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Improving the mechanical and wear performance of AISI D2 steel with a cryogenic treatment

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AISI D2 çeliğinin mekanik ve aşınma performansının kriyojenik işlemle iyileştirilmesi

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Abstract

This research investigated the effect of cryogenic treatment on the notch impact strength, wear behaviour, microstructure, and hardness of AISI D2 steels. The samples prepared in the research were subjected to cryogenic treatment four times (12-48 hours) at -145°C and -196°C after heat treatment to achieve the desired mechanical improvement. The cryogenic process was carried out by cooling to -196 °C with a cooling rate of 2 °C per minute and keeping at this temperature for the specified time. Room temperature reached -196 °C with a heating rate of 2 °C per minute. Afterward, the specimens were tempered for an hour at two different temperatures, 200°C and 520°C. After cryogenic treatment, microhardness, microstructural investigations, wear, and notch impact tests were conducted and compared with the untreated material. Under optimum conditions, the cryogenic treatment caused a maximum increase of 4% in the microhardness of AISI D2 steels. After notch impact tests, the fracture energy of the material decreased at different rates in all groups except for the tempered sample with a holding time of 12 hours. Following cryogenic treatment at -196°C for 12 hours and then tempering at 520°C for 1 hour, the wear resistance of specimen D11 increased by up to 88%. In conclusion, in this study, cryogenic treatment at -196°C and subsequent tempering positively affected the abrasive wear resistance of D2 steel.

Keywords *Cryogenic (sub-zero) treatment; AISI D2 steel; hardness; impact resistance; abrasive wear*

Öz

Bu araştırma, kriyojenik işlemin AISI D2 çeliklerinin çentik darbe dayanımı, aşınma davranışı, mikro yapısı ve sertliği üzerindeki etkisini incelemiştir. Araştırmada hazırlanan numuneler, ısıl işlemden sonra -145°C ve -196°C'de dört kez (12-48 saat) kriyojenik işlem uygulanarak istenilen mekanik iyileşmeyi sağlamak için işleme tabi tutulmuştur. Kriyojenik işlem, dakikada 2 °C soğutma hızıyla -196 °C'ye soğutularak belirlenen sürelerde bu sıcaklıkta tutularak gerçekleştirilmiştir. -196 °C'den oda sıcaklığına yine dakikada 2 °C ısıtma hızı ile ulaşılmıştır. Daha sonra numuneler, 200°C ve 520°C olmak üzere iki farklı sıcaklıkta birer saat süreyle temperlenmiştir. Kriyojenik işlemden sonra, mikro sertlik, mikro yapısal incelemeler, aşınma ve çentik darbe testleri yapılmış ve işlem görmemiş malzeme ile karşılaştırılmıştır. Optimum koşullar altında, kriyojenik işlem AISI D2 çeliklerinin mikro sertliğinde maksimum %4'lük bir artışa neden olmuştur. Çentik darbe testlerinden sonra, malzemenin kırılma enerjisi, 12 saat bekletilen temperlenmiş numune hariç tüm gruplarda farklı oranlarda azalmıştır. Kriyojenik işlem sonrası -196°C'de 12 saat ve ardından 520°C'de 1 saat temperleme işlemi uygulanan D11 numunesinin aşınma direnci %88'e kadar artmıştır. Sonuç olarak, bu çalışmada -196°C'de uygulanan kriyojenik işlem ve sonrasında yapılan temperleme işlemi, D2 çeliğinin abrasive aşınma dayanımı üzerinde pozitif etkiler bırakmıştır.

Anahtar Kelimeler *Kriyojenik (sıfır-altı) işlem, AISI D2 çelik, Sertlik, Darbe direnci, Abrasive aşınma.*

1. Introduction

In the 1960s, a continuously evolving heat treatment method for materials was sub-zero treatment, which has been developed up to the present day. Cryogenic treatment refers to an additional process conducted to enhance material properties following conventional heat treatment. This process involves the controlled cooling of materials to cryogenic temperatures (< -145°C), holding them at these temperatures for a specific period (typically between 12 to 72 hours), and then gradually heating them back to room temperature (Baldisseara and Delprete 2008). Based on existing literature, cryogenic treatment is observed to transform any remaining austenite within the tool steel structure into martensite, while also boosting wear resistance by fostering the development of secondary carbides (Meng *et al.* 1994, Collins 1996). These processes collectively improve wear resistance by hindering the movement of dislocations and refining the microstructure (Lal et al.2001).

Tool steels are widely used in industry due to their chemical compositions and the prominent properties resulting from them (Arslan 2010). In the classification established by the American Iron and Steel Institute (AISI), cold work tool steel characterized by elevated levels of carbon and chromium has been classified as group D, denoted for its proficiency in deep hardening processes.

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AISI D2 steel is a commonly used cold work tool steel for blades, forming knives, and various applications due to its low wear, cost, sufficient hardness, and toughness. One of the main problems with conventional hardening and tempering of these steels is the persistent austenite (R) content, which is soft and unstable at low temperatures and changes to brittle martensite in service. The transformation from austenite to martensite is associated with a volume expansion of approximately 4%, which leads to component degradation. Therefore, to minimize the amount of R content in automotive steels, either subzero treatment or multiple quenching and tempering at relatively high temperatures and/or for long periods of time is used (Das *et al.* 2010).

