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Investigation of the tribological and mechanical properties of boron steels in terms of potential usage in agricultural applications

Tarımsal uygulamalarda borlu çeliğin kullanım potansiyelinin tribolojik ve mekanik özellikler bakımından incelenmesi

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Highlights

- ❖ Boron steel
- ❖ Cryogenic treatment
- ❖ Wear resistance
- ❖ Quenching
- ❖ Agricultural mechanization

Graphical Abstract

In this study, the usage potential of 30MnB5 steel in agricultural applications is investigated. Different heat treatments such as quenching and quenching, tempering and cryogenic treatment were applied.

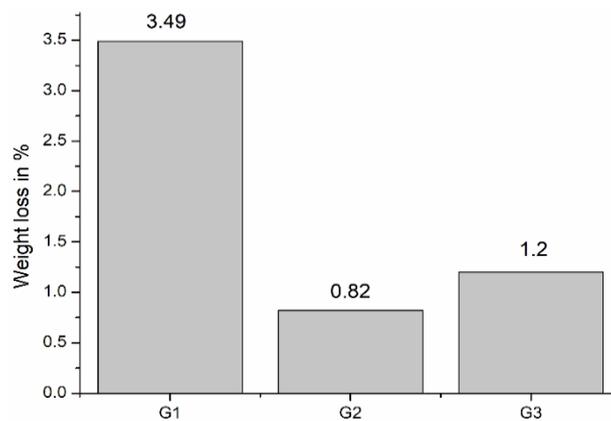


Figure. Comparison of wear loss of a different group of 30MnB5 alloy

Aim

To evaluate the the impact strength, hardness and abrasive wear resistance of the as supplied, quenched and quenched cryo treated-tempered samples of 30MnB5 boron steel.

Design & Methodology

By applying three different heat treatment procedures, the tribological and mechanical properties of 30MnB5 boron steel used were investigated.

Originality

The effect of quenching and cryogenic treatment on the abrasive wear behavior of 30MnB5 boron steels is investigated

Findings

The most abrasive wear resistant specimen was austenitized at 860 °C for 1 hour and water quenched one.

Conclusion

It was observed that the quenching is an essential heat treatment for usage of boron steel in agricultural field.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Investigation of the Tribological and Mechanical Properties of Boron Steels in Terms of Potential Usage in Agricultural Applications

Araştırma Makalesi / Research Article

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ABSTRACT

The usage amounts of boron steels are increasing gradually, especially in industrial applications requiring high wear resistance. One of the usages of this type of steel is tillage tools, which are working in harsh conditions. Prominent desired properties for materials that face the soil in agricultural machining are hardness, abrasive wear resistance, impact toughness. In this study, the tribological and mechanical properties of 30MnB5 boron steel used in agricultural mechanization are investigated, applying three different heat treatment procedures. The impact strength, hardness and abrasive wear resistance of the as supplied, quenched and quenched cryo treated-tempered samples are evaluated. It was observed that the quenching is an essential heat treatment for usage of boron steel in agricultural field. The tempering reduces hardness of the specimen and cryogenic treatment and tempering increased the impact toughness.

Keywords: Boron steel, 30MnB5, quenching, wear resistance, agricultural mechanization.

Tarımsal Uygulamalarda Borlu Çeliğin Kullanım Potansiyelinin Tribolojik ve Mekanik Özellikler Bakımından İncelenmesi

ÖZ

Bor çeliklerinin kullanım miktarları, özellikle yüksek aşınma direnci gerektiren endüstriyel uygulamalarda giderek artmaktadır. Bu tür çeliklerin kullanım alanlarından biri, zorlu koşullarda çalışan toprak işleme aletleridir. Tarımsal işlemede toprağa bakan malzemeler için istenen özellikler sertlik, aşındırıcı aşınma direnci, darbe tokluğudur. Bu çalışmada, tarımsal mekanizasyonda kullanılan 30MnB5 çeliğinin tribolojik ve mekanik özellikleri üç farklı ısı işlem prosedürü uygulanarak araştırılmıştır. Tedarik edildiği haliyle, su verilmiş ve su verilmiş, kriyojenik işlem görmüş ve temperlenmiş numunelerin darbe dayanımı, sertliği ve aşınma direnci değerlendirilmiştir. Su vermenin, borlu çeliğin tarımsal uygulamalarda kullanımı için gerekli bir ısı işlem olduğu gözlemlenmiştir. Temperleme işleminin numunenin sertliğini bir miktar azalttığı ve kriyojenik işlem ve temperlemenin birlikte uygulandığında, darbe tokluğunu arttırdığı görülmüştür

Anahtar Kelimeler: Borlu çelikler, 30MnB5, su verme, aşınma direnci, tarımsal mekanizasyon.

