OKU Fen Bilimleri Enstitüsü Dergisi
8(5): 2094-2110, 2025

OKU Journal of The Institute of Science and Technology, 8(5): 2094-2110, 2025

Osmaniye Korkut Ata Üniversitesi
Fen Bilimleri Enstitüsü
Dergisi

Osmaniye Korkut Ata University
Journal of The Institute of Science
and Technology

Endüstriyel Borlama Uygulamaları için AISI D2 Soğuk İş Takım Çeliğinin Optimum Yüzey Pürüzlülüğünün Belirlenmesi

Yasin GÜRCAN[1], Arzum IŞITAN[2*]

[1,2]Pamukkale Üniversitesi, Teknoloji Fakültesi, Makine Mühendisliği Bölümü, 20160, Denizli

[1]https://orcid.org/0009-0002-0798-4578
[2]https://orcid.org/0000-0002-5228-9788
*Sorumlu yazar: aisitan@pau.edu.tr

Araştırma Makalesi

Makale Tarihçesi:
Geliş tarihi: 15.02.2025
Kabul tarihi: 12.05.2025
Online Yayınlanma:15.12.2025

Anahtar Kelimeler:
Borlama
Takım çeliği
Yüzey pürüzlülüğü
Boyut toleransı

ÖZ

Borlama işlemi sırasında, malzemenin yüzeyinde çok ince ve son derece sert bir seramik tabaka oluşur. Bu işlem, aşınma ve korozyona karşı yüksek direnç gerektiren bileşenlerde yaygın olarak uygulanmaktadır. Borlanmış parçalar üstün özellikler kazansa da işlem sırasında kullanılan yüksek sıcaklıklar, parçanın son boyutlarını ve yüzey pürüzlülüğünü değiştirebildiğinden önemli bir zorluk oluşturmaktadır. Bu durum, yüksek boyutsal hassasiyet ve yüzey kalitesi gerektiren ancak işlevleri nedeniyle hızla aşınan zımbalar gibi hassas kesici takımlar için özellikle kritiktir. Bu çalışmada, hassas kalıp parçalarında yaygın olarak kullanılan AISI D2 (1.2379, X153CrMoV12) soğuk iş takım çeliğinin borlama sonrası yüzey pürüzlülüğündeki değişim incelenmiştir. Farklı başlangıç yüzey pürüzlülüğüne sahip numuneler, 900 °C ve 950 °C sıcaklıklarda, 6 ve 8 saat süreyle Ekabor® II katı ortamında borlanmıştır. İşlem öncesi nihai boyutlandırma ve yüzey durumları, tel erozyon ve hassas tornalama işlemleriyle hazırlanmıştır. Sonuçlar, başlangıç Ra değeri < 1 µm olan numunelerde yüzey pürüzlülüğünde %143’e kadar artış olduğunu, Ra değeri > 2 µm olan bazı numunelerde ise %26’ya varan azalma sergilediğini göstermiştir. Artan sıcaklık ve süre, bu etkileri daha da yoğunlaştırmıştır. Bulgular, başlangıç yüzey pürüzlülüğünün borlama sonrası yüzey morfolojisi üzerinde kritik bir rol oynadığını ve hassas uygulamalarda dikkatle kontrol edilmesi gerektiğini vurgulamaktadır.

Determination of the Optimum Surface Roughness of AISI D2 Cold Work Tool Steel for Industrial Boronizing Applications

Research Article

Article History:
Received: 15.02.2025
Accepted: 12.05.2025
Published online:15.12.2025

Keywords:
Boronizing
Tool steel
Surface roughness
Dimension tolerance

ABSTRACT

During the boronizing process, a very thin and extremely hard ceramic layer forms on the surface of the material. This procedure is commonly applied to components requiring high resistance to wear and corrosion. Although boronized parts acquire superior properties, a key challenge is the elevated temperatures used during the process, which can alter the final dimensions and surface roughness of the part. This issue is particularly critical for precision cutting tools such as punches, which require high dimensional accuracy and surface quality but often suffer from rapid wear due to their function. In this study, the surface roughness evolution of AISI D2 (1.2379, X153CrMoV12) cold work tool steel—widely used in precision mold parts—was investigated after boronizing. Specimens with different initial surface roughness values were boronized in a solid Ekabor® II medium at 900 °C and 950 °C for 6 and 8 hours. Final dimensions and surface conditions were prepared via wire erosion and fine turning before treatment. The results showed that samples with Ra < 1 µm experienced up to 143% increase in surface roughness, while some Ra > 2 µm samples exhibited reductions of up to 26%. Increased temperature and duration intensified these effects. The findings emphasize that the initial surface roughness plays a critical role in the post-boronizing surface morphology and must be carefully controlled in precision applications.

To Cite: Gürcan Y., Işıtan A. Determination of The Optimum Surface Roughness of AISI D2 Cold Work Tool Steel for Industrial Boronizing Applications.. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi 2025; 8(5): 2094-2110.

1. Introduction

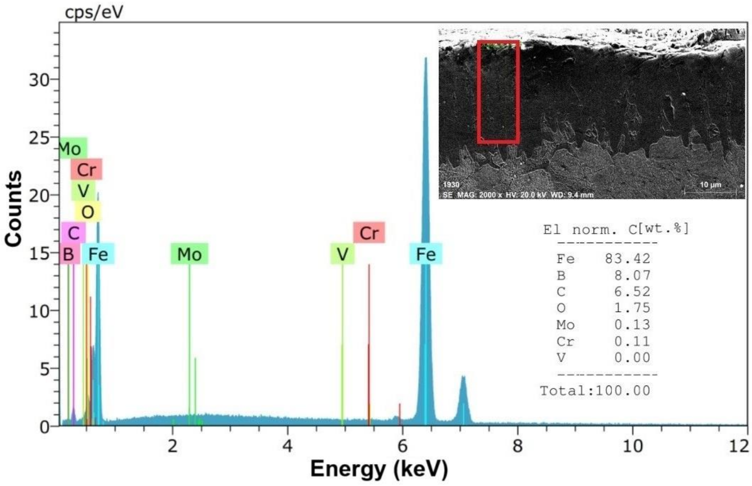
According to ASTM 681 standard, tool steels are categorized into hot work, cold work, shock-resisting, special-purpose, and mold tool steel (ASTM, 2018). Cold work tool steels, particularly those in groups A, D, and O, are extensively used in the molding industry. Within the D types, ranging from D2 to D7, high carbon and chromium contents contribute to exceptional wear resistance. AISI D2 steel (DIN 1.2379 / X155CrVMo12-1) is notably prevalent in the manufacturing of various molding parts, including blanking, forming, and trim dies, gages, slitting cutters, wear parts, lamination dies, thread rolling dies, drawing dies, rotary cutting dies, knurls, bending dies, gages, shear blades, burnishing tools, rolls, machine parts, master parts, injection screw and tip components, seaming rolls, extrusion dies, tire shredders, scrap choppers, stamping dies, and more (Hunan Fushun Metal Co., 2024; Precision Punch and Tooling, 2024; Thyssenkrupp Steel, 2024).