When the relevant literature is examined, numerous studies on the mentioned material and process are encountered. (Das *et al.* 2010, Dhokey *et al.* 2020, Moscoso *et al. 2020,* Pillai *et al.* 2017). Das et al. (2010) observed improvements in toughness in their shallow and deep cryogenic treatment studies, primarily focusing on AISI D2 tool steels. Molinari et al. (2001) specified materials and cutting tools were subjected to a dry cooling process at -196°C to examine the wear behavior of certain tool steels and uncoated sintered carbide cutting tools. Subsequently, a wear test was conducted. Results showed an approximately 200% enhancement in wear resistance, consistent with findings from other tool steels. In another study, a researcher investigated the effect of deep cryogenic treatment on the wear resistance of AISI D2. In this work, steel was exposed to temperatures ranging from -140°C to -196°C. They found that steel treated at -196°C exhibited increased hardness, toughness, and wear resistance (Collins and Dormer 1997). Bourithis et al. examined the changes in the wear resistance and mechanical properties of D2 steel in their study. The deep cryogenic process provided higher hardness and wear resistance compared to shallow cryogenic treatment. In another study conducted by Villa et al, D2 steel was subjected to various austenitization treatments, followed by various cryogenic treatments and tempering treatments. The results obtained revealed that regardless of the austenitization conditions and applied cryogenic treatments, there was generally a certain amount of retained austenite present in the material prior to tempering (Villa *et al.* 2018). Korade et al. conducted research on the role of multiple tempering processes on the tribological behavior of D2 tool steel, both before and after deep cryogenic treatment. The optimal heat treatment combination obtained was hardening, cryotreatment, and single-stage tempering. In specimens tempered at a single stage, a significant decrease in wear volume, wear rate (WR), and coefficient of friction was observed, along with a notable increase in the hardness of the D2 tool steel (Korade *et al.* 2017).

Abrasive wear, which can be defined as the process where a hard substance wears away a softer one, occurs when a cut or shaped workpiece abrades the cutting tool through its own hardness or the presence of hard particles. To prevent this form of wear, the desirable attributes in tool steel involve possessing elevated hardness levels and a substantial concentration of hard, coarse carbides (Bensely *et al.* 2007, Baldissera 2009, Zhirafar *et al.* 2007). In published works, there is more research on the adhesive wear behavior of AISI D2 steel, while studies on the abrasive wear behavior are still relatively limited. Singh et al. have investigated the effect of heat treatment applied to AISI D2 steel on the steel's microstructure and abrasive wear resistance. The increase in tempering temperature was observed to result in an increase in abrasive wear volume loss. (Singh *et al.* 2015). Collins and Dormer (2012) investigated the hardness and impact toughness of conventionally heat treated and several types of cryogenically treated samples of AISI D2 steel. However, the abrasive wear rate measurements did not include cold-treated samples and the microstructural characterization was limited to conventionally heat treated and cryogenically treated samples. Therefore, it is scientifically and technologically important to investigate the effect of cryogenic treatments under different conditions on the abrasive wear behavior of D2 steel and its relationship with microstructure and hardness, which was done in this study. The impact of cryogenic treatment, conventional heat treatment, and tempering process on the abrasive wear behavior of AISI D2 steels was investigated in the present study.

2. Materials and Methods

Table 1 displays the material composition of AISI D2 steel. AISI D2 steel was obtained from Özgün Iron and Steel Company. The samples were prepared as rectangular bars with dimensions of 25×100×447 mm. Sample codes are given in Table 2. The samples supplied and prepared in appropriate dimensions were subjected to the austenization process at 1030 °C for 30 min, the recommended austenization temperature for steels, and then quenched using compressed air. After quenching, the steel samples underwent cryogenic treatment at temperatures of -145°C and -196°C for varying durations (12, 24, 36, and 48 hours) as shown in Table 2. The samples were subjected to cryogenic treatment for the specified time, then removed from the cooling oven and allowed to reach room temperature. Cryogenic treatments were carried out using the "Cryo Manufacturing" brand device from MMD Machinery and Material Technologies R&D Consultancy Engineering Services Industry and Trade Ltd. The device has an internal volume of 80 liters and can reach a temperature of -196°C. Cryogenic treatments were applied by holding at -196°C, reached with a cooling rate of 2°C per minute, for different durations as mentioned above. The introduction of liquid nitrogen into the system for cooling to these temperatures was carried out using a liquid nitrogen dosing system. After cryogenic treatments, AISI D2 steel specimens have undergone a two-stage tempering process at temperatures of 200°C and 520°C, each lasting 1 hour.

Table 1. Chemical content of AISI D2 steel (Özgün Iron and Steel Comp.).

ISO/DIN	AISI	%C	%Cr	%Mo	%V	%Si
1.2379	D2	1.55	12	0.7	1	0.4

Table 2. Treatments applied to samples.