1. INTRODUCTION

The phenomenon of wear can be encountered in many areas from home to industry. It has great economic importance, especially on industrial applications. In the literature, the definition of wear is “the removal of material from a solid surface as a result of mechanical interactions.” The categories and the percentage of the wear which encountered in industrial situations are abrasive 50%, adhesive 15%, erosive 8%, fretting 8%, chemical 5% and others 14% [1]. It is clear that the abrasive wear is the most problematic one among the other wear types. Abrasive wear can be seen in coal conversion processes, earthmoving, mining, mineral beneficiation, agriculture, and many different situations. Abrasive wear processes are divided into two categories:

two-body and three-body abrasive wear. When a rough surface or fixed abrasive particles slide across a surface to remove material, it is called two-body abrasive wear. In three-body abrasive wear, the particles are loose and may move relative to one another, while sliding across the wearing surface. Abrasive wear is a significant problem for the component of soil engaging because of the high amount of material loss and increased the cost and time in replacing worn parts of agricultural machinery. Generally, there is a direct correlation between wear resistance and the hardness of the material [2]. In addition to hardness, these factors have also affected the wear of tillage tools in the field: the particle shape, size, strength, density and moisture of the soil; type, size and population of the stones present in the soil and the relative velocity and impact angle between soil and the implement. The choosing material type to be used

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in soil-engaging components is critical because it should be hard enough to resist wear but also should be tough to resist impact due to stones, rocks in the soil. The hardness and the toughness of the material are inversely proportional to the strength but it should have optimum values to reduce the wear of the soil-engaging components [3]–[5]. However, there is one known exception for this case; it is known that austempering both improves hardness and toughness at the same time. But the austempered hardness is still not enough for many abrasive processes [6].

In order to give adequate performance with a reasonable cost to the tillage tools such as ploughshares, sweeps, shovels and chisels in average soil conditions, it is necessary to be made from high carbon or low alloy steels. Additional treatments are done to improve wear resistance properties such as different surface hardening methods such as carburizing, nitriding, and boriding can be applied. A considerable amount of literature has been published on reducing abrasive wear of tillage tools by using high wear resistance materials or application of different surface hardening methods [3], [5], [7]–[10]. The basis of the surface hardening process is the idea of forming hard layer which increases the surface hardness. Although these methods increase wear resistance, it is not widely used in practice due to their costs and initial investment. Instead of the surface hardening methods, it is possible to increase the hardness in almost all cross sections in the materials by adding specific elements. Adding carbon which is the main element for increasing strength and hardness to steel, makes the steel more durable and tougher up to a point. As adding more carbon, the steel becomes less flexible, and it has negative impacts on the formability and weldability. On the other hand, the presence of the boron element in the structure does not cause any negativity in the material, which lowers the critical cooling duration, and it is added to steels to increase hardenability. The addition of only 0.0015% soluble boron to steel can achieve hardenability property compared to that obtained by additions of about 0.6% Mn, 0.7 % Cr, 0.5 % Mo, or 1.5 % Ni [11]. According to a study, the addition of boron into the structure of low carbon A-UHSS steels promotes the formation of ferritic – pearlitic phase at low cooling rates (0.1 – 0.5 °C/s), while at high cooling rates (50 – 200 °C/s) it promotes the bainitic – martensitic transformation. It also increases the property of quenchable by shifting the TTT curve to the right. This effect is thought to be since B atom, which is of tiny size, is segregated at the austenitic grain boundaries, thereby delaying the formation of the ferritic and pearlitic structure [12]. Since the added boron amount is so small considering other alloying elements it is relatively low cost considering its effect of material properties.

