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Investigation of The Effect of Accelerated Quenching Process and Quenching Parameters on The Strength of Low-Carbon Railway Forged Steel

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Düşük Karbonlu Demiryolu Dövme Çeliğine Uygulanan Hızlandırılmış Su Verme İşlemi ve Su Verme Parametrelerinin Dayanıma Etkisinin İncelenmesi

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Abstract

This study examined the impact of the 'Accelerated Cooling and Self-Tempering (AC-ST)' heat treatment on the mechanical and microstructural properties of S355J2 grade steel forgings, specifically the component known as the 'Lower Side Bearer.' The AC-ST heat treatment was conducted under 12 bar air pressure for a specific cooling duration. In the microstructure of untreated samples, a Ferrite+Pearlite phase was observed. With an increase in the cooling rate, the structure transformed into polygonal ferrite and/or acicular ferrite, followed by the formation of sorbite and/or upper bainite, and finally, martensite and/or lower bainite phases. It was noted that with an increasing cooling rate, martensite and bainite phases coexisted within the structure. At even higher cooling rates, the structure fully transformed into martensite. Additionally, the applied heat treatment was found to enhance the mechanical properties of the material. Especially, the highest value was obtained with 377 HB hardness value in the edge region of the sample with the highest cooling rate (1-fold distance). Similarly, the highest tensile strength (1002 N/mm²) and yield strength (663.93 N/mm²) were obtained in the 1-fold distance sample. However, in the 2-fold distance sample with lower hardness, the impact energy exhibited the highest value as 81.22 J at room temperature and 95.38 J at -20°C.

***Keywords:** Accelerated cooling; Mechanical properties; Steel; Self-tempering.*

Öz

Bu araştırmada, S355J2 kalite çelikten üretilen ve “Alt Oturma” olarak adlandırılan dövme parçaya, üretim sonrası uygulanan “Hızlandırılmış Soğutma ve Kendi Kendini Temperleme (HS-KT)” ısıl işleminin mikroyapısal ve mekanik özellikler üzerindeki etkisi değerlendirilmiştir. HS-KT ısıl işlemi, 12 bar hava basıncı altında belirli bir soğutma süresi boyunca gerçekleştirilmiştir. Isıl işlem uygulanmamış numunelerin mikroyapısında Ferrit+Perlit fazları tespit edilirken, soğutma hızı etkisi ile yapı, önce poligonal ferrit ve/veya iğnemsi ferrit, ardından sorbit ve/veya üst beynit, son olarak ise martenzit ve/veya alt beynit fazlarına dönüşmüştür. Soğutma hızının artmasıyla birlikte martenzit ve beynit fazlarının birlikte oluştuğu gözlemlenmiştir. Daha yüksek soğutma hızlarında ise yapının tamamen martenzite dönüştüğü belirlenmiştir. Ayrıca uygulanan ısıl işlemin, malzemenin mekanik özellikleri üzerinde olumlu yönde etkiler meydana getirdiği tespit edilmiştir. Özellikle en yüksek soğuma hızına (1 kat mesafe) sahip numunenin kenar bölgesinde 377 HB sertlik değeri ile en yüksek değer elde edilmiştir. Aynı şekilde en yüksek çekme dayanımı (1002 N/mm²) ve akma dayanımı (663,93 N/mm²) 1 kat mesafeli numunede elde edilmiştir. Fakat, daha düşük sertliğe sahip 2 kat mesafeli numunede darbe enerjisi oda sıcaklığında 81,22 J, -20°C'de 95,38 J olarak en büyük değeri sergilemiştir.

***Anahtar Kelimeler:** Çelik; Hızlandırılmış soğutma; Kendi kendini temperleme; Mekanik özellikler.*

1. Introduction

Among the steels used in the railway sector, S355J2 quality steel has an important place. It is also considered one of the high-strength structural steels and has a wide range of applications. (Meester 1997; Lee et al. 2012; Ufuah and Ikhayere 2013). One of the important applications aimed at reducing the consumption of steel materials is to increase the strength of steel (Zavdoveev et al. 2021). Forging is an effective method of plastic deformation that helps increase the strength of steels. This is because plastic deformation closes internal voids and reduces non-metallic residues by breaking them into smaller particles and redistributing them evenly (Penha et al. 2015). In addition, applied heat treatments are another important application that is effective in increasing the strength of steels. Heat treatment enhances the mechanical properties of steel, achieving the required quality without additional alloying (Kominek et al. 2013). Furthermore, heat treatment can improve the mechanical properties of forged parts even further.