Components like cutting and forming punches in the molding industry, as well as those involved in sensitive processes like female plates, experience substantial wear. Simultaneously, these elements are expected to maintain the desired surface and geometric tolerances. Wear not only shortens component life but also results in production downtime, increased maintenance costs, and energy inefficiency. Friction and wear in industrial systems account for approximately 23% of global energy consumption. Technological advancements in surface engineering could reduce these losses by up to 40%, equating to an 8.7% reduction in global energy use and 1.4% of annual gross domestic product (GDP) (Holmberg and Erdemir, 2017; Bastidas, 2020; Woydt, 2021).

Improving surface hardness is one of the most effective approaches for enhancing wear resistance. Surface hardening methods for steels can be broadly classified into surface exchange processes and hard coating processes. Surface exchange processes can be either hardening-based or diffusion-based (Lampman, 1991). Diffusion-free methods include quenching, flame, induction, and laser hardening, while diffusion-based methods—such as carburizing, nitriding, carbonitriding, and boronizing—alter the surface composition. Hard coatings, including CVD, PVD, and thermal spraying, offer abrasion resistance through thin, durable surface films (Lampman, 1991; Bahrami et al., 2005; Qamar, 2009; Işıtan, 2019).

Boronizing is a thermochemical surface treatment in which boron atoms diffuse into the metal substrate, forming hard boride compounds. The resulting ceramic-like surface layer exhibits high hardness values ranging from 1450 to 2000 HV and thicknesses between a few microns and 100 µm, depending on process parameters. Steels, cast irons, non-ferrous alloys, and sintered metals can all be boronized using solid, paste, gas, or plasma media under temperatures of 700–1100 °C for durations of 1–12 hours

(Matuschka, 1980; Özbek, 2000; Uluköy and Can, 2006; Ulukoy et al., 2013). Figure 1 shows, as an example, the boride layer and EDS analysis of AISI 1040 steel obtained by solid boronizing.



```
El norm. C[wt.%]
-----------
 Fe   83.42
 B     8.07
 C     6.52
 O     1.75
 Mo    0.13
 Cr    0.11
 V     0.00
-----------
Total:100.00
```

Figure 1. EDS analysis of the boride layer obtained by solid boronizing on AISI 1040 steel

Cold work tool steels are widely used in the mold manufacturing industry. Nowadays, it is expected to produce elements with high wear resistance and at the same time with the required surface and geometric tolerance levels for precision operations such as cutting, punching and forming punches, female plates used in the molding industry. These components operate under high force/pressure and are subject to high friction. These conditions have a great influence on the wear of the parts. Due to its high wear and corrosion resistance, studies are ongoing to understand the boronizing of steels, in particular tool steels and its effect on industrial applications (de Mendonça Ferreira et al., 2021; Nair et al., 2022; Çakır, 2022; Kantoríková et al., 2023). In an industrial application, three times more serviceable part life and four times more cost-effectiveness were achieved for AISI 1040 steel (Işıtan, 2018). According to Armagan et al. (2016), boriding treatment resulted in a 170% reduction in wear loss of AISI D2 tool steel.

Nevertheless, the part's surface quality after boronizing is not the same as before the procedure. As a result of the process, there can be changes in the dimensions of the part, as there is a 5-25% volume expansion in the boron layer (Matuschka, 1980; Sinha, 1991). VillaVelázquez-Mendoza et al. (2014) investigated the influence of surface roughness, treatment time, and temperature on the iron boride layer thickness formed on AISI 1018 steel via the paste boronizing process. The initial surface roughness of the steel substrates ranged from 0.015 to 1.2 µm. It was observed that the boride layer thickness increased with substrate roughness up to an optimal value of approximately 0.8 µm. This enhancement was attributed to the increased contact area between the boronizing paste and the steel surface, which facilitated boron diffusion into the steel's crystalline lattice. However, when the surface roughness exceeded 0.8 µm, a deterioration in the adhesion between the paste and the substrate was reported, leading to a reduction in boride layer thickness due to hindered diffusion kinetics (VillaVelázquez-Mendoza et al., 2014). Jain and Sundararajan (2002) investigated the effect of boronizing on the surface roughness of low carbon steel. In their study, a steel specimen with an initial surface roughness (Ra) of 0.2–0.3 μm exhibited an approximately 2–3-fold increase in roughness after undergoing boronizing at 940 °C for 2 hours. The observed increase in surface roughness was reported to be independent of the thickness of the boronizing medium. Instead, it was attributed to the chemical reaction occurring during the process, which led to the formation of iron boride phases on the surface (Jain and Sundararajan, 2002). Yu et al. (2005) also found that the surface roughness of a mild steel increased during the boronizing process at 850 °C with maximum 4 hours boronizing durations (Yu et al., 2005). Turkmen and Yalamac (2022) boronized SAE 1020 steel specimens with a surface roughness value of 0.28 μm at 850 °C for 4 hours with different boronizing mixtures by powder-pack method. The surface roughness values increased between 63% and 96% after the boronizing processes (Turkmen and Yalamac, 2022). In the study by Belaid et al. (2022), a modified cold work tool steel treated by powder-pack boronizing within the temperature range from 800 °C to 1000 °C for boronizing time of 2, 4, 6 and 8 hours. The pre-boronizing surface roughness value of Ra=0.07 μm increased up to Ra=0.46 μm depending on the boronizing conditions (Belaid et al., 2022). In the study by Sahin (2009), the AISI 1020, AISI 1040, and AISI 2714 were chosen as substrate materials and were boronized at 900 °C by a solid boronizing method using Ekabor® I for 2 and 4 hours. Surface roughness values decreased after boronizing for surfaces that were rough before boronizing and increased for surfaces that were smooth before boronizing (Sahin, 2009).

