



Investigation of the effect of shallow and deep cryogenic treatment on wear and impact performance of DIN 1.2344 steel

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ABSTRACT

Hot work tool steels are preferred in different areas of industry due to their high toughness values and high impact resistance at high temperatures. Although there are many studies in the literature on DIN 1.2344 hot work tool steel, which is widely used in hot work tool steels, it has been determined that the studies examining the effects of cryogenic treatment on this material are limited. In this study, hardness, impact, tensile, wear tests were applied on DIN 1.2344 hot work tool steel and microstructure examination was carried out. In the study, the effects of shallow cryogenic treatment (SCT) and deep cryogenic treatment (DCT) at two different waiting times on mechanical properties (microhardness, macrohardness, yield and tensile strength, elongation amount, impact energy) were investigated compared to the conventional heat treated (CHT) sample. Microstructure, surface roughness and wear performance were investigated as a result of wear tests. As a result, it was found that shallow and deep cryogenic treatment provided 1.34%, 9.31% and 13% improvement on wear resistance for SCT-12, SCT-24 and DCT-36, respectively, compared to conventional heat treatment. In terms of impact resistance, the highest value was 2.37% improvement in DCT sample.

1. Introduction

DIN 1.2344 tool steel is a widely used hot work steel. They are used in the production of materials in the extrusion and forging method of light metals. In addition, DIN 1.2344 tool steel, which is preferred as a mold material in hot runner molds and bakelite molds in plastic production and shaping enterprises, is widely preferred in the mold field [1]. It is a tool steel with high mechanical properties and wear resistance as a result of its resistance to high temperatures. It is very good in terms of toughness and thermal stability. It is also preferred in the defense industry sector due to its high wear resistance. For this reason, this material must have high wear and toughness values. In addition to traditional heat treatment, it is known in the literature that cryogenic treatment applied to the material has a positive effect on the material. However, in the studies conducted, it has been observed that the effect of shallow and deep cryogenic treatment on wear and toughness values is not sufficient. For this purpose, it is aimed to apply shallow and deep cryogenic processes at different holding times to DIN 1.2344 hot work tool steel and to have a positive effect on mechanical properties. In this

way, it is foreseen to increase the mechanical properties of DIN 1.2344 hot work tool steel used in industry and defense industry and to reduce costs. DIN 1.2344 tool steel is one of the most widely used steels in the tool, mold and die industry due to the superior mechanical behavior of the material especially in production processes at high temperatures ranging from 200 °C to 800 °C [2–4].

In addition, the mechanical properties of DIN 1.2344 tool steel can be improved through microstructural changes caused by conventional heat treatments, usually hardening and tempering [5]. When subjected to hardening with conventional heat treatment, it reaches 50 to 54 HRC hardness values [6]. After hardening, it is subjected to annealing processes to change its structure and adjust its mechanical properties [5,7]. CHT hot work tool steels reveal microstructures formed by thin martensite laths with dispersed carbides [8,9]. In this study, it is aimed to improve the mechanical properties of the material with the effect of shallow and deep cryogenic treatment, which is waited for different periods after conventional heat treatment. Cryogenic treatment provides significant improvements in tool steels in terms of increased hardness and tensile strength, increased wear resistance, more impact toughness,

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lower brittleness, lower residual stresses and higher thermal stability [10,11]. While improvements in tool life were recorded as 44–126% and 301% [12,13], it was stated that M2 HSS tool steels provided 56–87% improvement in wear rate [14]. Similarly, studies have been conducted in the literature on AISI H13 and Vanadis 6 type tool steels indicating improvements in wear rate by 16–25% [15] and 24% [16]. However, the microstructural mechanisms responsible for these improvements are not yet fully understood and it is known that further research is needed [13]. Some of the common mechanisms discussed in most of the literature are the complete transformation of retained austenite to martensite, precipitation of tertiary carbides (ETA carbides) and uniform distribution in the martensitic matrix and formation of a denser molecular structure. Jovicevic-Klug et al. studied the comparison of Böhler K340 cold work tool steel microstructure and mechanical properties using shallow and deep cryogenic treatment. SCT and DCT are effective methods in lowering RA presence within the matrix by 71% and 82%, accordingly. SCT and DCT groups have finer martensitic laths, which are oriented along [101] and [001]. The martensitic laths are finer by 21% and 33% with SCT and DCT, respectively. SCT and DCT influence the carbide precipitation of $M_{23}C_6$ (5% by SCT and 35% by DCT) and M_7C_3 (50% by SCT and 70% by DCT) carbide groups and also reduce the formation of transient carbide group (M_3C_2), which is directly linked to the cryogenic temperatures. Impact toughness was increased by both cryogenic treatments by more than 100% (by SCT 113% and by DCT 100%) [17].