Sample	Cryogenic treatment	Tempering
D1	HT	HT
D2	-145°C – 12 h	200°C – 1 h
D3	-145°C – 12 h	520°C – 1 h
D4	-145°C – 24 h	200°C – 1 h
D5	-145°C – 24 h	520°C – 1 h
D6	-145°C – 36 h	200°C – 1 h
D7	-145°C – 36 h	520°C – 1 h
D8	-145°C – 48 h	200°C – 1 h
D9	-145°C – 48 h	520°C – 1 h
D10	-196°C – 12 h	200°C – 1 h
D11	-196°C – 12 h	520°C – 1 h
D12	-196°C – 24 h	200°C – 1 h
D13	-196°C – 24 h	520°C – 1 h
D14	-196°C – 36 h	200°C – 1 h
D15	-196°C – 36 h	520°C – 1 h
D16	-196°C – 48 h	200°C – 1 h
D17	-196°C – 48 h	520°C – 1 h

Cryogenic process parameters and tempering temperatures were investigated to reveal the changes in the microstructure of steel samples. SEM (Scanning Electron Microscopy) was used for the micro structural analysis, while X-ray diffraction (XRD) and Rietveld analysis were used to determine the types and quantities of structures formed in the material. Microhardness measurements were conducted to observe the impact of cryogenic process parameters and tempering temperatures on the hardness of AISI D2 steel. Charpy notch impact tests were performed to reveal the effect on dynamic toughness. The abrasive wear resistance of the samples was determined by carrying out tests according to the ASTM G105 standard. The effect of different temperatures and times applied during the cryogenic process, as well as different tempering temperatures used on the samples afterward, on the specific wear rate was investigated.

3. Results and Discussions

3.1 Microstructure Analysis

The samples were prepared by hot moulding, sanding, and polishing in a standard metallographic process. The grinding and polishing processes of the samples were carried out using the Metkon brand Forcipol-2V+Forcimat model automatic grinding (120#→320#→600#→ 800#→1200#) and polishing (6 µm→3 µm→1 µm) device. The samples were polished and then etched with a 2% Nital solution for different durations. The surfaces of the prepared samples were examined using the FEI NOVA NanoSEM 650 brand electron microscope. The microstructures of AISI D2 steel treated under the conditions specified in Table 2 are given in Figures 1-3.

Abrasive wear in multiphase steels is influenced by carbide morphology, abrasive particle properties and material properties. In addition, both the fineness of the matrix grain and the uniform distribution of the carbide grains play an effective role in improving the wear resistance of the D2 steel.

The results of microstructure analyses reveal carbides of varying dimensions observed on the martensitic structure. It is reported that after the traditional quenching process in tool steels, large-sized carbides form. These carbides are referred to as primary carbides in the literature. Das *et al.* (2010) associated the observed improvement in toughness during their shallow and deep cryogenic treatment studies on AISI D2 tool steels with the formation of micro-layers resulting from the cracking of large and long primary carbides, as well as the decomposition of secondary carbides (Das *et al.* 2010). Researchers [Akhbarizadeh *et al.* 2009, Gill *et al.* 2011, Huang *et al.* 2003 and Das and Ray 2012) have clearly stated that deep cryogenic treatment significantly alters the size and distribution of carbide particles, but they have not provided quantitative data to support these claims. Furthermore, it is well known that the average size of carbide particles and their spacing have a strong influence on the mechanical properties of tool and die steels (Güney and Kam, 2022, Şenel *et al.* 2021). After the traditional heat treatment, some residual austenite remains in the structure. Cryogenic treatment is applied to reduce the amount of residual austenite and form new secondary carbides in smaller sizes (Das *et al.*2010). The presence of secondary carbides is confirmed by observing smaller carbide structures in the microstructures of samples that underwent cryogenic treatment. When examining the microstructures in Figures 1-3, it is observed that primary carbides (PCs), along with a dissolved austenite phase, exhibit uniformly distributed secondary carbides

(SCs) at the grain boundaries of tempered martensitic phase, along with the non-uniform distribution of primary carbides. The primary carbides are represented by the wide, elongated dendritic-type regions, while the secondary carbides (SCs)are visible as small white regions. EDS analyses were conducted on all samples. Since the results were similar for all samples, the EDS analyses of the sample coded as D2 are provided as an example. The SEM image in Figure 4 shows the points where EDS analysis was performed on the D2 coded sample, and the elements present in the selected area are listed in Table 3. The existence of carbide structures formed after cryogenic treatment was confirmed in the EDS analyses. EDS analyses were used to examine the chemical compositions of carbide structures in the samples. The carbide structures contained C, Fe, Si, Mo, V, and Cr elements, suggesting they may be M7C3 and M23C6 carbide types (Serna *et al.* 2006).

3.2 Rietveld Analysis Results

XRD and Rietveld analyses were conducted to determine the types and quantities of phases in the materials. Rietveld analyses were performed using the MAUD (Material Analysis Using Diffraction) program. The Rietveld analyses were continued until the Sigma value, reflecting the goodness-of-fit, was closest to 1. The types and quantities of phases obtained for the samples are presented in Table 4.