The increase in surface roughness after boronizing is primarily attributed to the formation of iron boride phases (FeB and Fe_2B), which possess distinct crystal structures and hardness values. The heterogeneous growth of these phases, influenced by boronizing temperature, duration, and the substrate's initial roughness, often leads to uneven surface profiles, micro-cracks, and the formation of micropores due to gas evolution (e.g., B_2O_3 vapors) during the process. While many studies confirm an increase in surface roughness after boronizing, others have reported reductions in roughness, particularly when the initial Ra values were relatively high. These contrasting outcomes highlight the complex interaction between initial surface conditions and boride layer development.

Surface quality and dimensional control are critical in the molding industry, especially for precision parts. While boronizing is advantageous for hardness and wear resistance, the process inevitably alters the surface texture. Most literature studies use polished samples with low initial roughness and standard processing times of 2–8 hours. However, there is limited data on how initial surface roughness affects post-boronizing surface quality in tool steels like AISI D2. In industrial settings, particularly in the mold and forming industries, boronized punches, dies, and inserts are increasingly used to extend tool life under high-load, abrasive conditions. However, dimensional instability and surface quality deviations after boronizing can lead to assembly mismatches, reduced precision, and even tool rejection. Therefore, understanding and controlling surface roughness and dimensional changes post-boronizing is critical for ensuring seamless integration into high-precision tooling systems. By identifying optimal initial surface conditions, this study directly contributes to improving process reliability and reducing costly post-processing steps such as regrinding or finishing.

This study aims to determine the optimum initial surface roughness for AISI D2 cold work tool steel to be boronized and used in precision mold part production. In this investigation, AISI D2 steel was boronized with Ekabor® II solid powder. Before boronizing, the final dimensions and surface conditions were given to the parts by wire erosion and fine turning processes. Samples with varying amounts of surface roughness were boronized in a solid medium for 6 and 8 hours at 900 °C and 950 °C. The effect of the boronizing and finishing process parameters on the final surface roughness of the parts was investigated.

2. Materials and Methods

2.1. Materials

In this study, a cold work tool steel AISI D2 (DIN 1.2379, X155CrVMo12-1) was used. The chemical composition can be seen in Table 1. It is widely used in many areas such as cutting tools, hot and cold deformation molds, and measuring devices.

Table 1. Chemical composition of AISI D2 cold work tool steel

Element	**C**	**Si**	**Cr**	**Mo**	**V**	**Fe**
wt. %	1.55	0.40	12	0.70	1.00	Bal.

Ekabor® II powders are commercially produced by BorTec as a boronizing solid agent (BorTec, 2024). The approximate chemical composition is composed of 90% SiC, 5% B_4C and 5% KBF_4, with a particle size below 850 µm (Çalık, 2013). Ekabor® II powder was preferred for its reliable performance and proven industrial applicability.

2.2. Methods

The samples to be subjected to boronizing were brought to Ø10±0.4 x 20 mm dimensions by turning and wire erosion processes as final finishing processes, and thus different surface roughness's were obtained on the surface of the samples. The dimensions of the samples were measured using a digital micrometer (Mitutoyo, Japan) with an accuracy of ±0.001 mm. Measurements were taken at five random locations, and the average thickness was calculated. Surface roughness measurements were made using the Mahr MarSurf PS1 surface roughness measuring device (Figure 2a). The surface roughness values obtained before boronizing were averaged by making 3 measurements on each piece. These results, obtained as Ra<1µm as a result of wire erosion, Ra<2µm as a result of fine turning, and Ra<4µm as a result of rough turning, are basically grouped under 3 groups (Table 2).

The boronizing parameters (900 °C and 950 °C, 6 and 8 hours) were selected based on prior research, which demonstrated significant effects of these values on boride layer formation and surface hardness

(Armagan et al., 2016; Gürcan et al., 2019; Kutlubay et al., 2019; Belaid et al., 2022). The boronizing process was carried out in Ø48 x 65 mm stainless steel containers/crucibles using Ekabor® II powders in 6 and 8 hours at 900 °C and 950 °C parameters, as shown in Table 2. The test specimens, which were cleaned with alcohol prior to the process, were placed on Ekabor® II powder placed 15 mm high in stainless steel crucibles, as shown in Figure 2b. A 15 mm thick layer of Ekabor® II powder was placed around and above the specimen and the crucible cover was closed. After that, graphite powder was used to cover the top of the cover to prevent oxidation between the boronizing medium and the furnace atmosphere. The crucible was then placed in a Nabertherm furnace (Figure 2c). After the boronizing process, the crucible was removed from the furnace and allowed to cool at room temperature. Any residual Ekabor® II on the cooled parts was removed with hot water and alcohol.

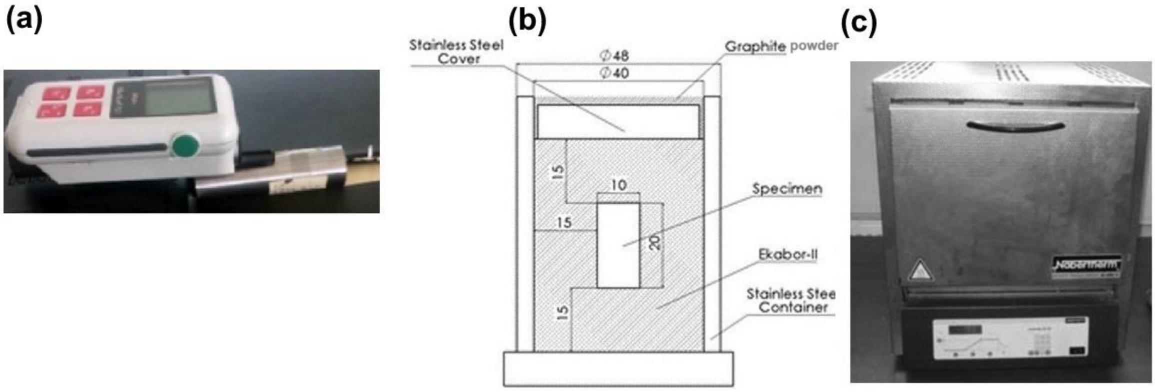


Figure 2. Instruments used in the study: Surface roughness measuring device (a), a schematic view of boriding container (b), furnace (c).