In this study, the effects of shallow and deep cryogenic treatment on the mechanical properties of the material were investigated by performing hardness, tensile, impact and wear tests. In addition, microstructure and phase analysis were performed to determine the effects on carbide distribution after shallow and deep cryogenic treatment applied at different waiting times. Additionally, the surface and microstructures of DIN 1.2344 tool steel after wear were investigated.

2. Material and methods

In this study, impact, tensile and wear tests were performed on materials subjected to shallow and deep cryogenic treatment after conventional heat treatment. In addition, metallographic examination, hardness tests and microstructure, micro and macro hardness changes were investigated. The chemical composition of the material used in the experiments is given in Table 1. Material chemical analysis was performed with OXFORD Foundry Master – X line brand spectrometer device.

The graph showing the heat treatment process of the samples is given in Fig. 1. As seen in the graph, the temperature was reached by gradually increasing it by 10 °C/min and heating it for 2 h and 45 min at 300 °C, 600 °C and 850 °C with a waiting time of 20 min, and reaching 1020 °C. After cooling with nitrogen gas, the desired hardness values were obtained in the samples by tempering twice.

In the samples to which cryogenic treatment was applied after conventional heat treatment; the samples held at –80 °C for 12 h were named as SCT-12, the samples held at –80 °C for 24 h were named as SCT-24 and the samples held at –180 °C for 36 h were named as DCT-36. Nitrogen gas was continuously fed during the cooling process. Cryogenic treatment was applied in the MMD cooling furnace shown in Fig. 2.

Macro and micro hardness measurements were made on the prepared samples. Disk samples with a diameter of 10 mm and a height of 10 mm were used in the measurements. In the hardness measurements, the average of at least 5 measurement results from each sample group was taken. Macro and micro hardness values were measured on a

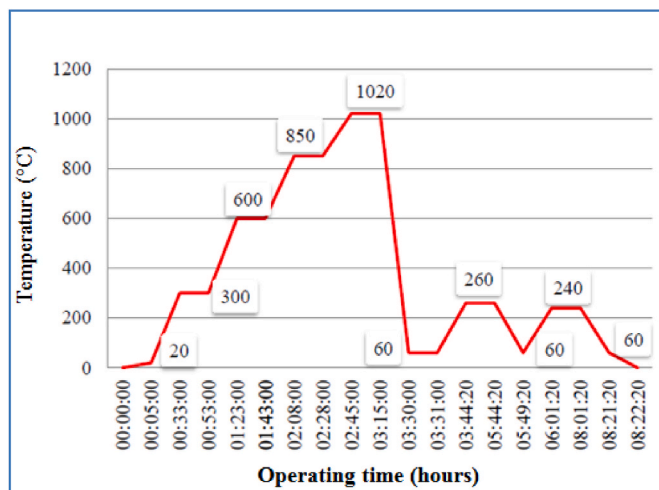


Fig. 1. Conventional heat treatment curve.

NOVOTEST brand hardness measuring device. Macro hardnesses were measured using the Rockwell (HRC) method. Measurements were made by applying a 200 g load for 10 s to the micro hardness values. In the study, an impact test was applied to the samples to examine the effect of fracture with dynamic strain on the mechanical properties of the samples after cryogenic treatment. In the test, a 150 J impact was applied to the sample with a hammer. JB-W300A brand impact testing device was used for the impact test.