Boron steels are generally used in applications under harsh conditions such as agricultural tools and mining equipment, as they reach high hardness values after applied heat treatments and, at the same time, exhibit excellent resistance to friction and wear. In addition,

automotive manufacturers have started to use boron steels in order to make a lighter vehicle in structural parts and to increase driver and passenger safety in a section that may be exposed to impacts [3]. Boron steels play a vital role in the preventing of the components from the abrasive wear. Hernandez et al. investigated the effect of temperature on the three-body abrasive wear behavior of pre-hardened tool steels and boron steels [13]. Bialobrzaska and Kostencki compared the results of field tests of plowshares with results from a dry sand-rubber wheel laboratory abrasion test of selected low alloy boron steels [14]. Hardell et al. studied on tribological investigations both on high strength boron steel – tool steel tribological pairs at elevated temperatures as well as self-mated hardened high strength boron steel tribological pairs [15]. Cryogenic treatment which also known as cold or sub-zero treatment is another method at low temperatures in the range of -80 °C to -196 °C. This technique is used for improving mechanical and tribological behavior of materials especially steels and ferrous materials [16]–[18]. As mentioned in the literature review, boron steels can be used in heavy working environments for a long time. To date, there has been a little experimental investigation on effect of the cryogenic treatment on the abrasive wear behavior of boron steels. In the literature, there is a study which is published by Liu et al. They investigated the effects of cryogenic treatment on microstructure and abrasion resistance of CrMnB high chromium cast iron subjected to sub-critical treatment [19].

In this study, the usage potential of 30MnB5 steel in agricultural applications is investigated. Different heat treatments such as quenching and quenching, tempering and cryogenic treatment were applied. The properties of 30MnB5 alloy samples were examined in a total three different groups. Charpy impact test is conducted to specimens that were taken parallel to the rolling direction for all group samples. Abrasive wear tests are carried out with block-on-disc configuration and the hardness measurement of the samples is performed.

2. EXPERIMENTAL PROCEDURE

The boron steel was supplied by Turan Tarım Company from Erdemir. The material of commercially available ploughshare is 30MnB5. At the beginning of the experimental work, the supplied boron steel was investigated and verified. The chemical composition of the boron steel is listed in the following Table 1. After the chemical composition verification, the microstructure of the supplied material was checked. It was observed that the microstructure of the received material contains extended grains in rolling direction, and the observed phases were pearlite and ferrite.

Table 1. 30MnB5 boron steel spectral analysis results

C	Si	Ni	B	S
0.32	0.29	0.05	0.035	0.002

Mn	P	Cr	Mo
1.33	0.012	0.14	0.006

The test material was supplied as a plate. The plate was cut into rough pieces, and parts of the pieces were shaped as a Charpy impact sample with machining by using a milling machine. For each group, three samples were prepared. After the machining process, the samples were heat-treated with the parameters shown in Table 2. A group of samples remained as the supplied state. 30MnB5 steel hardness is low and suitable for machining and hot forming as supplied condition. However, the pearlitic and ferritic structure is not enough for harsh working conditions. In order to combine the manufacturability and high wear performance the alloy needs to be heat treated. In applications like ploughshare the final shape of the part is not so precise. Therefore, the well-known method of manufacturing is forming the tool at moderate temperatures (300 °C – 350 °C) after austenitization then quenching. TTT (Time-temperature-transformation) diagram and phase ratio prepared for 30MnB5 alloy with CalPhad technique is given in Figure 1. This technique is useful to predict heat treatment results numerically, but it is not sufficient to reach an exact conclusion. According to the outcome of this numerical analysis, the estimated critical cooling rate for 30MnB5 alloy to obtain martensite is to be between 7-8 seconds. For the 30MnB5 steel the austenitization temperature was chosen as 860°C, considering the carbon content. The quenching media was chosen as water.

Table 2. Heat treatment procedure

G1	As supplied
G2	Austenized at (860 °C) for 1 hour and water quenched
G3	Austenized at (860 °C) for 1 hour and water quenched, cryo-treated at (-196 °C) tempered at 200 °C for 2 Hours

The calculated TTT diagram also calculates the approximate transition temperatures. Since the 30MnB5 steel does not contain a significant amount of carbon, the expected martensite finish temperature is above room temperature. The calculated temperature for %90 of martensite formation is about 240°C. In this work, the main objective of additional heat treatments to quenching such as cryogenic treatment and tempering is performed to reduce the internal stress and enhance the toughness. In previous studies cryogenic treatment reported as improving the toughness and reducing residual stress in low carbon steels [20].

