameter (±0.3%) and 4.96 mm in thickness (±0.2%)—to ensure dimensional consistency across the experimental group. The approximate mass of each specimen was calculated as 10.2 g based on a material density of 7.85 g/cm³. The initial Vickers hardness of the untreated base material was 232.25 HV, which served as a reference for post-treatment comparisons.

Table 1 lists the elemental composition of the AISI 1040 steel, highlighting elements such as C, Mn, Si, and Cu, which are critical in determining the steel’s thermal and mechanical behavior during heat treatment. Table 2 summarizes the applied processing parameters, including the constant austenitization temperature (950 °C), heating durations, and cooling methods for both induction and furnace treatments.

Figure 1a shows the laboratory-scale high-frequency induction system (2.8 kW, 900 kHz, 99% power, coil diameter 24 mm) used for durations of 2, 3, 4, 5, and 10 minutes. Figure 1b illustrates the conventional furnace employed for the furnace-based procedure, in which the specimen was heated to 950 °C and held isothermally for 60 minutes. The average heating rate of the furnace was approximately 15.42 °C/min, taking around 60 minutes to reach the target temperature. This slow, uniform heating was intended to minimize thermal gradients and achieve a homogeneous temperature distribution throughout the specimen. Figure 1c shows the appearance of the induction system during heat treatment.

Table 1. Elemental composition of 1040 sample

Element in Material	C	Mn	Si	S	P	Cu
Percentage in Element (%)	0.38	0.72	0.18	0.025	0.021	0.041

Table 2. Process parameters

No.	Prosses	Heating (°C)	Dwell Time	Cooling
1	Induction	950°C	2 min.	Quenching
2	Induction	950°C	3 min	Quenching
3	Induction	950°C	4 min	Quenching
4	Induction	950°C	5 min	Quenching
5	Induction	950°C	10 min	Quenching
6	Furnace	950°C	60 min	Quenching

(a) (b) (c)

Fig. 1. (a) Induction device, (b) furnace, (c) view of the induction system during heat treatment

Following heat treatment, all samples were subjected to rapid water quenching under atmospheric and still-air conditions at approximately 25 °C. Rapid cooling was employed to induce martensitic transformation, particularly near the surface, and to preserve a soft ferrite–pearlite structure at the core. For the induction process, direct thermocouple-based temperature measurements were not performed due to equipment limitations; instead, exposure time under constant power served as the heating control parameter.

Microstructural analysis was conducted on polished and etched cross-sectional specimens using a Nikon H600L optical microscope. Sample preparation involved sequential grinding with silicon carbide papers (100–2500 grit), followed by polishing with diamond suspensions (6 µm and 1 µm). Etching was performed with 3% Nital for 5 seconds to reveal microstructural features.

Hardness measurements were carried out using a Metkon Duroline LV Vickers hardness tester with a 10 kgf load and 10-second dwell time. Measurements were taken radially at intervals of 1–3 mm from the surface inward (3 tracks with 1 mm spacing and 2 tracks to the center with 3 mm spacing). As shown in Figure 2, five indents were made from the surface to the core to determine penetration depth, which was defined as the distance from the surface to the region where the hardness value dropped below ~550 HV, approaching core hardness.

Energy consumption during heat treatment was measured using a Fluke 434-II power quality and energy analyzer, calibrated in an accredited laboratory. Readings were standardized using root mean square (RMS) values to enable consistent comparisons. Energy consumption per unit mass ($kWh \cdot kg^{-1}$) was calculated and multiplied by specimen mass to obtain energy use per sample (kWh). Subsequently, cost was determined using a standard electricity tariff of 1 TL/kWh (for the year 2025), based on national rates in Turkiye.