After cleaning, surface roughness and size measurements were repeated. The boronized specimens were cut 5 mm from the forehead for microstructure examination and then grinded with 200, 360, 600, 800, 1000 grit SiO_2 paper. For the polishing process, 3 and 6 µm diamond polishing solutions were used. Then, a 2% nital (nitric acid and ethanol) solution was used for the etching process. The Scanning Electron Microscopy (SEM) were employed to illustrate the boride layers. SEM analysis of the prepared samples was performed using a Zeiss Supra V40 FESEM device, operating at 20 kV, located at Pamukkale University's Advanced Research Center (ILTAM). The hardness values of the borided specimens were taken at 50 g load using a digital micro-Vickers hardness tester (Hardway Hardness Testing Equipment DV-IAT-4.3) at specified increments from the surface to the inner parts of the specimen.

Table 2. Boronizing parameters and surface roughness values before boronizing process

Specimen number	Ra, µm	Boronizing temperature, °C	Boronizing time, h
		Ra<1 µm	
1	0.337	900 °C	8
2	0.335	900 °C	8
3	0.347	900 °C	8
4	0.350	900 °C	6
5	0.355	900 °C	6
6	0.350	900 °C	6
7	0.342	950 °C	8
8	0.399	950 °C	8
9	0.364	950 °C	6
10	0.372	950 °C	6
11	0.356	950 °C	6
		Ra<2µm	
12	1.233	900 °C	8
13	1.754	900 °C	6
14	1.146	900 °C	6
		Ra>2µm	
15	3.649	900 °C	8
16	4.342	900 °C	8
17	3.492	900 °C	8
18	2.217	900 °C	6
19	2.211	950 °C	8

3. Results and Discussion

3.1. Microstructural Results

The formation of a sawtooth structure in the boronized samples was revealed in SEM examinations, as shown in Figure 3. The average thickness of the layers formed was between 23 µm and 40 µm and increased depending on the boronizing time and temperature.

Boron layer thickness and morphology can vary depending on the base material, boronizing medium, temperature, and time (Matuschka, 1980; Sinha, 1991). The 25-40 µm layer thickness and sawtooth morphology obtained in this study are consistent with several studies in the literature (Armagan et al., 2016; Reséndiz-Calderón et al., 2024).

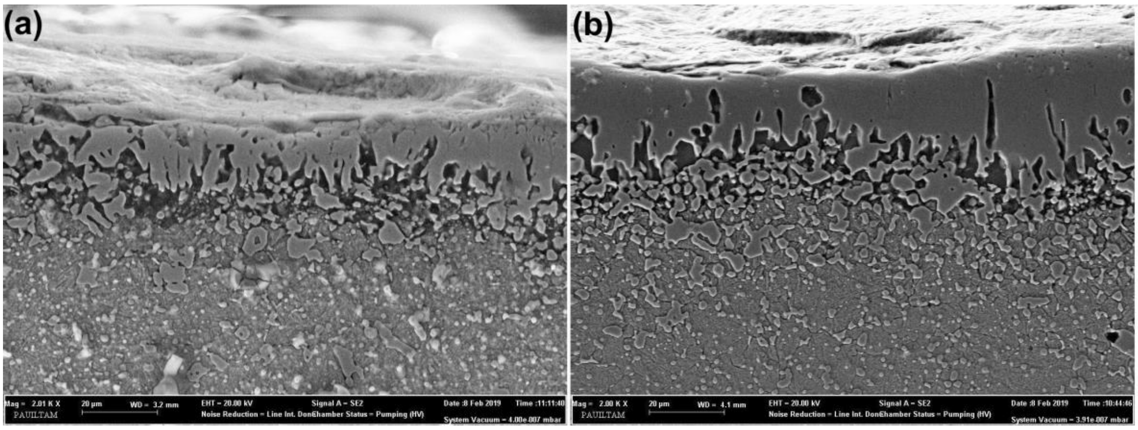
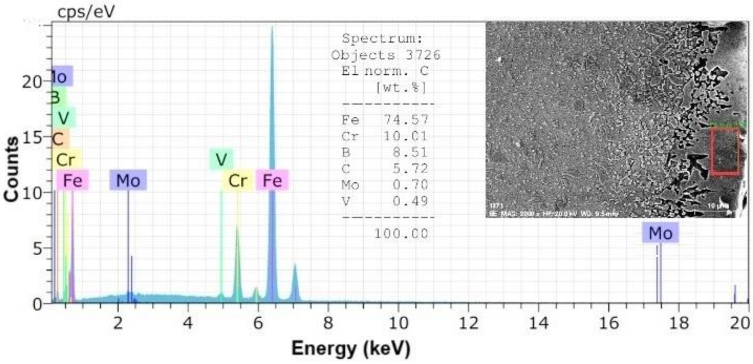


Figure 3. SEM images of boronized samples: a) at 900 °C for 6 h, b) at 900 °C for 8 h

Figure 4 shows the EDS area spectra of AISI D2 steel boride layer boronized at 900 °C for 8 hours. Apart from the main alloying elements carbon, chromium, molybdenum, and vanadium, 8.51 % (wt. %) boron was identified. In ferrous alloys, since the atomic diameter of boron is 27% smaller than the atomic diameter of iron, boron dissolves in α-Fe as a solid in both the ground and intermediate positions, in the order of ppm. The alloying elements also affect the crystallographic arrangement, phase composition, and the thickness of the boride layer at the interface between the boride layer and the steel. An increase in hardness is observed with increasing carbon content up to 0.4% carbon content, above which it remains almost constant for higher carbon content. Since carbon does not dissolve in FeB and Fe_2B type phases but accumulates in areas near the matrix in the form of carbides going Fe_3C, Cr_3C, Fe_6C_3, it is believed that this affects the boronizing mechanism and makes the layer in question tighter and harder. Silicon behaves like carbon and does not dissolve in the boride layer. Chromium affects both the morphology and the depth of the boride layer in steels. Since chromium is an element with a lower atomic number than iron, it is the most boron-rich element (Fe, Cr) B. It diffuses first and systematically from the matrix into the phase and diffuses towards the surface. When the characteristics of the boride layers of chromium alloys are compared with non-chromium alloys, it is seen that the boride layers of chromium alloys are much thinner depending on the carbon percentage (Matuschka, 1980; Sinha, 1991; Özbek, 2000).



```
Spectrum:
Objects 3726
El norm. C
     [wt.%]
-----------
Fe   74.57
Cr   10.01
B     8.51
C     5.72
Mo    0.70
V     0.49
-----------
    100.00
```