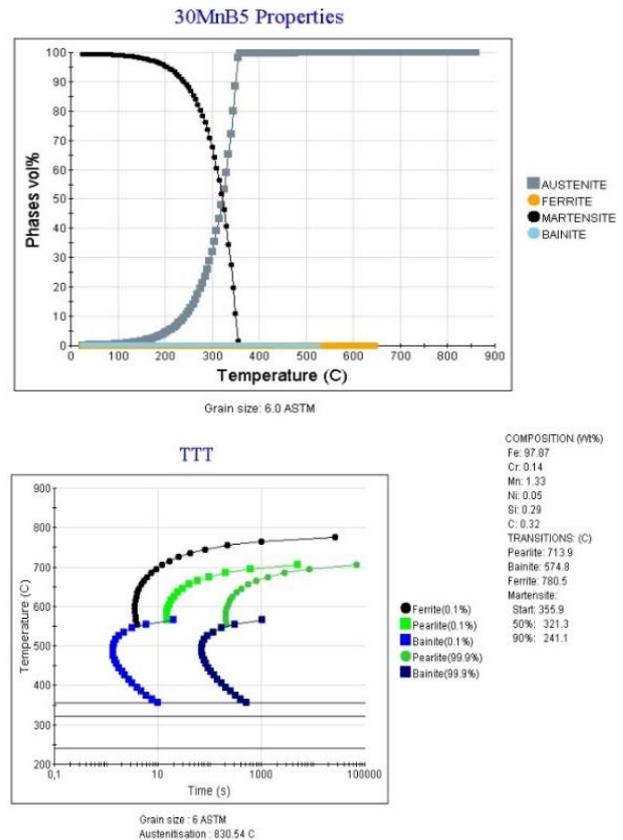


Figure 1. TTT and phase curves obtained with CalPhad technique

2.1. Charpy Impact Test

Charpy impact test was performed at room temperature. The purpose of this test is to get the dynamic behavior of specimens. The Charpy impact test is a good indicator of impact loading cases and crack propagation rate. The pendulum was released freely before tests in order to determine the loss of the test unit itself. The loss of the device used was measured and confirmed that the loss is lower than 1% of load capacity loss. All sample dimension was checked before tests. Figure 2 shows the dimension of Charpy impact test samples. ASTM A370 standard was followed in preparing samples and evaluating the results of experiments.

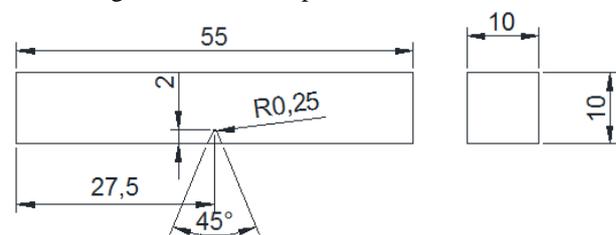


Figure 2. Dimensions of the Charpy impact test specimen

2.2. Hardness Test

Hardness is a measure of the resistance of the material to localized plastic deformation. The hardness of the samples was measured by using the FM310 microhardness tester. The measurements were conducted and evaluated according to the ASTM E384 standard. This method was chosen because the reference material sample was not suitable for the Hardness of Rockwell measurement scale, so a microhardness measurement was conducted for all samples, and the results were given in the Hardness of Vickers (Hv) scale. Hardness measurements were taken from all samples repeatedly. Three samples were used in each group. Average values of the samples were given.

2.3. Microstructure Analysis

The microstructure of the samples was examined in the Nikon Eclipse L150 Optical microscope with Nikon Clemex software module. To obtain the microstructural images a metallographic preparation was done. The samples were mounted on polymer at approximately 180°C for 3 minutes. The surfaces of the samples were ground using a Struers Tegraforce automatic grinding machine at three stages mesh number of 220, 500 and 700. The grinding load for each sample was 30 N for 10 minutes. After grinding, the samples were polished using the same machine for 3 minutes with a 3 µm solution. The samples were etched with a 2% nital. The surface roughness value of the polished samples was produced below $R_a = 0.02 \mu\text{m}$.

2.4. Abrasive Wear Test

The dimensions of 30MnB5 alloy samples were $12.7 \times 12.7 \times 12.7 \text{ mm}^3$ in cubic shape for the abrasive wear tests. The wear test samples were ground, and the polished surface roughness of the samples was between similar to each other. The samples were ground with 700 grit sandpaper before the wear test. Abrasive wear tests were performed with the block-on-disc configuration on a Plint TE53 universal wear test machine, as shown in Figure 3. The metal disc, whose diameter 60 mm and width 16 mm, was coated with 320 grit aluminum oxide (Al_2O_3) abrasive paper. The contact between the cubic specimen and the disc was supplied by a constant 42 N load. The speed of the disc was specified as 200 rpm for all test groups. The method used in this study is a self-developed method by taking account of the ASTM G 77 standard. The test standard contains a pin on disc configuration, the proposed method was used, but sandpapers were added to simulate the abrasive wear environment of agricultural applications. Prior to each test all samples are cleaned with alcohol. The weight losses were measured with the Precisa XB 220A scale (precision degree of 10^{-4} g) before and after 2500 revolutions. All abrasive wear experiments were performed three times at room temperature and humidity, and the average results were calculated for comparison.