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Therefore, heat treatment (e.g. normalizing, quenching, tempering) determines the final microstructure and mechanical properties of forged parts (Mladenović and Petrović 2022). However, as it is known, the most important part of heat treatment is the controllability of the cooling process. Therefore, the cooling strategy should be based on the continuous cooling conversion scheme and metallurgical requirements, with numerical simulations guiding the appropriate cooling process (Hnizdil and Chabicovsky 2018). In this regard (Abdullah et al. 2022), investigated the microstructure and mechanical properties of low carbon steel by heating it to a certain temperature and then rapidly cooling it in 8 different quenching media (Cold water, Normal water, Salt solution 25% /L, Salt solution 50 %/L, Salt solution 100 %/L, Engine Oil, Used Engine Oil, Vegetables Oil). According to the results obtained, the Ultimate Tensile Strength value of the unheated sample was 665 MPa, while the highest Ultimate Tensile Strength value was reported as 822 MPa in the sample quenched in Engine Oil media. (Cao et al. 2024) investigated the effects of different cooling rates and final cooling temperatures on the microstructure and mechanical properties of low carbon bainitic steel. As a result of the research, they reported that varying cooling rates and final cooling temperatures affect the phase transformation process and microstructure of the steel, thus indirectly affecting its mechanical properties. In their study (Chu et al. 2023), investigated the effect of different quenching temperatures (140, 180, 240 and 300 °C) on the strengthening mechanism of low carbon microalloyed steels. According to the results obtained, it was reported that with the increase in quenching temperatures, yield strength (YS) decreased, tensile strength (TS) increased and elongation first increased and then decreased. Also in the literature (Özlü et al. 2023), the workability of the samples obtained by cooling DIN 41Cr4 tempered steel in sand and air was investigated. According to the results obtained, it was reported that the cooling rate in air was higher than the cooling rate in sand and the DIN 41Cr4 tempered steel cooled in air gave the highest (309 HV) value. In another study (Özlü et al. 2021), the machinability of 38MnVS6 microalloyed steel, which was hot forged and cooled in different environments (sand, air, oil and polymerized water), was investigated. It was reported that the 38MnVS6 microalloyed steel, which was cooled in polymerized water after forging, exhibited the highest hardness (651 HV). (Nasibullina and Tyusenkov 2020) study investigated the mechanical and corrosion resistance of St52-3 steel quenched at various temperatures. As a result, it was found that the maximum hardness value was observed after quenching at 100ºC and then annealing, while the minimum annealing temperature was 500 °C. In the study conducted by (Hassan et al. 2022), low carbon steel subjected to heat treatment at 850 °C in the furnace for 30 minutes was quenched in oil and then annealed at 400 °C for different times of 2, 3 and 4 hours. As a result of the study, it was reported that the annealing time period was effective on the fatigue coefficients and that increasing the annealing time decreased the strength of the shear fatigue and increased the shear fatigue ductility coefficients.

Therefore, in this study, the S355J2 quality steel used in railway applications and referred to as the Lower Side Bearer was heated at 900 °C and cooled with an air-water mixture cooling system in line with different pressures and times. As a result of these processes, it was aimed to determine the effect of the accelerated quenching and self-tempering (AC-ST) process on the mechanical properties and the air pressure, time, and distance that gives the optimum mechanical properties. In addition, the changes in microstructure and mechanical properties in different regions (ear and edge) of the Bottom Side Carrier with different cross-sectional areas were analyzed.

2. Materials and Methods

In this study, parts called “Lower Side Bearer” which are produced from forged S355J2 quality steel, which has a very important place in the steel sector, and positioned on the railway bogie chassis, were used.