Figure 4. EDS area spectra of AISI D2 steel boride layer boronized at 900 °C for 8 hours

3.2. Microhardness Results

The highest hardness value of 1674 HV0.05 was obtained in the sample boronized at 950 °C for 8 hours. While the hardness value was 1505 HV0.05 in the sample boronized at 900 °C for 6 hours, it was obtained as 1580 and 1650 HV0.05 in the sample boronized at 950 °C for 6 hours and 900 °C for 8 hours, respectively. After about 230-250 µm from the surface, the hardening depth lost its effectiveness and decreased to 300-350 HV0.05.

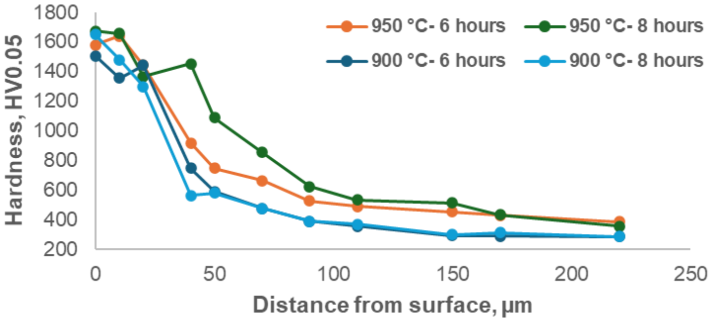


Figure 5. Microhardness measurement results after boronizing process

The microhardness values obtained in this study are in strong agreement with findings reported in the literature. The hardness obtained on the surface increased with the increase in boronizing temperature and time, as expected (Matuschka, 1980; Sista et al., 2011; Pereira et al., 2016). The highest surface hardness of 1674 HV0.05 was recorded in the sample boronized at 950 °C for 8 hours, whereas other boronizing conditions yielded hardness values ranging from 1505 to 1650 HV0.05. These values fall well within the typical hardness range (1450–2000 HV) of boride layers reported by Matuschka (1980), Sista et al. (2011), and Pereira et al. (2016), depending on the substrate and process parameters. The observed increase in surface hardness with higher boronizing temperature and time also aligns with the aforementioned studies.

The presence of alloying elements such as carbon, chromium, molybdenum and vanadium significantly affect the structure and hardness of the boride layer. As can be seen in the EDS area spectra of AISI D2 steel boride layer (boronized at 900 °C for 8 hours) given in Figure 4, it can be seen that the ratio of insoluble carbon increase in the FeB or Fe_2B phases just below the surface. Carbon accumulates as carbides near the surface just below the surface, contributing to a denser and harder layer. Chromium promotes the formation of (Fe,Cr)B phases and affects both the morphology and thickness of the boride layer, often resulting in higher microhardness and thinner layers in chromium-rich steels (Matuschka, 1980; Sista et al., 2011; Pereira et al., 2016).

Additionally, Armağan et al. (2016) reported up to a 77% increase in surface hardness in boronized AISI D2 steel when compared to non-boronized tool steels, which is comparable to the current study. This improvement is attributed to the formation of dense iron boride phases, as also confirmed by SEM-EDS analyses in this study. Moreover, the obtained boride layer thicknesses (23–40 µm) and their sawtooth morphology are consistent with prior literature (Matuschka, 1980; Reséndiz-Calderón et al., 2024), further validating the reliability of the microstructural and mechanical transformations observed after boronizing.

3.3. Surface Roughness Results

The surface roughness measurement results before and after the boronizing process are shown in Table 3 and summarized in Figure 6. As a result of the measurements, for parts with a surface roughness Ra<1 µm before boronizing, an average of 64% increase in average surface roughness with 900 °C 6 hours boronizing, 70% increase in surface roughness was observed with 900 °C 8 hours boronizing, 88% increase in average surface roughness for 950 °C 6 hours, and 104% increase in average surface roughness for 950 °C 8 hours. The roughness of the surface increased significantly as the boronizing time and temperature increased. The initial Ra values before boronizing range from approximately 0.33 to 0.39 µm. After boronizing, the Ra values range from 0.49 to 0.86 µm. The percentage change in Ra values varies from 36% to 143%. Notably, specimen 11, boronized at 950 °C for 6 hours, exhibits a 143% increase in surface roughness. Generally, higher temperatures (950 °C) and longer durations (8 hours) result in increased roughness in surface.

For the samples having 1<Ra<2 µm, the initial Ra values before boronizing range from 1.15 to 1.75 µm. After boronizing, the Ra values range from 1.29 to 2.03 µm. The percentage change in Ra values ranges between 15% and 46%. Specimen 12, boronized for 8 hours at 900 °C, shows the highest increase in roughness at 46%.

For specimens with Ra>2 µm, the initial Ra values before boronizing ranged from 2.21 to 4.34 µm. After boronizing, the Ra values range from 2.32 to 3.64 µm. The percentage change in Ra values is predominantly negative, ranging from -26% to 20%. For instance, specimen 15, boronized at 900 °C for 8 hours, demonstrates a 26% reduction in surface roughness.

Higher temperatures and longer boronizing durations (e.g., 950 °C for 8 hours) tend to result in greater increases in surface roughness. Specimens with lower initial Ra values (Ra < 1 µm) generally exhibit more significant changes in surface roughness after boronizing, with a higher percentage increase. In contrast, specimens in the Ra> 2 µm category can sometimes experience a decrease in surface roughness following the boronizing process.