3. RESULS

3.1. Hardness Results

The application of high-frequency induction heat treatment significantly enhanced the surface hardness of AISI 1040 steel specimens. While the untreated base material exhibited an initial hardness of 232.25 HV, the sample subjected to a 4-minute induction cycle reached a peak hardness of 647.51 HV, corresponding to an approximate increase of 179%. Fig. 2. Hardness points by measured

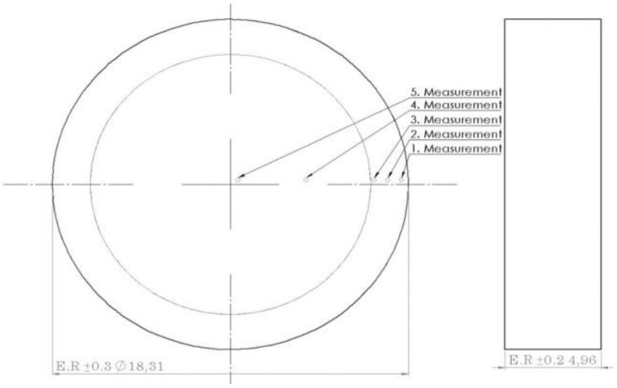


Fig. 2. Hardness points by measured

All induction-treated specimens displayed a gradual reduction in hardness from the surface toward the core, characteristic of localized martensitic transformation. As shown in Fig. 3a, 2 min treatment resulted in an average surface hardness of 593.73 HV, which increased to an average of 619.59 HV at 3 min (Fig. 3b). The highest hardness was recorded in the 4 min sample (Fig. 3c), confirming the optimum time for martensite formation under the applied parameters.However, extended durations led to a decrease in hardness, with average values of 639.82 HV at 5 minutes (Figure 3d) and 605.52 HV at 10 minutes (Figure 3e), likely due to over-tempering or grain coarsening associated with prolonged thermal exposure.

The conventionally furnace-treated specimen, which was held at 950 °C for 60 minutes and then water-quenched, exhibited a more uniform but lower average surface hardness of 613.08 HV (Figure 3f). Although this value falls below the maximum obtained through induction, it still reflects a substantial ~164% increase over the base material. The uniformity of this profile can be attributed to the steady heating rate and extended soaking period.
The overall trend, summarized in Figure 3g, illustrates that surface hardness increases with induction duration up to 4 minutes, beyond which thermal degradation becomes evident. These findings suggest that the 4-minute induction cycle represents the optimal condition for achieving both high surface hardness and structural integrity.

The results of this study are in strong agreement with previous literature. For example, Sanusi and Akunlabi (2018) [1] reported increased hardness and reduced ductility in AISI 1040 steel following water quenching after 950 °C annealing—a trend that parallels the hardness gradient observed here. Additionally, Onan et al. (2012) [19] documented hardness values ranging from 630 to 690 HV in induction-hardened AISI 1040 steels, depending on duration and frequency. The 647.51 HV recorded in the present 4-minute sample fits well within this range, further validating the effectiveness of the selected parameters.

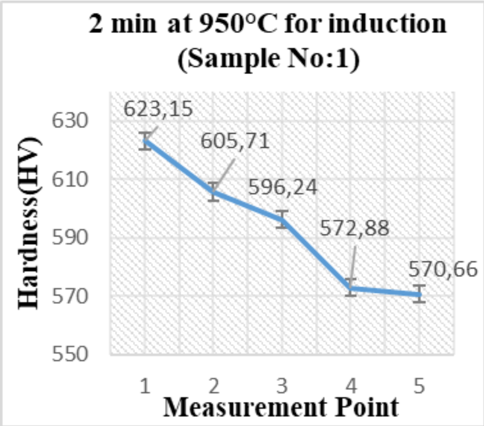
These findings, supported by quantitative data and related studies, reveal that short-term induction heating provides the same hardness in medium carbon steels such as AISI 1040 in a shorter time. Figure 3 shows the hardness data obtained in the study in detail.