For the production of the Lower Side Bearer by forging, first, it was cut from S355J2 quality raw material with a diameter of 60 mm and heated in the oven to 1180 °C. Then, it was kept in the oven for approximately 45 seconds, and then the forging process was carried out with a LASCO brand forging press with 4 rough and 2 finish strokes. The final product of the produced Lower Side Bearer is given in Figure 1.

Figure 1. Final product shape of the Lower Side Bearer.

The chemical composition of the Lower Side Bearer (% by weight) is presented in Table 1. When the results are analyzed, it is observed that they conform to the EN 10025-2 standard.

In heat treatment applications, austenitization process was performed in a Telmika model, temperature control unit muffle furnace with a volume of 290x290x450 mm³.

Heat treatment was performed according to the 1-hour annealing method for 1" (inch) thickness.

For the AC-ST heat treatment applied to the Lower Side Bearer, thermocouples were placed in the places shown in Figure 2 and indicated with numbers 1 (edge) - 2 (ear) on the piece in order to monitor the temperature changes that may occur during the application. Temperature changes were monitored with an ADAM brand computer-controlled program. At the end of the heat treatment process, a cooling plate (Figure 3) was designed and manufactured to provide an air+water mixture through eight nozzles for the quenching process. The cross-sectional image and dimensions of the nozzle made of steel material are given in Figure 3. The Lower Side Bearers were positioned between 2 opposite cooling plates and AC-ST heat treatment was applied along the part.

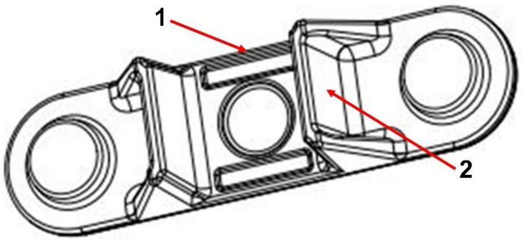


Figure 2. Placed areas of thermocouples.

The effects of two different cooling times and distances between the part and the cooling system, as well as two different air pressure levels, on the AC-ST heat treatment were investigated. The process parameters are presented in Table 2.

Table 1. Chemical composition of EN 10025-2 standard and base material.

Material Quality	(% wt.)					
	C	Si	Mn	P	S	Cu
EN 10025-2 (max.)	0.22	0.55	1.6	0.03	0.03	0.55
Lower Side Bearer (S355J2)	0.19	0.21	1.37	0.012	0.007	0.22

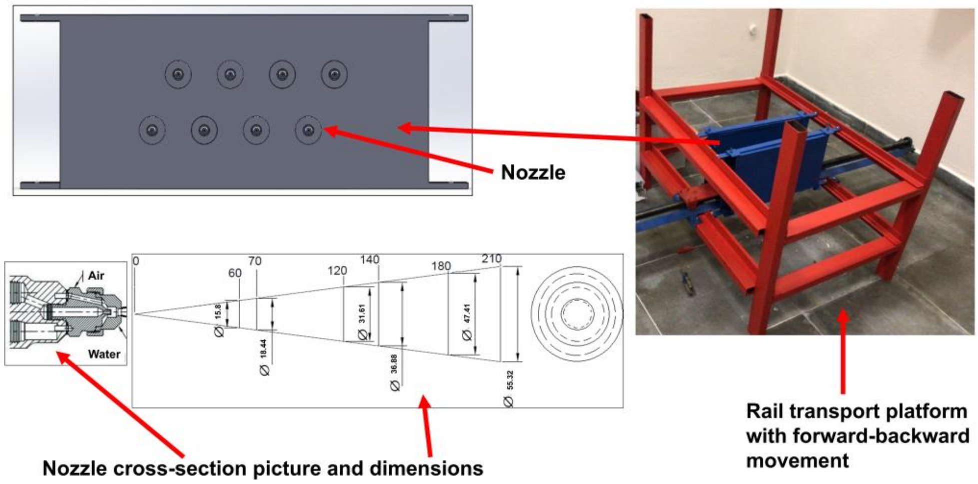


Figure 3. AC-ST heat treatment system and design.

Table 2. AC-ST heat treatment parameters.