Tensile test was applied to the samples to examine the changes in tensile, elongation and yield values of the material after cryogenic treatment. The test was carried out with a tensile speed of 10 mm/min. The tensile test was carried out with an INSTRON 3382 brand 100 kN capacity tensile device. TRD brand wear device was used for wear test. Disk samples with 10 mm diameter and 10 mm height were used in the experiments. Each group of materials was measured with a 0.001 precision scale before and after wear. Specific wear losses were determined according to the measurement results by averaging the values taken for each sample. The test was carried out under dry conditions, at room temperature, under 20 N load, at 1 m/s sliding speed. Wear tests were carried out at 1000 m and 2000 m distances. The formula in Equation (1) was used to calculate the wear rate.

$$\text{Wear rate} = \text{Wear volume} / (\text{Load Amount} \times \text{Distance}), \text{mm}^3/\text{Nm} \quad (1)$$

One 10 × 8 mm sample was prepared for each type of heat treatment for use in the microstructure studies. After conventional heat treatment, SCT-12, SCT-24 and DCT-36 samples sanding with 120, 240, 600, 800 and 1200 grit SiC sand paper was carried out on the samples and they were then polished in the sample shaver for about 5 min. They were then examined by optical microscopy and prepared for scanning electron microscopy (SEM) imaging with 2% Nital (98 mL of ethyl alcohol, 2 g of nitric acid). To determine the percentage ratios of carbides in the microstructure, drawings were made on the images in the CAD program. As seen in Fig. 3, geometric drawings of all carbides were made. Then, the percentage ratios of carbides were determined by area calculation.

Table 1
Chemical composition of test samples (%).

Element (%)	C	Si	Mn	Cr	Mo	V
Standard	0.35–0.42	0.8–1.2	0.25–0.50	4.80–5.50	1.20–1.50	0.85–1.15
Measured	0.38	0.92	0.33	4.87	1.28	0.98

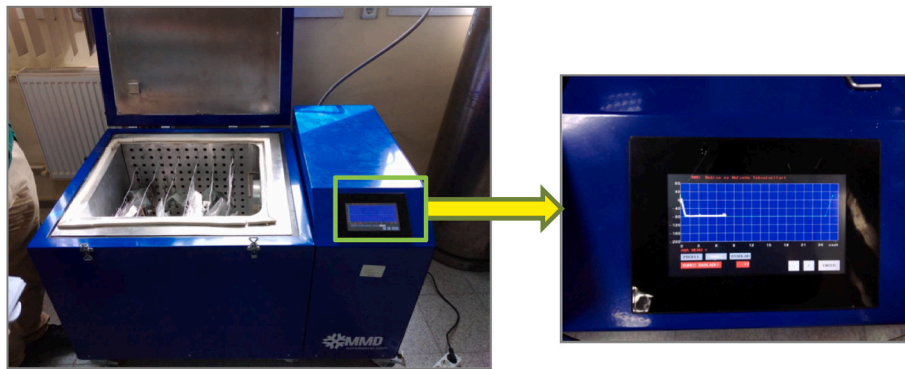


Fig. 2. Shallow and deep cryogenic treatment device.