3.2. Microstructure Results

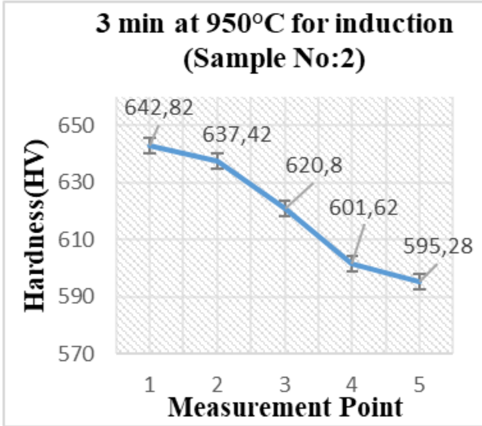
The influence of induction heating duration on the microstructure of AISI 1040 steel was investigated using optical microscopy and quantified by measuring the martensitic layer penetration depth. No elemental (EDX), carbon diffusion, or tribocorrosion analyses were performed in this study; thus, interpretations are limited to morphological observations and hardness-based depth measurements.

Optical images revealed a clear martensitic transformation near the surface for samples subjected to induction treatment, with increasing depth and structural changes as the duration extended. Short durations (2–4 minutes) resulted in a compact, well-defined martensitic layer adjacent to a ferrite–pearlite core, which supports high surface hardness while maintaining ductile properties internally.

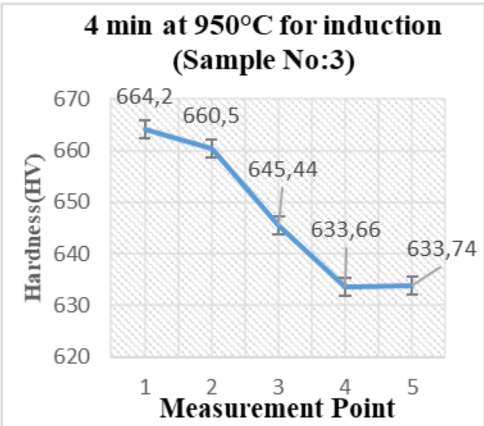
The penetration depth of the martensitic layer varied significantly with induction duration. Specifically, depths of 123.87 μm, 151.70 μm, 172.75 μm, 196.49 μm, and 238.41 μm were measured for the 2-, 3-, 4-, 5-, and 10-minute treatments, respectively. The 4-minute condition exhibited a 39.5% increase over the 2-minute sample and a 13.9% increase compared to the 3-minute sample, while being 13.7% shallower than the 5-minute sample. The 10-minute duration showed a 38.0% higher depth than the 4-minute condition. Due to the absence of a distinct martensitic structure, the furnace-treated specimen was not included in the penetration depth evaluation.


2 min at 950°C for induction
(Sample No:1)
Hardness(HV)
Measurement Point
623,15
605,71
596,24
572,88
570,66
630
610
590
570
550
1
2
3
4
5

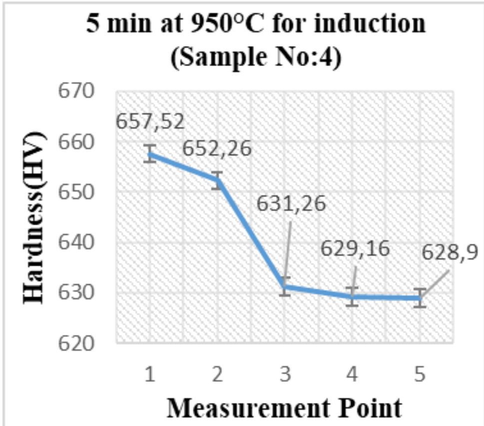
(a)


3 min at 950°C for induction
(Sample No:2)
Hardness(HV)
Measurement Point
642,82
637,42
620,8
601,62
595,28
650
630
610
590
570
1
2
3
4
5

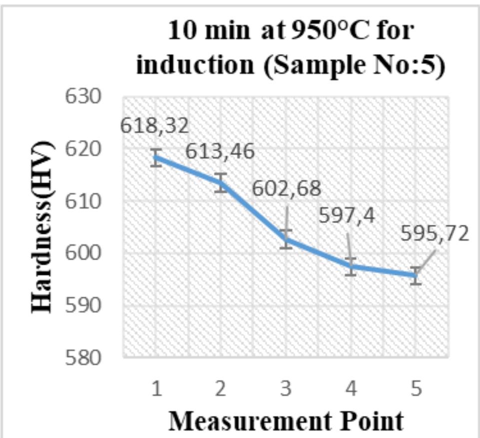
(b)