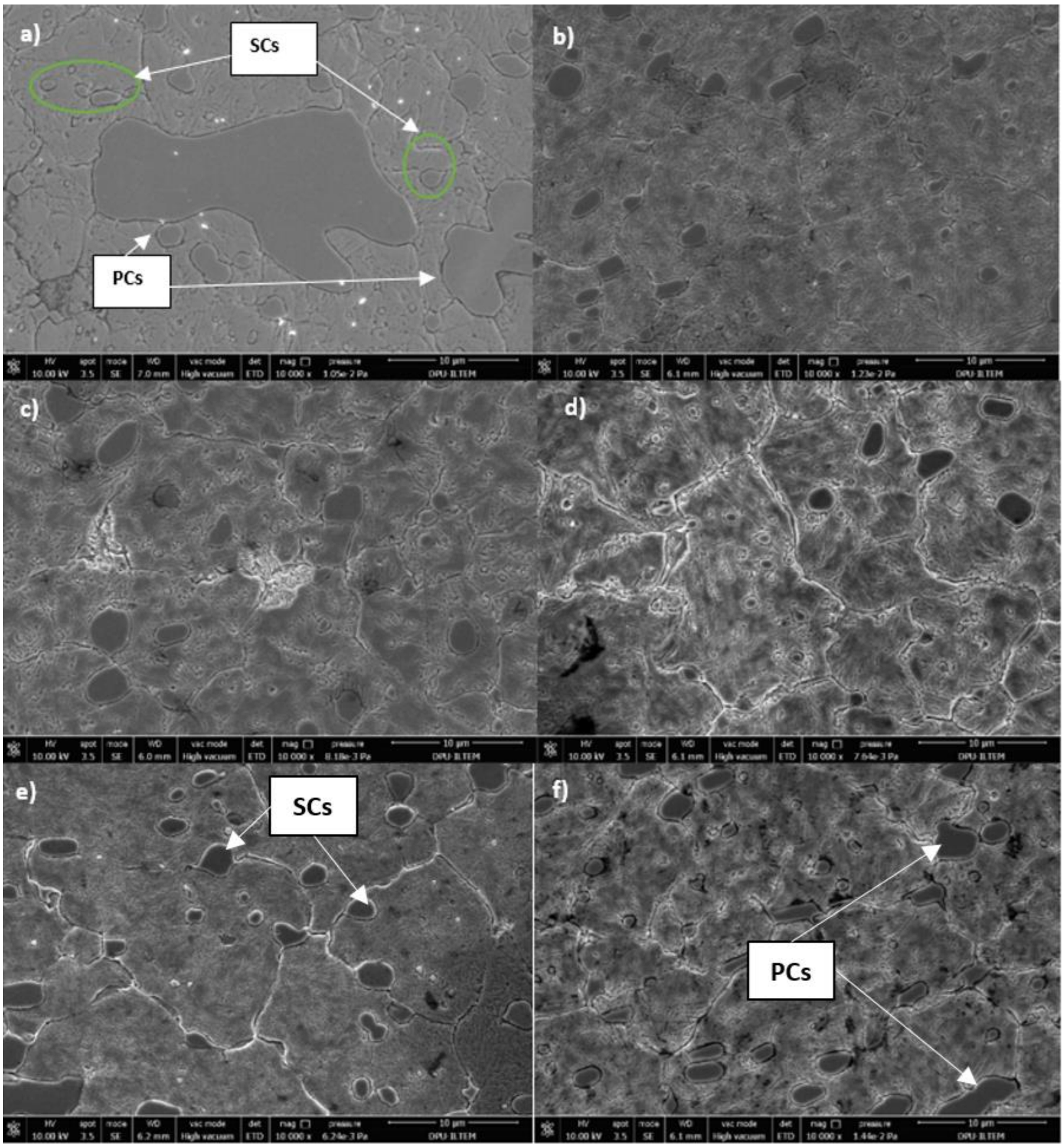

Figure 1. Microstructure images of the samples (10,000x): (a) D1; (b) D2; (c); D3; (d) D4; (e) D5; (f) D6.