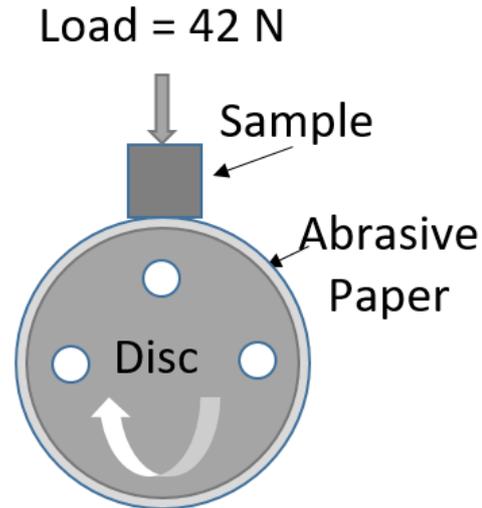
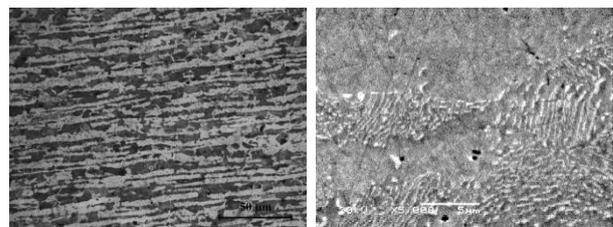


Figure 3. Schematic illustration of the abrasive wear test configuration

3. RESULTS AND DISCUSSION

3.1. Microstructure

The microstructures of all group samples are taken with the optical microscopy and scanning electron microscopy and are depicted in Figure 4. G1 was the received material and it consisted of pearlite and ferrite structure that formed in the direction of rolling. G2, which was the quenched samples, were shown needle like features, which indicated the formation of martensite. During the austenitization process, ferrite and pearlite phases were transformed austenite phase. In comparison to pearlite, austenite is softer, and it transformed into the martensite phase upon quenching in the water. Martensite phase is a hard form of crystalline steel structure and it has caused an increase in the hardness of the materials. The dual composition, which is consisted of martensite and ferrite, is visible in the SEM micrograph for the G2 group. G3 group was the austenitized at (860 °C) for 1 hour and water quenched, cryo-treated at (-196 °C), and tempered at 200 °C for 2 hours. As seen from Figure 4, the microstructure of the sample G3 group was very similar to that of the G2 group. The microstructures of both G2 and G3 group samples exhibited carbide particles. But after cryogenic treatment, finer and more homogeneous secondary carbide particles were observed for G3 group samples.



Sample G1

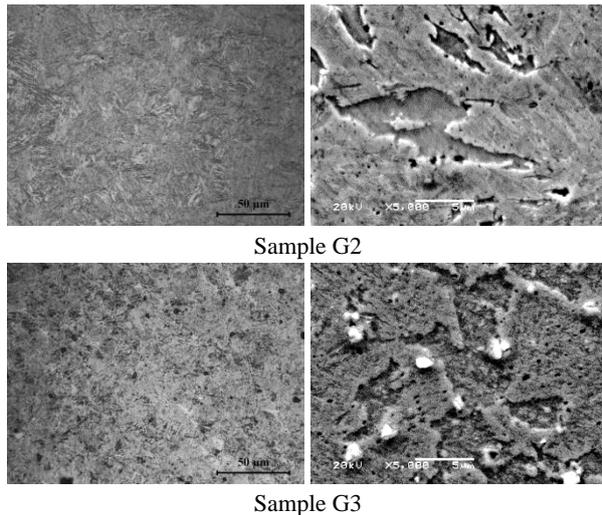


Figure 4. Microstructure of samples (500x and 5000x)