4 min at 950°C for induction
(Sample No:3)
Hardness(HV)
Measurement Point
664,2
660,5
645,44
633,66
633,74
670
660
650
640
630
620
1
2
3
4
5

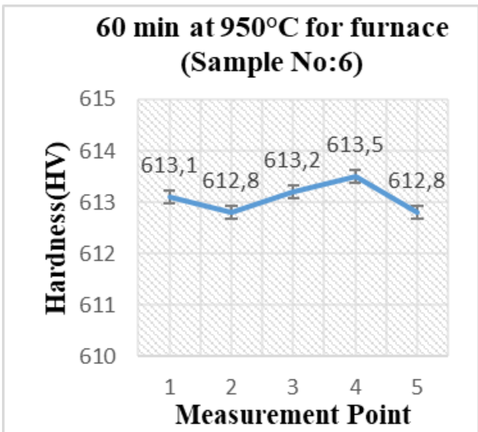
(c)


5 min at 950°C for induction
(Sample No:4)
Hardness(HV)
Measurement Point
657,52
652,26
631,26
629,16
628,9
670
660
650
640
630
620
1
2
3
4
5

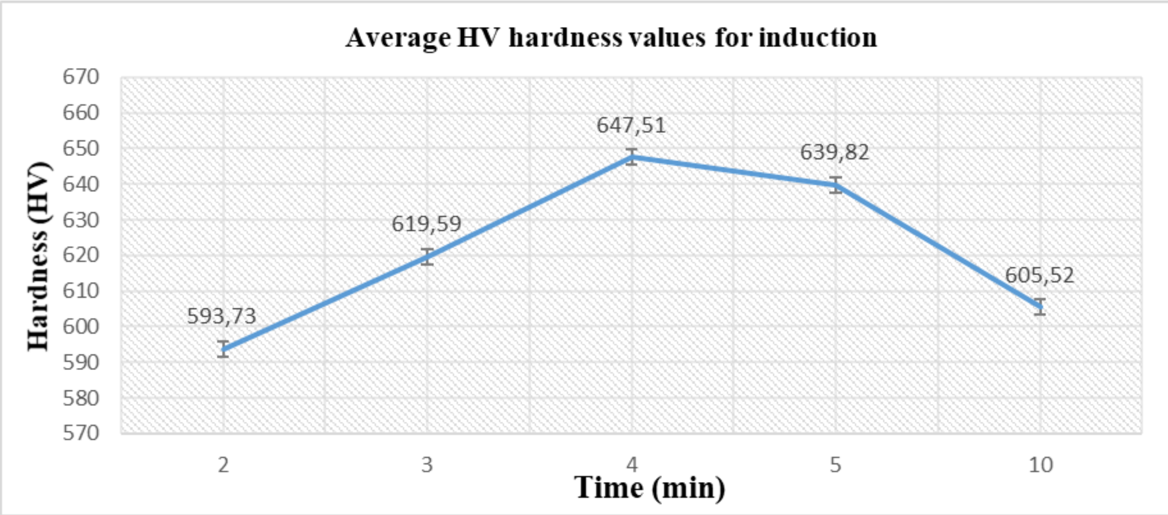
(d)


10 min at 950°C for
induction (Sample No:5)
Hardness(HV)
Measurement Point
618,32
613,46
602,68
597,4
595,72
630
620
610
600
590
580
1
2
3
4
5

(e)


60 min at 950°C for furnace
(Sample No:6)
Hardness(HV)
Measurement Point
613,1
612,8
613,2
613,5
612,8
615
614
613
612
611
610
1
2
3
4
5

(f)



(g)

Fig 3. HV hardness results after induction of (a) 2 minutes (Sample No: 1); (b) 3 minutes (Sample No: 2); (c) 4 minutes (Sample No:3); (d) 5 minutes (Sample No: 4); (e) 10 minutes (Sample No: 5); (f) 60 minutes for furnace (Sample No:6); and (g) average HV hardness values after induction applied to 1040 steel material

The sample treated in the conventional furnace was excluded from penetration depth evaluation due to the absence of a distinct martensitic layer. Its microstructure exhibited a fully ferrite–pearlite composition across the cross-section, consistent with slow heating and long soaking conditions. While more uniform, this configuration lacks the targeted hardening characteristics achieved through induction. The findings obtained here are also consistent with previous literature studies[1,15-22].