Oven Temperature (°C)	Cooling Time (s)	Cooling Plate - Distance Between Parts (mm)	Air Pressure (Bar)
900	30	1X: 70 mm, 2X: 140 mm	12

Tensile tests were performed according to the ISO 6892 standard, and three tensile samples were prepared from each sample. Hardness tests were conducted using the Brinell method on the OPTOBUL brand device in accordance with the standard, under a 750 g load, for 10 seconds, and with a 5 mm ball.

Hardness measurements were taken from seven different points on each sample, and the values were averaged.

The Charpy impact test was performed on the ZWICK/ROELL Rkp450 brand motorized pendulum-type dynamic testing device with an impact energy capacity of 450 Joules. The tests were performed at room temperature (~20 °C) by machining a V-notch on the samples both with and without AC-ST heat treatment, and the center areas were marked according to the ISO 148-3 standard.

For microstructure examinations, the samples were ground with 400, 600, 1000, and 1200 mesh SiC sandpaper, then polished with a 0.1 μm alumina suspension and etched with a 3% Nital acid solution. Nital solution contains 3% nitric acid and 97% ethyl alcohol. The etching process was carried out for 3 seconds. After etching, the microstructures of the samples were examined with a NIKON optical microscope. After optical microscope examinations, SEM images of the samples were taken with a CARL ZEISS Ultra Plus SEM device, and EDX analyses were conducted

3. Results

The cooling rates of the samples are given in Figure 4. The cooling rate was measured as 49.09 °C/s maximum in the sample where the distance between the cooling plate and the material was 1 layer, and 46.53 °C/s maximum in the sample where it was 2 layers. The lowest cooling rates were measured as 14.94 °C/s in the sample where it was 1 layer, and 10.4 °C/s in the sample where it was 2 layers.

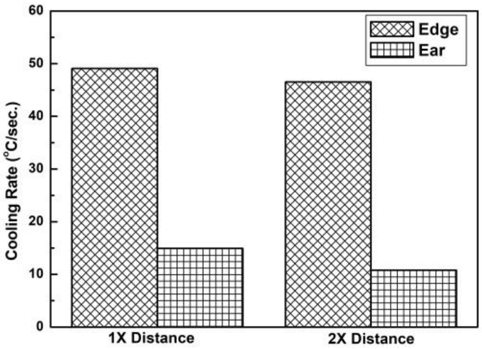


Figure 4. Cooling rate graph.

The optical microscope images of the samples that were and were not heat treated are presented in Figure 5. When the microstructure images of the parts that were not subjected to AC-ST heat treatment were examined, it was determined that Ferrite + Pearlite phases were formed. In the parts that were subjected to AC-ST, it was observed that the Ferrite + Pearlite phases transformed into acicular / polygonal and thin lamellae in the regions with high cooling rates. In addition, it is thought that the formation of bainite, acicular ferrite and sorbite structures formed from thin and long cementite by the diffusion of carbon from the extremely rich martensite in carbon is due to the spontaneous tempering process after the accelerated cooling process (Zengin et al. 2019; Koo 2021).