Table 3. Variation of surface roughness after boronizing depending on boronizing time, temperature, and surface roughness before boronizing

Specimen number	Boronizing time, hours	Boronizing temperature, °C	Ra, µm (after boronizing)	Change in Ra, %
Ra<1 µm				
1	8	900 °C	0.586	73
2	8	900 °C	0.573	71
3	8	900 °C	0.570	65
4	6	900 °C	0.593	69
5	6	900 °C	0.552	55
6	6	900 °C	0.593	69
7	8	950 °C	0.766	124
8	8	950 °C	0.744	86
9	6	950 °C	0.497	36
10	6	950 °C	0.697	87
11	6	950 °C	0.865	143
Ra<2µm				
12	8	900 °C	1.809	46
13	6	900 °C	2.032	15
14	6	900 °C	1.288	16
Ra>2µm				
15	8	900 °C	2.678	-26
16	8	900 °C	3.641	-16
17	8	900 °C	2.928	-16
18	6	900 °C	2.318	4
19	8	950 °C	2.655	20

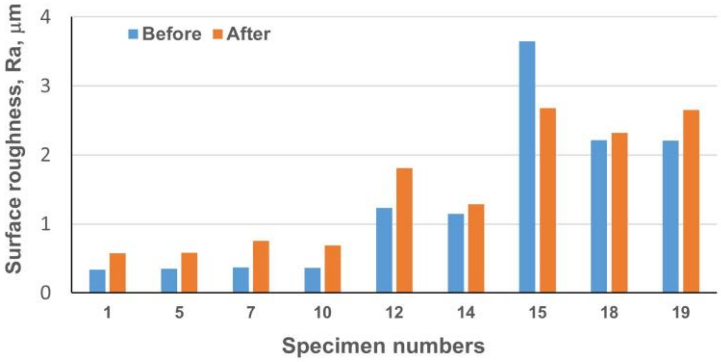


Figure 6. Surface roughness measurement results

In the study by Cetin et al. (2021), while the Ra value of all samples before boronizing was 0.110 µm, the average surface roughness (Ra) values of all boronized samples were higher than untreated AISI 904L (Cetin et al., 2021). In the substrate material used by Basir et al. (2015) 316 austenitic stainless steel, the surface roughness value of Ra=2.130 µm decreased to 0.937 µm as a result of the paste boronizing process (Basir et al., 2015). In the study by Peng (2020), the average Ra value of unboronized AISI 1018 steel sample was 0.7955 µm, while that of AISI 1018 sample boronized at 900 °C for 4 h was 1.3545 µm (Peng, 2020). Krelling et al. (2015) used solid boronizing media on AISI H13 steel. Before treatment, all the samples had an average roughness Ra of 0.05 µm. The roughness increased up to 1 μm with thermochemical treatment (Krelling et al., 2015). Şahin (2009) examined the effects of the boronizing process on surface roughness and dimensions of various steels, including AISI 1020, AISI 1040, and AISI 2714. For each of the steel materials used in the study, the final surface roughness threshold value before boronizing was determined. The base material surface roughness values below this value showed a tendency to increase in surface roughness after the boronizing process, while the surface roughness tended to decrease for threshold values above this value. The study concluded that the boronizing process generally increased the surface roughness, particularly at higher temperatures and for longer durations (Şahin, 2009). In this study, it was also observed that the surface roughness increase was more pronounced in samples with initially lower Ra values, whereas samples with initially higher Ra values exhibited less change or even a decrease in roughness. In the Ra < 1 μm category, a substantial increase in surface roughness is observed after boronizing, particularly at higher temperatures and longer durations. Additionally, the decrease in surface roughness seen in some specimens in the Ra > 2 μm category (e.g., a -26% change for specimen 15) aligns with Şahin's observation that surfaces with initially higher roughness may experience less of an increase or a decrease after the boronizing process (Şahin, 2009).

In this study, at all boronizing conditions and parameters, the specimens grew in diameter and length (Figure 7). The dimensional alterations observed in AISI D2 steel samples after boronizing varied depending on both the processing temperature and duration. As shown in Figure 7a, the increase in sample diameter was more pronounced at shorter boronizing durations. Specifically, the maximum radial expansion occurred at 900 °C for 6 hours (~0.35%), while a noticeable reduction was observed when the duration was extended to 8 hours (~0.12%). A similar trend, albeit less prominent, was seen at 950 °C, where the diameter increases slightly decreased from ~0.3% at 6 hours to ~0.2% at 8 hours. This reduction in dimensional growth with prolonged treatment time may be attributed to the stabilization of the boride layer and a potential reduction in compressive stresses at the surface due to deeper diffusion of boron atoms.

In contrast, the elongation behavior of the specimens along their length exhibited an opposing trend, as illustrated in Figure 7b. At 900 °C, increasing the boronizing time from 6 to 8 hours resulted in a decrease in elongation percentage (from ~0.22% to ~0.13%). However, at 950 °C, a slight increase in elongation was observed with extended treatment (from ~0.14% to ~0.18%). This may be related to enhanced diffusion kinetics and possible anisotropic layer growth at elevated temperatures, leading to differential expansion along the axial direction.

The boron layer formed during the boronizing of steels may also consist of other metal borides depending on the alloying elements of the steel, the boronizing medium used, and the boronizing conditions, but generally and predominantly consists of FeB and Fe_2B borides or only Fe_2B borides. The formation of Fe_2B also causes a non-uniform volume change on the steel surface (Matuschka, 1980; Sinha, 1991). As a result of the boronizing process, dimensional increases occur in steel materials depending on the type of steel and boronizing conditions. For example, while the dimensional increase in the boronizing processes using Ekabor I was one fifth of the boride layer thickness for AISI 1020 and AISI 1040, it was one third of the boride layer thickness for AISI 2714 (Şahin, 2009).

When boronizing was performed at 900 °C for 8 hours, the increase in both diameter and length was minimal. Overall, these findings indicate that both radial and axial dimensional changes are strongly influenced by boronizing temperature and time. The condition of 900 °C for 8 hours was found to yield the most controlled dimensional behavior, suggesting its suitability for precision applications where dimensional stability is critical.