These findings validate the efficiency of short-duration, high-frequency induction hardening as a surface treatment strategy for medium-carbon steels when controlled transformation depth and gradient are desired. "The previously presented optical images (Figure 4a–d) and the quantitative penetration depth values in Table 3 jointly support this interpretation.

3.3. Cost Analysis Results

To assess the energy efficiency of the applied heat treatment methods, a detailed cost analysis was conducted. The primary objective was to quantify energy consumption at different process durations and identify the most economically viable parameter in terms of surface performance and industrial scalability.

Energy consumption was measured using a Fluke 434-II power quality and energy analyzer, which records electrical data in real-time based on root mean square (RMS) values. During each heat treatment cycle, total power consumption was logged and normalized by the sample mass (10.2 g) to yield energy consumption values in units of $kWh \cdot kg^{-1}$. These values were then converted into cost per sample (TL (Turkısh Lira) /sample) using an average national electricity tariff of 1 TL per kWh applicable in Türkiye (2025) at the time of the study. All experimental runs were repeated three times to ensure accuracy and reproducibility.

As summarized in Table 4, a clear correlation was observed between induction duration and energy demand. The 2-minute induction cycle consumed $1.52\,kWh \cdot kg^{-1}$, while the 10-minute treatment reached $5.11\,kWh \cdot kg^{-1}$, indicating a 236% increase. Conversely, the conventional furnace process, which included 60 minutes of heating and 60 minutes of soaking, consumed $3.62\,kWh \cdot kg^{-1}$ despite its longer overall cycle.

From a performance-cost perspective, the 4-minute induction process was identified as optimal. It achieved the highest surface hardness (647.51 HV) with a moderate energy input of $2.42\,kWh \cdot kg^{-1}$, translating to a unit cost of only 0.048 TL per sample. In comparison, the furnace-based process incurred a higher cost of 0.072 TL per sample, while the 10-minute induction cycle reached 0.102 TL due to excess energy consumption.

This optimized result stems from a precise balance between heating time and energy transfer, promoting effective martensitic transformation without inducing grain coarsening or over-tempering. While direct abrasion or corrosion testing was beyond the scope of this study, the observed martensitic morphology is commonly associated with improved wear resistance, making the optimized condition promising for industrial applications subjected to surface loading [15-22]. In addition, the findings are consistent with prior studies. The U.S. Department of Energy (1998) reported that induction heating systems could achieve up to 84% energy efficiency, significantly outperforming electric radiant (71%) and gas-fired heaters (40%). Similar industrial-scale findings by Ultraflex Power Technologies highlighted that the cost per part using induction preheating could be less than $1, whereas conventional methods may exceed $6 per part depending on the energy source.

In conclusion, the 4-minute induction heat treatment not only produced the highest hardness performance, but also minimized energy consumption and associated cost. These advantages make it a suitable and scalable method for energy-sensitive, high-efficiency manufacturing applications involving medium-carbon stee. Table 4 shows the energy data