3.2. Hardness Test

The mean value of the hardness of the specimen for all groups was calculated and shown in the form of a bar chart in Figure 5. From the results drawn in Figure 5, it is clear that the quenched boron steel which belongs to the G2 group, showed the highest hardness. The hardness increased in the specimens G2 426.40%, G3 404.80%, as compared to G1. It can be said that the hardness increased significantly with the effect of the quenching. These findings suggest that the application of the cryogenic and tempering process to reduce the thermal stresses and create a more stable internal structure caused a slight decrease in hardness for the sample G3. Tempering is a well-known application that reduces the hardness and improves the stability of a material. On the other hand, deep cryogenic treatment is known for increasing the hardness for a little amount [21]. Another study about the effect of deep cryogenic treatment which was published by Özer, concluded that there is no significant difference between conventionally heat-treated and deep cryo treated samples [22]. Singh et al. performed five different thermal treatment procedures to 30MnCrB4 steel [23]. The first one conventionally heat-treated, the second one conventionally heat-treated and deep cryo treated at 185 °C for 12 h and the last three group of samples were subjected to conventionally heat treated, deep cryo treated and tempered at 200 °C, 250 °C and 300°C for 1 h, respectively. For hardness values, it was observed that there was small difference between cryo treated and conventionally heat-treated samples. The most remarkable result was the hardness value decreased as the temperature of the tempering increased. In general, it is known that the tempering process causes a decrease in hardness, but it is preferred because of its advantage in dynamic conditions. In this study, the primary mechanism of the decreased hardness was the temper treatment process for Group 3 samples.

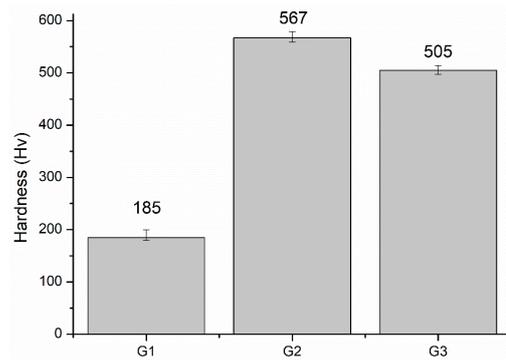


Figure 5. The average hardness of samples

3.3. Charpy Impact Test

The average value of fracture energy is shown in Figure 6 in the form of a bar chart for all groups of samples. The result of the Charpy impact test indicated that quenching of 30MnB5 alloy to increase the hardness and the abrasive wear resistance significantly reduced the toughness of the material. The highest average fracture energy was obtained for the specimen of the G1 group. However, after applying deep cryogenic treatment and tempering, a slight increase was observed for the sample of the G3 group. The slight improvement of the impact strength was attributed to the removal of residual stresses due to the temper treatment process. Another reason for increased impact strength was the precipitation of finer carbides.

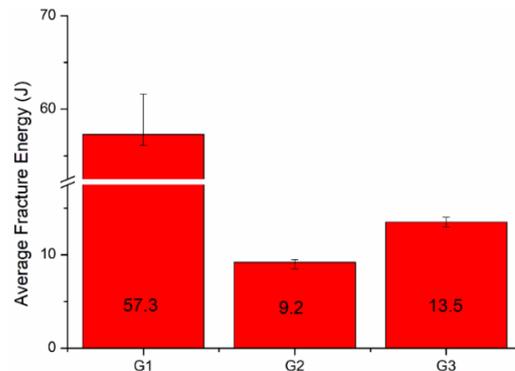


Figure 6. Average fracture energy values of the samples

SEM analysis of impact samples was performed to study the mechanism of fractured surface. The SEM fractography images were captured different magnifications from 35x to 1000x. For G1 group samples, cleavage fracture type was observed. The river patterns were visible and it was the proof of the rapid crack propagation and the brittle fracture mechanism. The smaller cleavage facets were observed for G2 and G3 group samples and it can be said that the quasi-cleavage fracture was dominant. The size of the cleavage facets depends on the grain size. Smaller cleavage facets were observed due to having fine grain structures in steels.