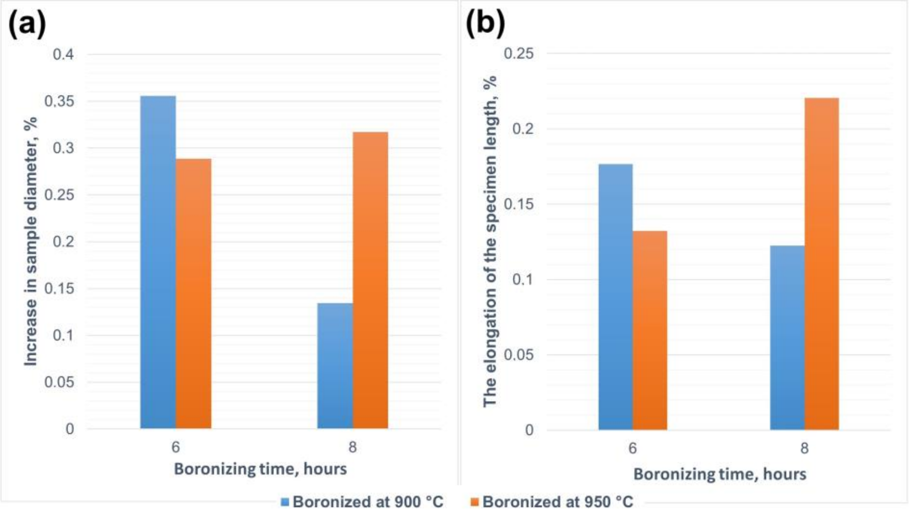


Figure 7. After boronizing, a) increase in specimen diameter (%) and b) increase in specimen length (%)

4. Conclusion

With the thermochemical boronizing process, a very thin boride layer with very high wear and corrosion resistance is obtained on the steel surface. Despite this superior layer obtained after the boronizing process, it is not widely used in the production of mold parts such as punches, where high wear performance is expected but surface roughness is important. Considering this difficulty, in this study, AISI D2 steel, which is widely used in the production of mold parts, was boronized at 900 °C and 950 °C for 6 and 8 hours. The variation of the surface roughness of the steel parts, which were divided into three different surface roughness groups, was investigated after the boronizing process. The formation of boride layers was revealed in SEM and EDS examinations. The results of this study can be summarized as follows:

- As the boriding temperature and time increased, the boride layer thickness increased from 23 µm to 40 µm and the maximum hardness obtained on the surface increased from 1505 HV0.05 to 1674 HV0.05 for samples boronized at 900 °C for 6 hours and 950 °C for 8 hours, respectively.
- Depending on the time and temperature, a 10% increase in the hardness values of the boronized samples was obtained.
- The hardening depth was obtained as 230-250 µm from the surface.

- For smoother surfaces (Ra < 1 μm), the boriding process led to a significant increase in surface roughness, especially under high temperature and prolonged conditions (up to 143% increase for 8 hours at 950 °C).
- Moderately rough surfaces (1 < Ra < 2 μm) exhibited a more controlled increase in Ra values, while rougher specimens (Ra > 2 μm) showed either a negligible change or a decrease in surface roughness, e.g. up to 26% reduction in surface roughness was observed in specimens boronized at 900°C for 8 hours.
- The boronizing process for specimens with an initial surface roughness Ra < 1 μm led to an increase of up to 143% in the final surface roughness value, especially under 950 °C and prolonged 8 hours conditions.
- Moderately rough surfaces (1 < Ra < 2 μm) exhibited a more controlled increase in Ra values, and the percentage change in Ra values ranged from 15% to 46%.
- Rougher specimens (Ra > 2 μm) showed either no negligible change in surface roughness or a reduction of up to 26%, as in the case of boriding at 900°C for 8 hours.
- Considering the boriding parameters used in this study, the results show that boronizing of AISI D2 steel using Ekabor II powders at 900 °C for 8 hours is an optimum condition for mold parts with surface roughness Ra > 2 μm, offering improved surface finish, high hardness and minimal dimensional variation.
- The results demonstrated that both radial and axial dimensional changes in AISI D2 steel are significantly influenced by boronizing temperature and duration, with higher stability observed at lower temperatures and longer treatment times.
- Among the evaluated conditions, boronizing at 900 °C for 8 hours provided the most controlled dimensional behavior, indicating its suitability for precision applications requiring tight dimensional tolerances.

The results of this study highlight that the initial surface roughness, along with boronizing temperature and duration, significantly affects the final surface morphology and dimensional changes in AISI D2 steel. While the findings suggest that lower initial Ra values tend to lead to greater increases in surface roughness, and that extended boronizing at 900 °C offers more stable dimensional behavior, these trends are based on a specific set of parameters. Therefore, the observations presented here may serve as a useful reference for industrial applications, particularly in precision tooling, but further studies are recommended under varying process conditions to confirm the broader applicability of these results.

Author Contribution Statement

The authors declare that they have contributed equally to the article.

Acknowledgements

This study was presented as an oral presentation at the 18th International Istanbul Scientific Research Congress on Life, Engineering, Architecture and Mathematical Sciences between August 19-21, 2024.

Conflict of Interest Statement

The authors declare that there is no conflict of interest between them.

References

Armagan E., Kaplan Y., Onar V., Ulukoy A. Wear behavior of boronized AISI D2 tool steel. 16th International Materials Symposium, 12-14 October 2016, pp: 353-358, Denizli, Türkiye.

American Society for Testing and Materials (ASTM). ASTM A681 Standard specification for tool steels alloy, 2018.

Bahrami A., Anijdan S., Golozar M., Shamanian M. Effects of conventional heat treatment on wear resistance of AISI H13 tool steel. Wear 2005; 258(5-6): 846–851.

Basir MHM., Abdullah B., Alias SK., Jumadin MH., Ismail MH. Analysis on microstructure, hardness and surface roughness of shot blasted-paste boronized 316 austenitic stainless steel. Jurnal Teknologi 2015; 76(3): 75–79.

Bastidas DM. Corrosion and protection of metals. Metals 2020; 10(4): 458.

Belaid M., Fares ML., Assalla O., Boukari F. Surface characterization of a modified cold work tool steel treated by powder-pack boronizing. Materialwissenschaft Und Werkstofftechnik 2022; 53(1): 15–38.

BorTec. Improve wear protection by boronizing. https://bortec-group.com/services/boronizing/. Accession date: 15.02.2025.

Çalık A. Effect of powder particle size on the mechanical properties of boronized EN H320 LA steel sheets. ISIJ International 2013; 53(1): 160–164.

Çakir MV. A comparative study on tribocorrosion wear behavior of boride and vanadium carbide coatings produced by TRD on AISI D2 steel. Protection of Metals and Physical Chemistry of Surfaces 2022; 58(3): 562-573.