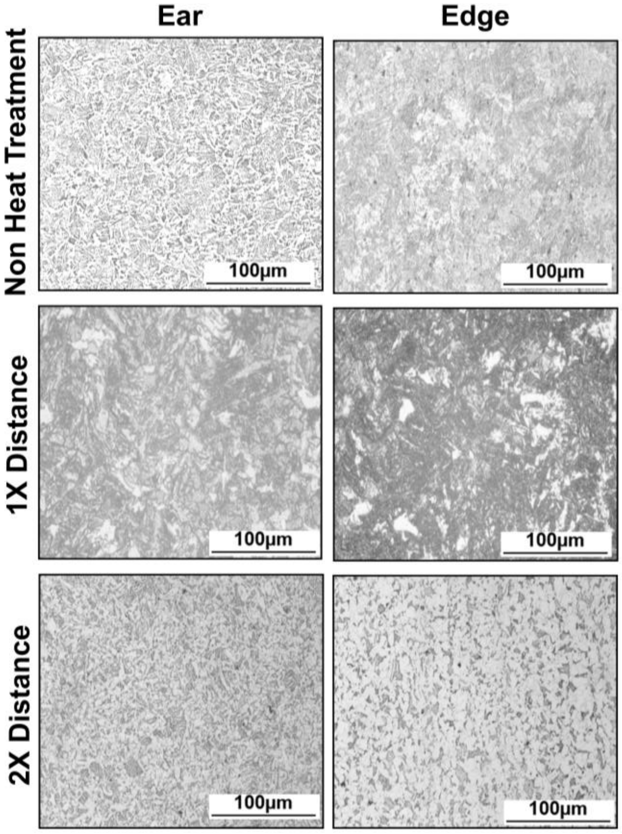
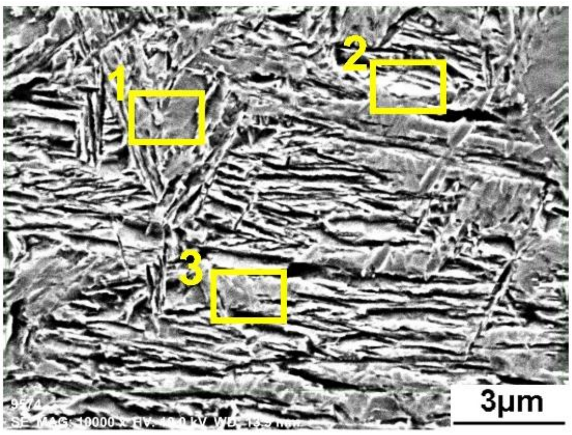
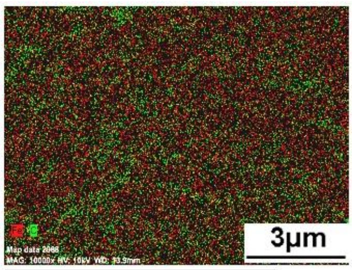


Figure 5. Optical microscope images of samples with and without heat treatment.

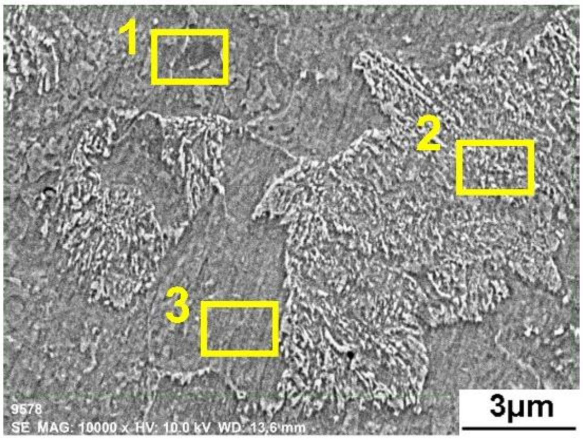
SEM images of the Lower Seat piece applied with AC-ST heat treatment are given in Figure 6 and Figure 7. When the cooling rate reached 10-15 °C/s, it was observed that bainite and martensite phases formed together in the structure. At a cooling rate of around 50 °C/s, the structure was completely transformed into martensite phase. It was also suggested that there may be a relationship between the cooling rate and grain size distribution (Rodrigues et al. 2000).

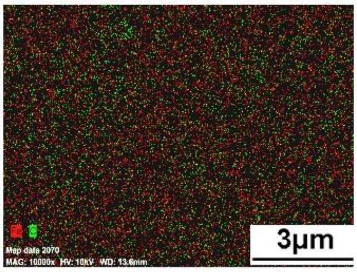




Spectrum	C	Fe
1	7.11	92.89
2	9.71	90.29
3	5.77	94.23

Figure 6. 1X SEM image and EDX analysis.





Spectrum	C	Fe
1	5.58	94.42
2	8.75	91.25
3	7.33	92.67

Figure 7. 2X SEM image and EDX analysis.