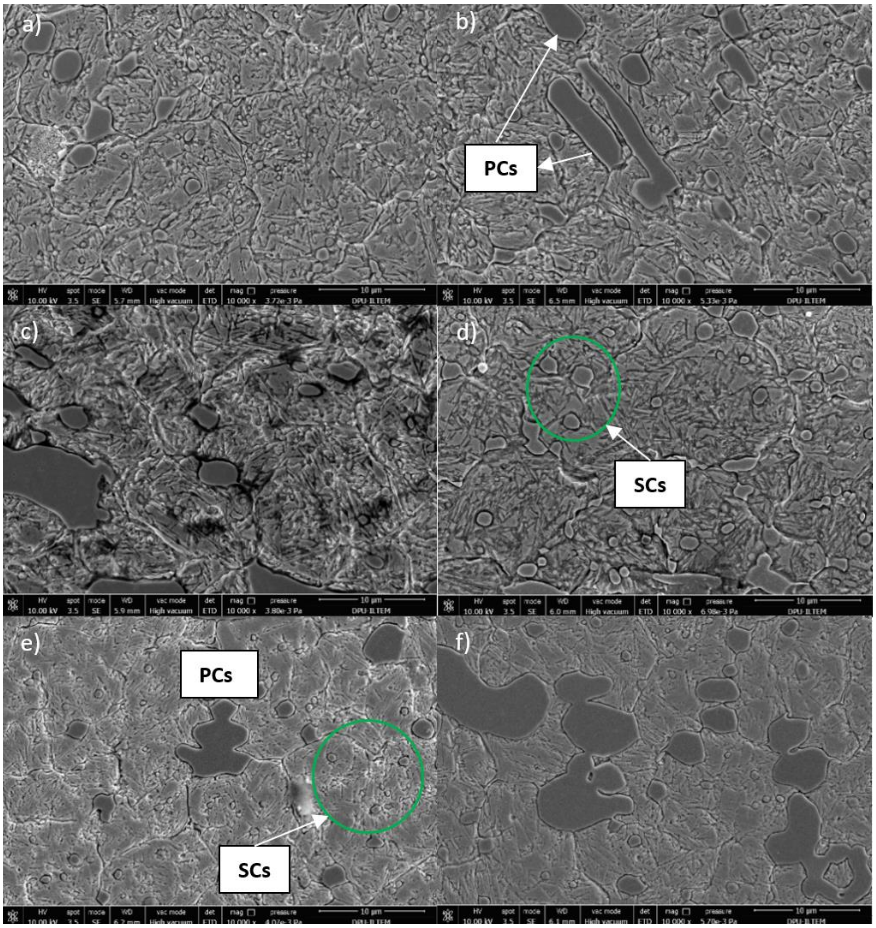

Figure 2. Microstructure images of the samples (10,000x): (a) D7; (b) D8; (c); D9; (d) D10; (e) D11; (f) D12.

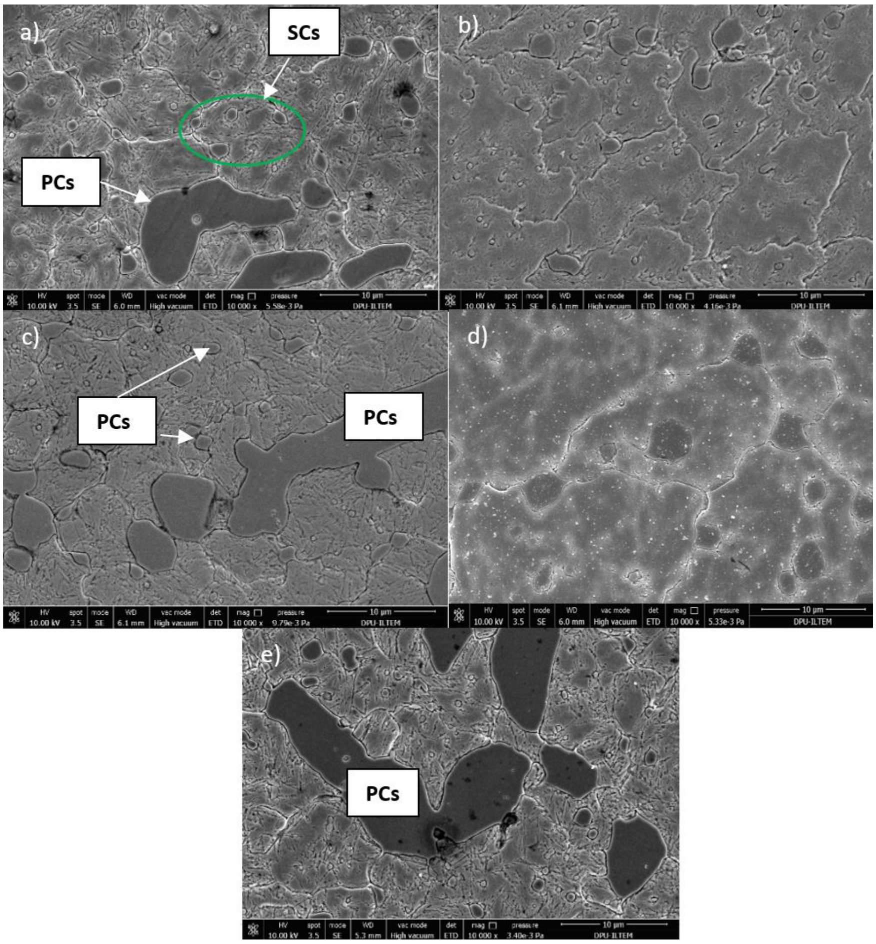

Figure 3. Microstructure images of the samples (10,000x): (a) D13; (b) D14; (c); D15; (d) D16; (e) D17.