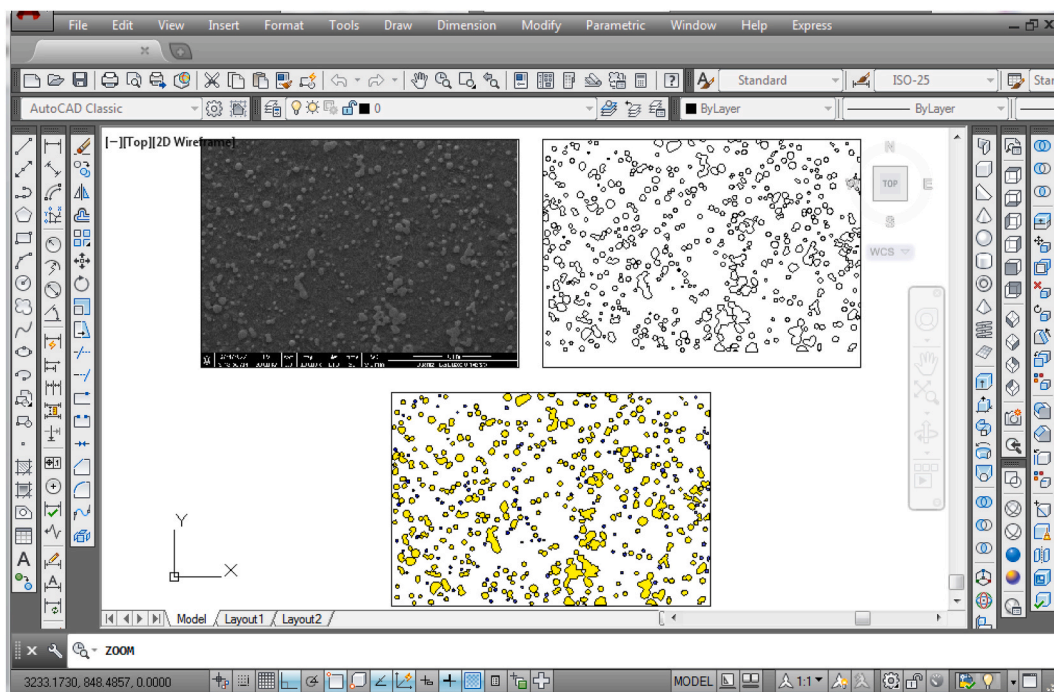


Fig. 3. Geometric drawings of carbides in CAD program.

3. Results and discussion

3.1. Evaluation of microstructure analyses

As a result of heating the DIN 1.2344 tool steel, the dispersion of the iron atoms causes the carbon atoms in the steel to form a solid solution to fill larger gaps. This carbon-rich iron solid solution is called austenite. The austenite structure has a cubic structure. This phase dissolves 2% carbon at 1147 °C [18]. After the heating process, the steel cools slowly and the carbons in the austenite phase undergo diffusion and dissolve and separate from the austenite structure. In the continuation of this situation, the iron atoms are mobilized and the α phase is formed. When the cooling rate increases, the carbon atoms cannot undergo diffusion and remain in the solution, causing a different structure. This structure formed due to the rapid cooling is called martensite. The martensite structure is known to be a hard phase. The reason for the hardness is stated as the distortion experienced during the transformation [19].

It is known that there is residual austenite in the microstructure after conventional heat treatment due to the C element in tool steels [20]. In cryogenic treatment applications, this situation causes the decrease of residual austenite with martensite transformation. After cryogenic

treatment, small-sized carbides are formed in the microstructure and homogeneous distributions are seen. Due to the change in the lattice structure in the martensite structure with conventional heat treatment, carbon atoms can move to the area where dislocations are intense. Carbides are formed in these areas with the applied tempering process. The main carbide types seen in the microstructure of tool steels are shown in Table 2 together with their properties [21].

When hot work tool steels are cryogenically treated, it is observed that less stable carbides are transformed into highly stable carbides [22].

Table 2
Types of carbides seen in hot work tool steels [21].

Types of Carbide	Elements That Form Carbide	Crystal Structure	Geometry
MC	V (dominant), W, Mo, Cr	Face-centered cubic	Agglomerated
M ₂ C	Mo, W (dominant), V, Cr	Hexagonal	Acicular
M ₆ C	Mo, W (dominant), V	Face-centered cubic	Lamellar
M ₇ C ₃	Cr (dominant), V, Mo, Fe	Hexagonal	Lamellar
M ₂₃ C ₆	Cr (dominant), V, Mo, Fe	Cubic (complex)	Lamellar

The carbide structure generally changes in its chemical structure as a result of tempering. Energy increases with increasing temperature and carbides cluster to form a stable structure. While it is known that the largest dimensional carbides are $M_{23}C_6$ (0.15–0.30 μm) and M_7C_3 (0.10–0.18 μm) carbides, there are also smaller M_6C , M_2C and MC (0.07–0.12 μm) carbides [23].