Çetin M., Günen A., Kalkandelen M., Karakaş MS. Microstructural, wear and corrosion characteristics of boronized AISI 904L superaustenitic stainless steel. Vacuum 2021; 187: 110145.

de Mendonça Ferreira ST., Bacco ALK., do Nascimento EM., Lepienski CM. Mechanical characterization and micro-wear of FeB-Fe_2B layers on boriding AISI D2 and AISI 4340 steels. Materials Sciences and Applications 2021; 12(7): 330-344.

Gürcan Y., Işıtan A., Kutlubay RÇ. Determination of microstructure and microhardness properties of boronized Vanadis 4 steel. 4th International Conference on Engineering Technology and Applied Sciences (ICETAS), 24-28 April 2019, pp:277-281, Kiev, Ukraine.

Holmberg K., Erdemir A. Influence of tribology on global energy consumption, costs and emissions. Friction 2017; 5: 263-284.

Hunan Fushun Metal Co. DIN 1.2379 cold work mould steel bars with ANSI D2 steel grade. https://www.fushunspecialsteel.com/1-2379-cold-work-mould-steel-bars-with-ansi-d2-steel-grade/. Accession date: 15.02.2025.

Işıtan A. Boronizing: In the industrial applications in Turkey, why not find the place it deserves?. International Symposium on Boron, 17-19 April 2019, pp:287-292, Nevşehir, Türkiye.

Işıtan A. Sondaj makinasında kullanılan ve üzerinde keçe çalışan araparçanın aşınma performansının ve kullanım ömrünün arttırılması. Mühendis ve Makine 2018; 59(693): 47–53.

Jain V., Sundararajan G. Influence of the pack thickness of the boronizing mixture on the boronizing of steel. Surface and Coatings Technology 2002; 149(1): 21–26.

Kantoríková E., Moravec J., Biňasová V. The effect of borides on the mechanical properties of tool steels and sintered carbides. Transportation Research Procedia 2023; 74: 522-529.

Krelling AP., Milan JCG., De Costa CE. Tribological behaviour of borided H13 steel with different boronizing agents. Surface Engineering 2015; 31(8): 581-587.

Kutlubay RÇ., Işıtan A., Gürcan Y. Borlama işleminin Vanadis 4 çeliğinin aşınma direnci üzerine etkisi. 4th International Conference on Engineering Technology and Applied Sciences (ICETAS), 24-28 April 2019, pp:282-285, Kiev, Ukraine.

Lampman S. Introduction to surface hardening of steels. In: Davis, JR. (ed.) ASM Handbook Volume 4 Heat Treating. ASM International 1991; 259–267.

Matuschka AG Von. Boronizing. Oxford England: The Alden Pres; 1980.

Nair F., Zafar HMN., Cerit AA., Karamış MB. Analyzing the influence of simultaneously austenitization and multi-directional boriding on the surface and subsurface of H13 tool steel. Journal of Materials Engineering and Performance 2022; 31(12): 9791-9801.

Özbek I. The improvement of surface performance of (AISI M50, AISI M2) high speed steels and AISI W1 steel by boronizing treatment. Sakarya University Graduate School of Natural and Applied Sciences PhD Thesis, Sakarya, Türkiye, 2001.

Peng C. The effect of boronizing on hardness, wear and corrosion properties of AISI 1018 and AISI 316L steels. University of Saskatchewan College of Graduate and Postdoctoral Studies PhD Thesis, Metis, Canada, 2020.

Pereira R., Mariani F., Lombardi AN., Totten GE., Casteletti L. Characterization of layers produced by boronizing and boronizing-PVD on AISI D2 tool steel. Materials Performance and Characterization 2016; 5(4): 406–413.

Precision Punch and Tooling. Technical reference. https://ppunch.com/technical-reference/. Accession date: 15.02.2025.

Qamar SZ. Effect of heat treatment on mechanical properties of H11 tool steel. Journal of Achievements in Materials and Manufacturing Engineering 2009; 35(2): 115-120.

Reséndiz-Calderón CD., Cao-Romero-Gallegos JA., Farfan-Cabrera LI., Campos-Silva I., Soriano-Vargas O. Influence of boronizing on the tribological behavior of AISI D2 tool steel for dry deep drawing of stainless steel and aluminum. Surface and Coatings Technology 2024; 484: 130832.

Sinha AK. Boronizing. In: Davis, JR. (ed.) ASM Handbook Volume 4 Heat Treating. ASM International 1991; 437.

Sista V., Kahvecioglu O., Eryilmaz OL., Erdemir A., Timur S. Electrochemical boronizing and characterization of AISI D2 tool steel. Thin Solid Films 2011; 520(5): 1582–1588.

Şahin S. Effects of boronizing process on the surface roughness and dimensions of AISI 1020, AISI 1040 and AISI 2714. Journal of Materials Processing Technology 2009; 209(4): 1736–1741.

Thyssenkrupp Steel. 2379 tool steel. https://thyssenkruppsteel.wordpress.com/tag/aisi-d2/. Accession date: 15.02.2025

Türkmen İ., Yalamaç E. Effect of alternative boronizing mixtures on boride layer and tribological behaviour of boronized SAE 1020 steel. Metals and Materials International 2022; 28(5): 1114–1128.

Ulukoy A., Can AC., Ozmen Y., Tasgetiren S. Borocarburizing of decarburized gears made from 21NiCrMo$_2$ (AISI 8620) steel. Proceedings of the Institution of Mechanical Engineers Part L: Journal of Materials: Design and Applications 2013; 229(3): 226–235.

Uluköy A., Can AÇ. Çeliklerin borlanması. Pamukkale University Journal of Engineering Sciences 2006; 12(2): 189–198.

VillaVelázquez-Mendoza CI., Rodriguez-Mendoza JL., Ibarra-Galván V., Hodgkins RP., López-Valdivieso A., Serrato-Palacios LL., Leal-Cruz AL., Ibarra-Junquera V. Effect of substrate roughness, time and temperature on the processing of iron boride coatings: Experimental and statistical approaches. International Journal of Surface Science and Engineering 2014; 8(1): 71–91.

Woydt M. The importance of tribology for reducing CO$_2$ emissions and for sustainability. Wear 2021; 474: 203768.

Yu L., Chen X., Khor K., Sundararajan G. FeB/Fe$_2$B phase transformation during SPS pack-boronizing: Boride layer growth kinetics. Acta Materialia 2005; 53(8): 2361–2368.