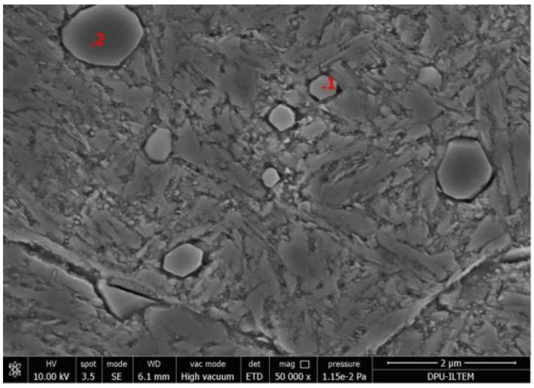

Figure 4. SEM image showing the points where EDS analysis was performed on the sample coded as D2.

Table 3. Elements present in the selected area.

Element	Area 1	Area 2
C	7,76	8,07
N	0,32	0,58
Fe	22,71	15,13
Si	0,39	0,36
Mo	1,57	1,91
V	5,44	6,65
Cr	61,8	67,29

.

Table 4. Rietveld analysis results for samples.

Phase/Sample	D1	D2	D3	D4	D5	D6	D7	D8	D9
Martensite	77,4	85,4	85,7	84,7	84,4	84,5	84,1	84,1	83,9
Cr_7C_3	6,9	7,1	7	7,1	7	6,9	7,1	7,2	6,9
Austenite	9,6	1,2	1,1	1	1,2	0,8	1,2	1,1	1,3
$Cr_{23}C_6$	6,1	6,3	6,2	7,2	7,4	7,8	7,6	7,6	7,9
Phase/Sample	**D10**	**D11**	**D12**	**D13**	**D14**	**D15**	**D16**	**D17**	
Martensite	83,6	83,11	82,53	81,82	82,49	82	81,78	80,83	
Cr_7C_3	7,2	7,1	7,3	7,3	6,9	7,4	7,3	7,6	
Austenite	0,9	1,19	0,77	1,28	0,41	0	0,62	1,07	
$Cr_{23}C_6$	8,3	8,6	9,4	9,6	10,2	10,6	10,3	10,5	

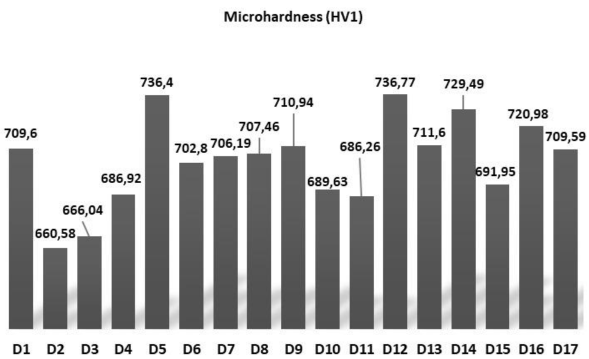

Figure 5. Microhardness values for the samples.

In Rietveld analyses, it has been determined that the samples contain phase types such as martensite, austenite, Cr7C3, and Cr23C6. According to the results of the Rietveld analyses, it is observed that a significant portion of the remaining austenite in the structure of the samples transforms into martensite after traditional heat treatment. Increasing cryogenic treatment duration has been observed to increase the amount of carbides in the samples. This observation is consistent with studies in the literature (Amini *et al.* 2012). Additionally, it has been noted that in deep cryogenic treatment (-196°C), carbide formation is promoted compared to shallow cryogenic treatment (-145°C).

3.3 Microhardness Analysis Results

Microhardness analyses were conducted using the Metkon brand DUROLINE-M model device, applying a load of 1000 gf for 10 seconds, hardness measurements were taken from 5 different points on the surface and the results are shown as an average in Figure 5.

After examining the microhardness results, it was observed that the samples subjected to a 12-hour cryogenic treatment showed a slight decrease in hardness. Depending on the holding times, the tempering process at 520°C provided higher hardness than tempering at 200°C for samples subjected to shallow cryogenic treatment. According to the hardness test results, except for the sample coded D5, shallow cryogenic treatment did not lead to a significant change in material hardness. However, deep cryogenic treatment was observed to slightly increase the hardness in samples D12, D14, and D16 tempered at 200°C. The D12-coded sample showed a maximum increase in hardness of almost 4%. The main effects believed to contribute to this improvement are the occurrence of β-α phase transformation, reduction in residual stresses in the specimens, and rearrangement of the microstructure. There has not been a significant increase in microhardness for the D-coded samples with cryogenic treatment (Das and Ray 2012).

Cryogenic processing generally increases the hardness of materials because the crystalline structures of the material become denser at low temperatures. This leads to changes in the atomic arrangement of the material and crystal defects that can cause the material to be harder. However, in some cases, cryogenic treatment may not increase the hardness of the material or the increase may be limited. These cases vary depending on the properties of the material, the processing conditions and the techniques used. To conclude, the effect of cryogenics on material hardness is complex and needs to be carefully studied.

3.4. Notch Impact Analysis Results

Impact tests were conducted on three U-notched samples prepared for each group according to the ASTM A370 standard using a Zwick Roell Amsler RKP450 model notch impact testing device located in the Department of Metallurgical and Materials Engineering at Eskişehir Osmangazi University, and average values were taken for each group. The notch impact analysis results for the samples are presented in Figure 6.