When the hardness values are examined (Figure 8 and Table 3), it is concluded that the hardness values in the edge region are partly higher than the values in the ear region. This is because each section of the Lower Side Bearer is exposed to different rates of quenching, cooling and tempering during the application of the AC-ST heat treatment. (Wang et al. 2023) investigated the effect of different heat treatment temperatures (950-110 C) on the microstructure and mechanical properties of low carbon steel. As a result of the study, it was reported that annealing at 930 °C, oil quenching at 1050 °C and annealing at 250 °C contributed to well-balanced properties in the steel and it was reported that the hardness was 51 HRC and the impact toughness was 40 J/cm2, which was almost four times better than the original casting sample. In addition, these differences in hardness values are attributed to the varying wall thicknesses between the edge and ear regions of the Lower Side Bearer.

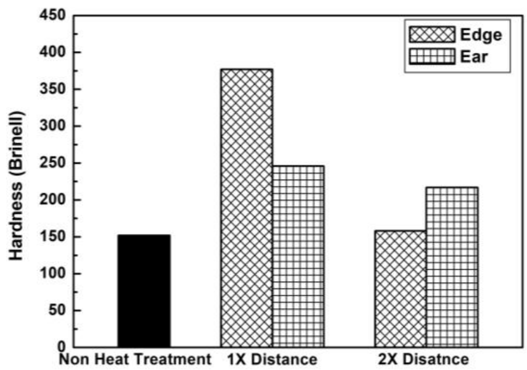


Figure 8. Hardness values of the samples.

Table 3. Numerical data of hardness values

Processes		Hardnes values
Non Heat Treatment		152
1X Distance	Edge	377
	Ear	246
2X Distance	Edge	158
	Ear	217

The impact notch test results are given in Figure 9 and Table 4. Upon examination of the results, the obtained data is found to be in compliance with the EN 10025-2 standard. The impact notch value of S355J2 quality steel is given as minimum 27 J in the EN 10025-2 standard. It was determined that the impact notch values obtained from the parts after AC-ST heat treatment were between 56.94 J and 81.22 J at room temperature, while they were between 30.02 J and 95.38 J at -20 °C.

The impact notch value of the Lower Side Carrier after the forging process at room temperature and -20 °C is 174.47 J and 113.98 J, respectively. As a result of the impact notch tests performed both at room temperature and -20 °C, improvements were observed in these values after the application of AC-ST heat treatment. (Kotrbacek 2016) investigated the effect of heat treatment applied to S355J2 steel on its mechanical properties. As a result of the study, it was reported that the impact energy of the sample at -20 C temperature increased up to 150 J.

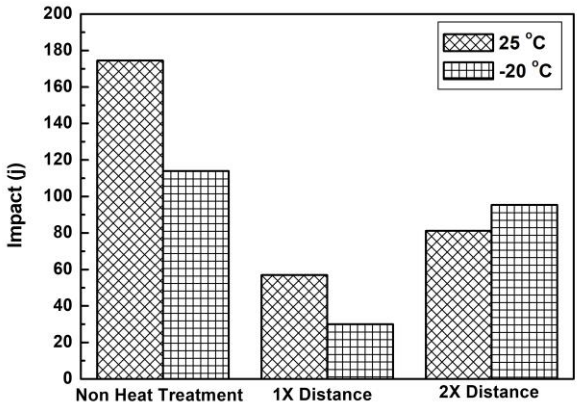


Figure 9. Impact notch test results.

Table 4. Numerical data of Impact notch test values.

Processes	25 °C	-20 °C
Non Heat Treatment	174.4	113.9
1X Distance	56.9	30.1
2X Distance	81.2	95.3

In their study, (Kang et al. 2012) investigated the mechanical properties of low carbon steel that was tempered to minimum austenite grain size, quenched, and tempered at different tempering temperatures (450 °C, 550 °C and 650 °C) and at different cooling rates (0.23, 36 and 50 °C/s). As a result of the study, it was reported that the impact energy for the samples tempered at 650 °C was significantly affected by the cooling rate and the highest value was obtained at a cooling rate of 50 °C/s. On the other hand, it was observed that the impact energy was at the lowest amount at the 1X distance where the cooling rate was approximately 50 C in our study. However, the highest hardness values (Figure 8 and Table 3) and tensile-yield strength (Figure 10 and Table 5) were observed in the sample at the 1X distance.