Figs. 4–7 show SEM images and EDAX graphs of CHT, SCT-12, SCT-24 and DCT-36 samples, respectively. In the microstructure examination, it was observed that Cr, Mo and W elements were generally dominant in the structure of the carbides formed in the CHT sample. In terms of their crystal structures, they were defined as hexagonal and face-centered cubic M_6C - M_2C carbides. In the EDAX graph where Cr, V, W, Mo and Fe elements are present in SCT-12 and SCT-24 samples, it is seen that W and Mo elements forming the main carbide are dominant. In the samples to which shallow cryogenic treatment was applied, secondary carbides were formed and the M_2C phase in hexagonal structure was present. In the DCT-36 sample, secondary carbide formation was

observed with small carbides formed in the microstructure. When EDAX is examined, it is observed that high density of Mo-rich M_2C carbides are observed in the interior of the martensite laths, while smaller V-rich MC carbides are dominant.

Fig. 8 shows the SEM image of the microstructure of the samples subjected to cryogenic treatment. When the microstructure is examined, it is seen that hexagonal and face-centered cubic structured M_6C – M_2C carbides are formed in the CHT sample. It is observed that martensite structure is formed in the samples subjected to cryogenic treatment. Surface cubic centered M_2C and MC phases have emerged with the cryogenic treatment. These carbide types have been associated with the dominance of V and W elements in it by EDAX. When examined compared to the CHT sample, it has been observed that the small structured MC type carbides in the microstructure of the DCT-36 sample have increased and have a homogeneous structure. The formation of this situation has been attributed to carbide precipitation. Zhang et al. (2021) determined that the microstructure of the annealed material