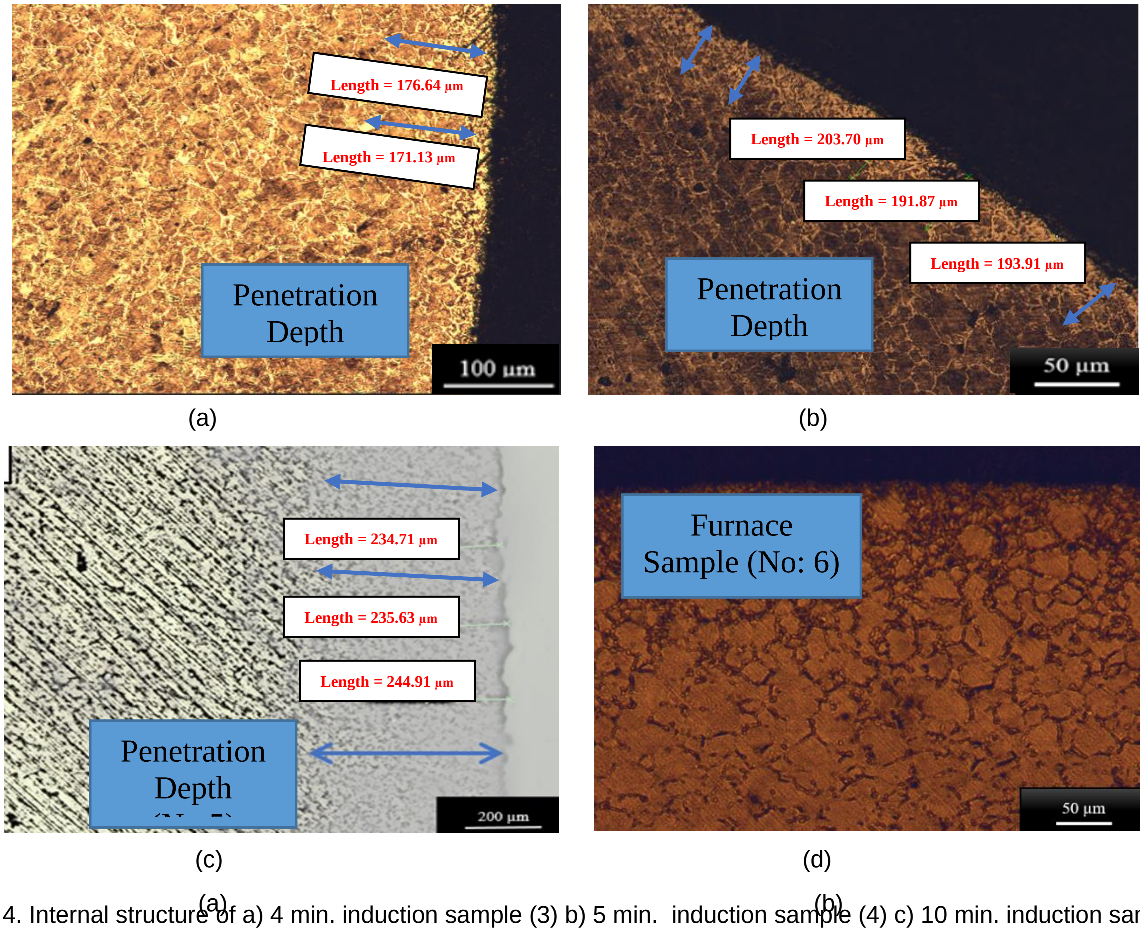


Fig. 4. Internal structure of a) 4 min. induction sample (3) b) 5 min. induction sample (4) c) 10 min. induction sample (5) d) oven sample (6)

Table 3. Penetration depth in induced samples

Duration-Penetration Depth	2 min Induction	3 min Induction	4 min Induction	5 min Induction	10 min Induction
I. measurement	125.85 µm	150.52 µm	176.64 µm	203.70 µm	234.71 µm
II. measurement	124.09 µm	152.84 µm	171.13 µm	191.87 µm	235.63 µm
III. measurement	121.68 µm	151.76 µm	170.48 µm	193.91 µm	244.91 µm
Average	*123.87 µm*	*151.70 µm*	*172.75 µm*	*196.49 µm*	*238.41 µm*