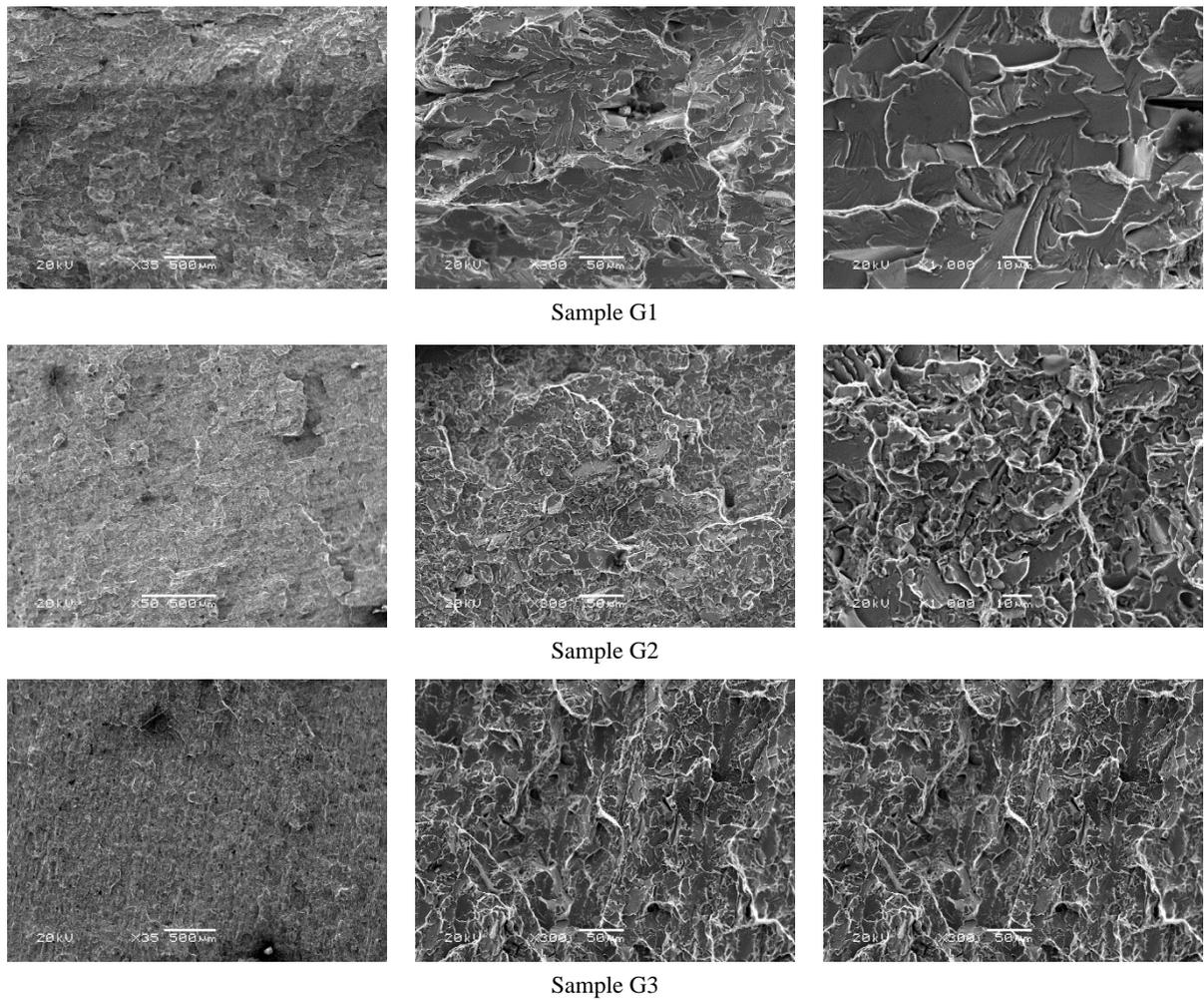


Figure 7. Fracture SEM photos of the samples at magnifications of 35x, 300x and 1000x

3.4. Abrasive Wear Test

Abrasive wear weight loss was calculated by measuring the weight of the cubic specimen before and after the wear test. The average abrasive wear weight loss was plotted in the form of the bar chart as shown in Figure 8. According to wear test results, the wear resistance of the quenched specimen increased significantly. The quenched specimen (G2 group) was worn four times less than the received specimen (G1 group). For the sample of the G3 group, which was firstly quenched after that applying the cryogenic and tempering process, the abrasive wear resistance was decreased slightly in comparison to the quenched sample. The main reason for reducing the abrasive wear resistance of G3 group samples was the loss of hardness due to the tempering process.