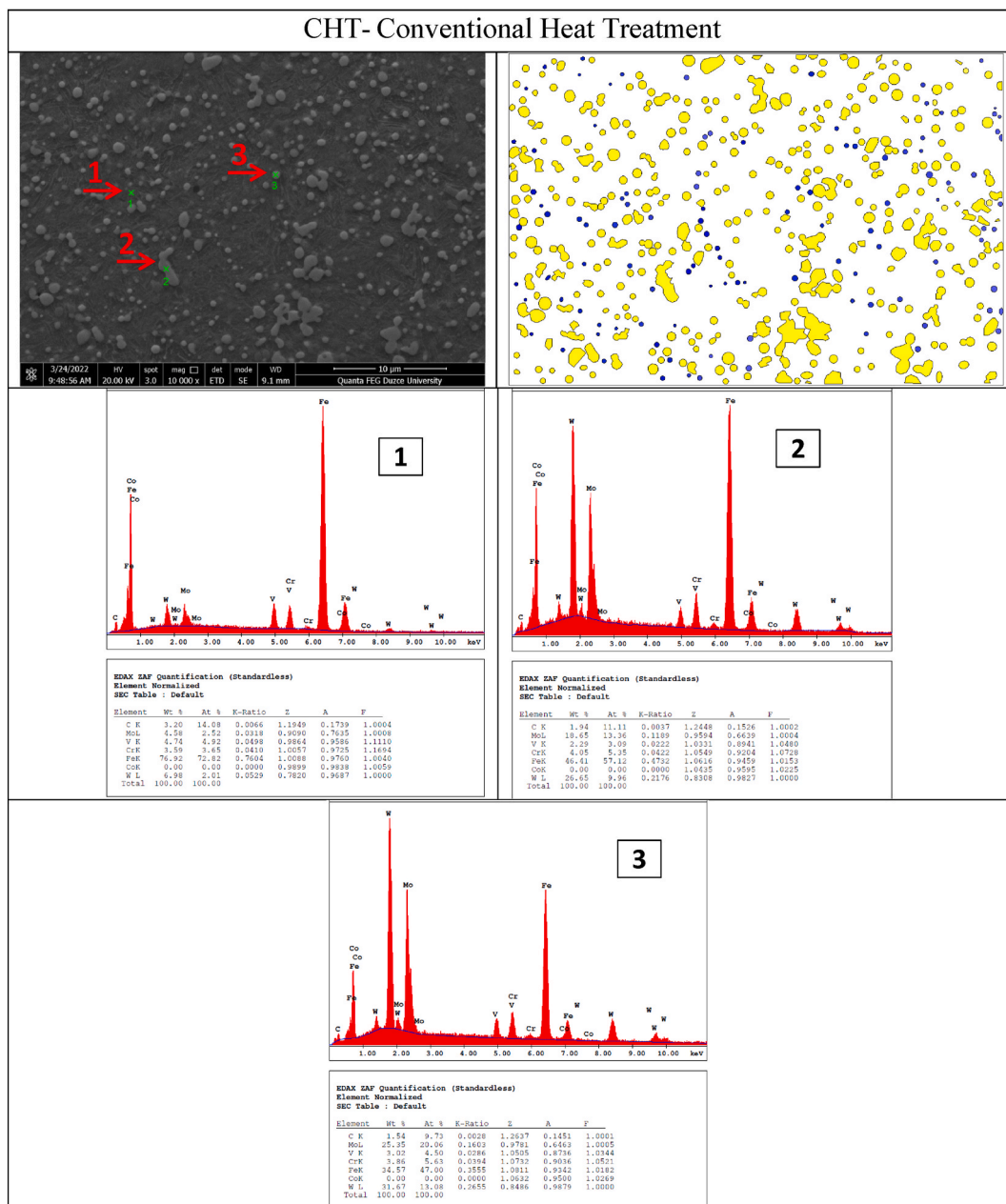


Fig. 4. SEM-EDX analysis of the microstructure of the CHT sample.