Table 4. Measured energy values

Features and Heat Treatment Type	Induction					Oven
Heating time	***2 min***	***3 min***	***4 min***	***5 min***	***10 min***	***(60 min stabilized + 60 min hold)***
Energy consumption values of the Fluke 434-II (kWh.kg^{-1})	1.52	1.82	2.42	2.74	5.11	3.62
Energy per Sample (kWh)	0.0155	0.0185	0.0246	0.0279	0.0521	0.0369
Cost per Sample (TL-₺)	0.0155	0.0185	0.0246	0.0279	0.0521	0.0369

4. CONCLUSION and DISCUSSION

This study comparatively examined the influence of high-frequency induction and conventional furnace heat treatments on the surface hardness, microstructural evolution, and energy efficiency of AISI 1040 medium-carbon steel. All samples were subjected to heat treatment at 950 °C followed by water quenching. Among the examined conditions, the 4-minute induction treatment yielded the highest surface hardness of 647.51 HV, marking a 179% improvement over the untreated base material (232 HV). Although extending the induction time to 10 minutes increased the hardening depth to 238.41 µm, this came at the cost of reduced surface hardness (605.52 HV), indicating the onset of grain coarsening due to excessive thermal exposure.

From an energy standpoint, the 4-minute induction process proved highly efficient, consuming 2.42 kWh·kg^{-1}, approximately 33% less than the furnace route (3.62 kWh·kg^{-1}). On a per-sample basis, this translated to a cost of 0.048 TL, compared to 0.072 TL for the furnace and 0.102 TL for the extended 10-minute induction cycle. These results demonstrate that the 4-minute induction treatment offers the most favorable compromise between surface hardness, hardening depth (172.75 µm), and energy cost. The enhanced performance is attributed to optimal energy input that facilitates complete martensitic transformation while minimizing structural degradation and excessive energy expenditure. In this context, optimization refers to achieving a process window where thermal exposure, energy use, and mechanical performance are effectively balanced.

ACKNOWLEDGMENT

This study was produced while conducting research within the scope of TÜBİTAK BİDEB 2210-C Priority Areas Master's Scholarship Program. (Capt. No: 1649B022215401). We would like to thank TÜBİTAK for increasing the scope of our research

1040 ÇELİĞİNE UYGULANAN ISIL İŞLEMLER SONRASI MEKANİK VE İÇ YAPI ÖZELLİKLERİNİN İNCELENMESİ

Bu çalışma, AISI 1040 orta karbonlu çeliğe uygulanan iki farklı ısıl işlem tekniğinin—yüksek frekanslı indüksiyon ve geleneksel fırın ile ısıtma yöntemlerinin—yüzey sertliği, mikro yapı ve enerji verimliliği üzerindeki etkilerini karşılaştırmalı olarak incelemeyi amaçlamaktadır. Her iki yöntem de 950 °C sıcaklıkta uygulanan ve su verme ile tamamlanan kontrollü termal koşullar altında gerçekleştirilmiştir. Toplam altı numune farklı sürelerde ısıtılmıştır: indüksiyon için 2 ila 10 dakika, fırın için ise 60 dakika. 4 dakikalık indüksiyon işlemi, en yüksek yüzey sertliğini (647 HV), optimum martensit derinliğini (172.75 µm) ve fırın işlemine göre %33 daha düşük enerji tüketimini sağlayarak en verimli seçenek olarak öne çıkmıştır. Fırın işlemine tabi tutulan örnek ise daha düşük yüzey sertliği (613 HV) sunmuş ancak daha homojen bir ferrit–perlit yapı sergilemiştir. Mikro yapı analizi, indüksiyonla işlem görmüş örneklerin yüzeye yakın bölgelerinde yoğun martensitik bir katman oluştuğunu ortaya koyarken, fırınla işlem görmüş numunelerin daha homojen ferrit–perlit yapıda olduğunu göstermiştir. Bu bulgular, kısa süreli indüksiyonla sertleştirmenin orta karbonlu çelikler için maliyet etkin ve teknik açıdan üstün bir yüzey işlem yöntemi olduğunu ortaya koymaktadır.

Anahtar Kelimeler: 1040 Çelik; indüksiyon; ısıl işlem; penetrasyon; sertlik

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