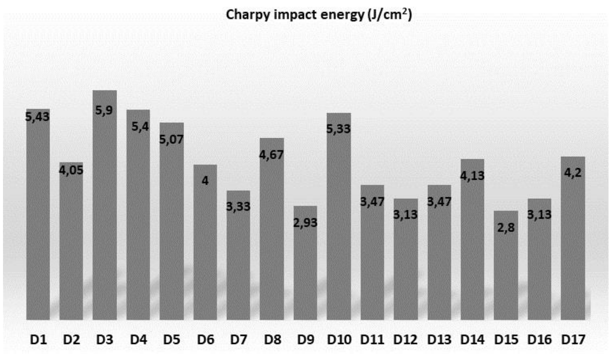

Figure 6. Notch impact analysis results for the samples.

After examining the results, it was observed that the notch impact analysis of the D2-coded sample decreased after 12 hours of cryogenic treatment at -145°C and tempering at 200°C, while an increase was observed in the sample tempered at 520°C (D3). A similar situation is observed in hardness values for these samples. However, this increase is not significant. The impact test results of the notched samples were lower after deep cryogenic treatment at -196°C than those treated with shallow cryogenic treatment. After deep cryogenic treatment, a decrease in fracture energy of the material was observed in all groups except for the tempered sample group with a 12-hour waiting period. The reason why the impact test results of notched samples subjected to deep cryogenic treatment are lower than those subjected to shallow cryogenic treatment could be that deep cryogenic treatment has a greater effect on the material. Deep cryogenic treatment exposes the material to lower temperatures, which can lead to changes in material properties. These changes typically occur in the microstructure and internal structure of the material, consequently negatively impacting impact resistance. Therefore, the impact resistance of samples subjected to deep cryogenic treatment is generally lower compared to those subjected to shallow cryogenic treatment. This supports Carlson's (1991) thesis that tempering after cryogenic treatment can improve the impact resistance of processed materials. The tempering process should be based on material characteristics and desired properties. In their study on the mechanical properties and microstructure of AISI 4340 steel, Zhirafar et al. (2007) found that cryogenic treatment resulted in a 14.3% decrease in the material's impact energy and toughness. In their study on the effects of cryogenic treatment on the mechanical properties of AISI 4140 steel, Senthilkumar et al. (2001) found that both shallow and deep cryogenic treatment groups experienced a decrease in impact energy.

3.5 Wear Test Results

The abrasive wear resistances of the samples were determined through wear tests conducted by ASTM G105 standards. The wear volume is determined by mass loss and density measurements. Under 5 N load, the wear behavior of the samples was evaluated in terms of volume loss, wear rate, and speed. Figure 7 shows graphs showing the samples' wear rate and wear speed. The wear rate and wear speeds for each sample were calculated using the equations given below.

$$Wr = \Delta V / S \tag{3.1}$$

Wr=Wear speed (mm^3/m)
ΔV=Volume loss (mm^3)
S= Sliding distance (m)

$$K = Wr / P \tag{3.2}$$

K=Wear rate ($mm^3/N.m$)
Wr=Wear speed (mm^3/m)
P=Load (N)

When Figure 7 is evaluated, it is determined that the D11-coded sample of D2 steel has the lowest wear rate, and the D2-coded sample has the highest wear rate.

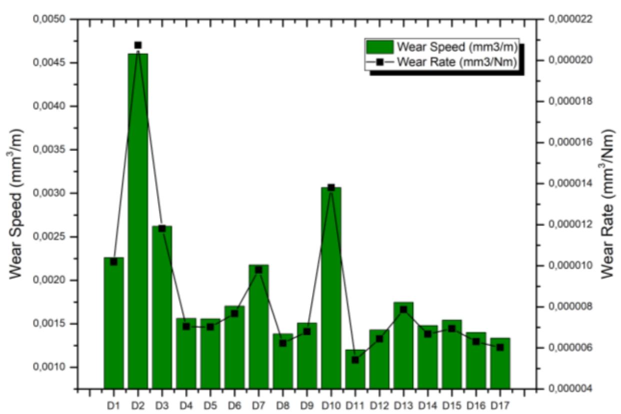

Figure 7. Wear rate and speed of the samples.

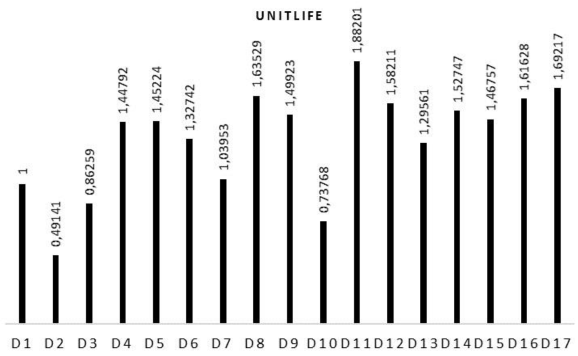

Figure 8. Unit lifetimes of the samples.

Based on the results of the wear tests, the unit lifetimes of the samples were calculated. Figure 8 shows the unit lifetimes for the samples.