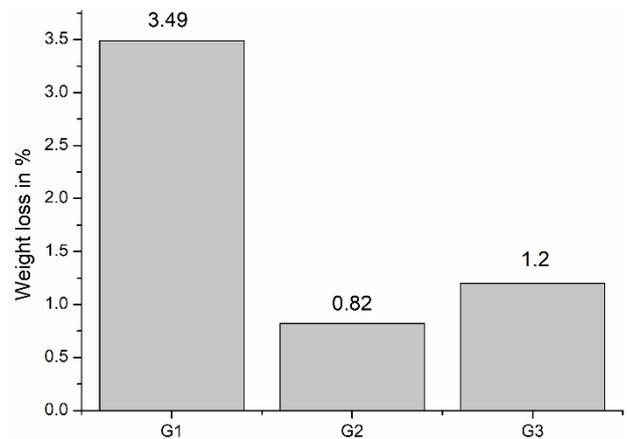


Figure 8. Comparison of wear loss of a different group of 30MnB5 alloy

4. DISCUSSION

Boron steels have become increasingly widespread in various applications requiring high wear resistance. It is almost certain that the research and the development of the surface properties of boron steels have a great impact on economic aspects. In this study, properties such as microstructure, hardness and the abrasive wear resistance of 30MnB5 steel samples were examined in a total of three different groups as received; quenched; quenched, cryogenically treated and tempered. After the application of the quenching process, the expected increase in hardness of the alloy was achieved. This significant increase in hardness values is one of the characteristics that make boron steels superior. It has been shown that the positive effect of boron additive as an alloying element at ppm levels on hardenability was also demonstrated for this material. It is known that the quenching medium does not make a significant difference in the hardness values of boron steels [5]. In this study, according to the results of the previous studies, the quenching medium was preferred as water because of being a more ecological approach. In previous studies the authors stated that the boron addition improves heat treatment performance [24]. During austenite decomposition, almost all alloying elements retard the transformation. Boron addition in the structure of the steel delays the transformation of austenite to ferrite; thus, it promotes the bainitic and martensitic structure. Another positive effect of boron addition is continuous cooling transformation (CCT) curve can be shifted to the right, and it results in increasing the hardenability of the steel. The elemental content of boron also encourages the formation of hard borides such as FeB, and Fe₂B, which improves the overall hardness and wear resistance of steel.

The tempering processes are performed after quenching and known to regulate the residual stress and improves the toughness of steel. In tempering, there is a tradeoff between hardness and toughness. The hardness drop by increasing tempering time and temperature is more dominant in low alloy steels [25]. However, in high alloy steels such as tool steels, the effect is not so detrimental. Since the investigated 30MnB5 steel contains less alloying elements, the effect of tempering severely reduces hardness and wear resistance with increasing tempering time. So, the tempering time and temperature is critical to remain the hardness of quenched boron steel.

It is thought that boron steels can be used in the pearlite and ferrite form have good hot forming capability, and the hardness and wear resistance can be improved by the austenitization and quenching process. The evidence from this study suggests that it may be beneficial to use boron steel with only quenched form in the fields where the impact effect is less. On the other hand, if the field environment has hard particles such as stones, gravel, rocks and roots, it will be beneficial to apply cryogenic treatment and tempering after the quenching process because of gaining impact resistance. Although it has been understood from the experimental results that the

cryogenically treated sample will be useful in terms of impact resistance, the final decision cannot be made without performing field tests. It can be said that the service life of 30MnB5 steel without heat treatment could be quite short. So, quenching is suggested for any soil engaging boron steel for an acceptable service life.

5. CONCLUSION

In the present study, the effect of quenching and cryogenic treatment on the abrasive wear behavior of 30MnB5 boron steels is investigated. Additionally, microstructural analysis and Charpy impact tests are also performed. The following conclusions are drawn:

- The highest hardness value is obtained for the specimen which is austenized at 860 °C for 1 hour and water quenched. After the application of the cryogenic treatment at -196 °C tempered at 200 °C for 2 hours, the hardness value is slightly decreased.
- The highest fracture energy is obtained for the untreated specimen. As the heat-treated samples have a martensite structure, the fracture energy is decreased drastically.
- According to the result of laboratory experiments, the cryogenically treated sample will be beneficial in terms of impact resistance. Still, it is necessary to conduct the field test with real size components.
- The most abrasive wear resistant specimen is austenized at 860 °C for 1 hour and water quenched one.
- A more detailed analysis is done to reveal the effects of cryogenic treatment on boron steels in future works considering different duration and temperature of cryogenic treatments.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Fatih BOZKURT: Performed the experiments and wrote the manuscript.

Fatih Hayati ÇAKIR: Performed the experiments and wrote the manuscript.

Ümit ER: Analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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