The tensile test results obtained after AC-ST heat treatment are given in Figure 10 and Table 5. When the obtained values are examined, it is determined that the tensile strength results are between 605.65 N/mm^2 and 1002 N/mm^2, while the yield strength is between 690.4 N/mm^2 and 425.70 N/mm^2.

The tensile strength value of the Lower Side Bearer after forging is 604.3 N/mm^2, while the yield strength value is 390.5 N/mm^2. As a result of the application of AC-ST heat treatment, significant improvements were observed in both tensile strength and yield strength values. In the study conducted by (Kotrbacek 2016), it was reported that the heat treatment applied to S355J2 steel increased the strength of the material up to 820 MPa.

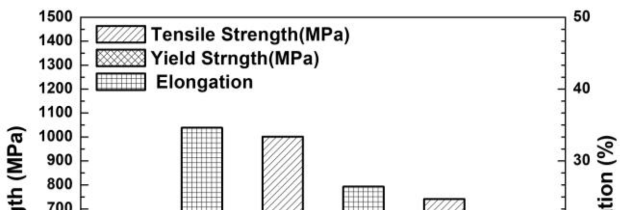


Figure 10. Tensile-yield strengths and %elongation values of the samples.

Table 5. Numerical data of tensile-yield strengths and %elongation values.

Processes	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Non Heat Treatment	604.3	390.5	34.62
1X Distance	1002	663.93	26.44
2X Distance	741.19	516.56	20.86

4. Conclusions

In this study, AC-ST heat treatment was applied to Bottom Seat parts, which were produced by forging, with the distance between the cooling plate and the material being 1-fold (7 cm) and 2-fold (14 cm), at 12-bar air pressure and 30 s cooling time. The effects of AC-ST heat treatment were investigated by applying different parameters to the usual properties of the Bottom Seat part. Accordingly:

1- The highest cooling rate was 49.09 °C/s when the distance between the cooling plate and the material was 1-fold (7 cm), while the lowest cooling rate was 10.4 °C/s in the ear region of the part with a 2-fold (14 cm) distance.

2- While the microstructure of the materials without heat treatment consisted of ferrite and pearlite, it was observed that, depending on the cooling rate, the structure evolved into polygonal and/or ferrite acicular ferrite, then progressed to sorbite and/or upper bainite, and ultimately transformed into martensite and/or lower bainite.

3- The highest hardness value (377 HB) was obtained in the edge region of the sample with the highest cooling rate (1-fold distance). The lowest hardness value (158 HB) among the heat-treated samples was observed in the edge region of the 2-fold distance sample. Compared to the hardness of the untreated sample (152 HB), only a slight increase was observed in the edge region of the 2-fold distance sample. However, the ear region of the 1-fold sample had a hardness value of 246 HB, whereas the ear region of the 2-fold sample had a hardness value of 217 HB.

4- The notch impact test result for the Lower Side Bearer with the highest hardness, subjected to 1-fold AC-ST heat treatment, was measured as 56.94 J at room temperature and 30.02 J at -20 °C. However, in the 2-fold distance sample, which had lower hardness, the impact energy was 81.22 J at room temperature and 95.38 J at -20 °C.

5- The highest tensile strength (1002 N/mm²) and yield strength (663.93 N/mm²) were obtained in the 1-fold distance sample. The highest elongation percentage (34.62 %) was observed in the untreated sample. In the 2-fold distance sample, tensile strength, yield strength, and elongation percentage were measured as 688.4 N/mm², 425.7 N/mm², and 20.27 %, respectively.

Declaration of Ethical Standards

This study is derived from master thesis (thesis number: 802017) under the supervision of Assoc. Prof. Dr. Yunus Türen and Asst. Prof. Levent Elen by 2023 on date of "The effect of accelerated quenching

parameters on the strength of non-alloy low carbon railway forged steel" Titled.
The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
Author-1: visualization and writing – original draft
Author-2: investigation and methodology, Project Manager
Author-3: Experimental design, methodology

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability
All data generated or analyzed during this study are included in this published article.

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