Upon examining the wear test results, it was found that cryogenic treatment generally increased the abrasive wear resistance of the D2 specimens. The wear test results show that the D11-coded sample of D2 steel had the highest increase in wear resistance, approximately 88%. This finding is consistent with research by numerous researchers (Das *et al.* 2009, Singh *et al.* 2015, Cho *et al.* 2015) who have emphasized the effect of cryogenic treatment in improving the wear resistance of tool steels.

The effect of cryogenic processing temperature on the wear resistance of AISI D2 steel has been investigated. Accordingly, it has been observed that in deep cryogenic processing, where the amount of austenite is minimized but the quantity and density of secondary carbides are higher, a more significant improvement in wear resistance is observed (Das and Dutta 2010). According to Rhyim et al. (2006), cryogenic processing has increased the necessary power for carbide nucleation and allowed for more abundant, finer carbide precipitation; consequently, toughness has increased, leading to an increase in wear resistance. Yun et al. (1998) have suggested that longer holding times are required for the formation of fine carbides. Unlike residual austenite transformation into martensite, the formation of fine carbides is a time-dependent phenomenon. When literature is examined, researchers claim that there is still no established mechanism regarding the increase in materials' wear resistance due to cryogenic treatment (Guney at al. 2022. Therefore, compiling and combining the existing results to obtain a comprehensive picture is challenging. SEM examination was conducted on the samples that gave the most and the least favourable surface wear after the wear tests to determine the effective wear mechanisms in both material groups. Figure 9 shows the worn surface images for D2 and D11 coded samples.

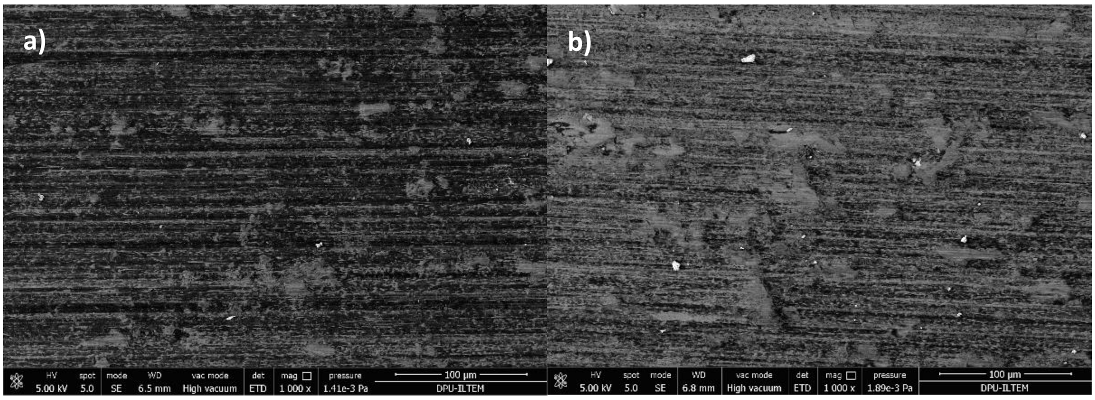

Figure 9. Worn surface images of the samples, (a) D2, (b) D11.

When examining the worn surface images, it is observed that wear marks occur parallel to the direction of sliding on the samples. During the wear test, it is observed that abrasive silica sand caused scraping on the sample surfaces. It is determined that the wear marks are deeper on the D2-coded sample, while they are shallower on the D11-coded sample.

4. Conclusion

The results obtained from cryogenic and subsequent tempering processes applied at different temperatures and times to improve the performance of AISI D2 steel are as follows.

- Cryogenic processing has resulted in a maximum increase of 4% in the microhardness of AISI D2 steels.
- When notch-impact results were examined, it was determined that the maximum impact resistance was achieved in samples under shallow cryogenic treatment conditions for 12 hours and at a tempering temperature of 520°C. Overall, it was observed that cryogenic processing did not consistently increase impact resistance.
- Wear tests showed an 88% increase in wear resistance for the sample coded D11.
- Cryogenic treatment was found to increase the hardness of the material by redistributing the primary

carbides in the microstructure and converting the residual austenite to martensite. This, in turn, has reduced tool wear and resulted in an increase in tool life. Cryogenic processing generally improves the abrasive wear behaviour of AISI D2 steels. Considering this improvement, a 38% increase in the lifespan of AISI D2 steel has been observed.

In consideration of the obtained findings, it has been ascertained that cryogenic processing, coupled with the subsequent tempering operation, imparts substantial contributions to the longevity of AISI D2 steels. The cryogenic treatment, commonly employed in our country for mold and tool steels predominantly utilized in mold fabrication, exhibits a significant potential for playing a pivotal role in the reduction of tool-related expenses within the industry through the augmentation of wear resistance. Prospective investigations delving into the ramifications of cryogenic processing on diverse materials and types, encompassing both mold and cutting tools, will consequently pave the way for novel research avenues for scholars engaged in this particular domain.

Declaration of Ethical Standards
The author declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
References, Research, Experiment, Writing - original draft Visualisation, Writing - original draft

Declaration of Competing Interest
The author has no conflicts of interest to declare regarding the content of this article.

Data Availability Statement
The authors declare that the main data supporting the findings of this work are available within the article.

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