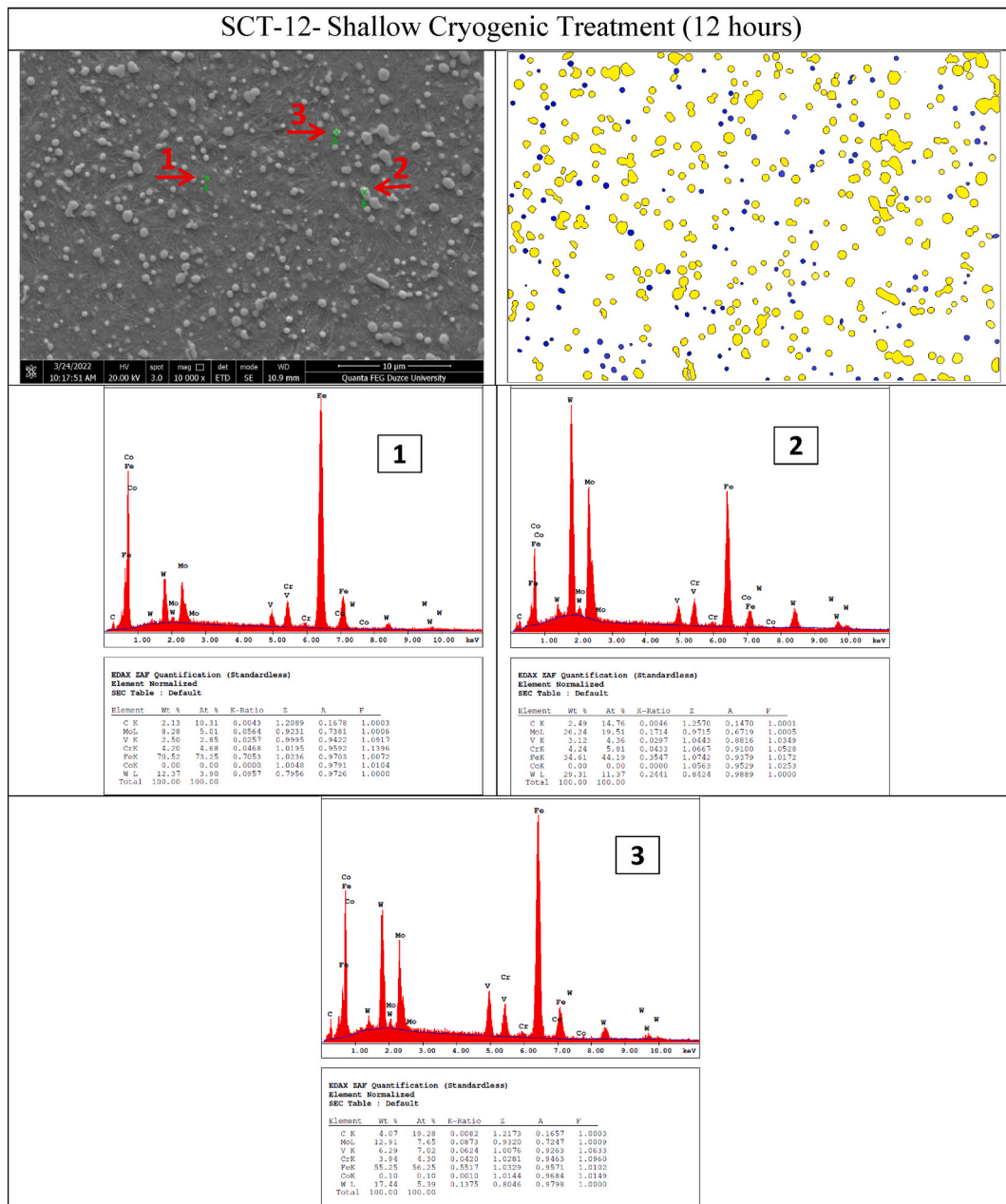


Fig. 5. SEM-EDX analysis of the microstructure of the SCT-12 sample.

developed $M_{23}C_6$ (0.15–0.30 μm), M_7C_3 (0.10–0.18 μm) and MC (0.07–0.10 μm) carbide species [21].

In Figs. 4–7, geometric drawings of carbides in the microstructure are also given with the help of CAD program. The areas of carbides drawn in CAD program are also calculated and given along with EDX analysis images. EDX analyzes in Figs. 4–7 confirmed the carbide types marked in Fig. 8. Percentage ratios of M_2C/M_6C carbides (yellow color) were found as 13.13, 8.80, 9.67 and 9.38 for CHT, SCT-12, SCT-24 and DCT-36 samples, respectively. The percentage ratios of MC carbides shown in dark blue color were found to be 0.85, 0.95, 1.26 and 1.55 for CHT, SCT-12, SCT-24 and DCT-36 samples, respectively. These results confirmed that the second carbide precipitation occurred after cryogenic treatment. It was also observed that the area of the white regions outside the yellow and dark blue color increased after cryogenic treatment. This is associated with the transformation of residual austenite to martensite and the increase in the ratio of martensite lamellae [24].

When Fig. 8 are examined, it is seen that the iron element is the

highest element. High amount of Mo element follows Fe element as a result of the analysis. Cr and V elements are seen in small amounts. Iron element exhibited a decreasing graph depending on the waiting time. This situation was determined that iron element decreased by 13.56% in the sample kept for 24 h compared to 12 h waiting time at -80°C . In the microstructure examination made after cryogenic treatment, it was seen that secondary carbides were formed and M_6C , M_2C , MC carbides were present. It was seen that smaller structured carbides were formed with cryogenic treatment and they were distributed homogeneously. This was attributed to the second carbide precipitation, austenite martensite transformation and formation of new carbides after cryogenic treatment [25]. Zhang et al. applied deep cryogenic treatment to AISI H13 hot work tool steel with a hardness of 50 HRC for 24 h. Fig. 9 shows the TEM images of Zhang et al.'s study showing the austenite martensite transformation after cryogenic treatment [26]. The lath martensite and a thin film retained austenite were observed in samples subjected to Q + T, as shown in Fig. 9(a). Fig. 9(b) reveals that the crystal plane (110) of

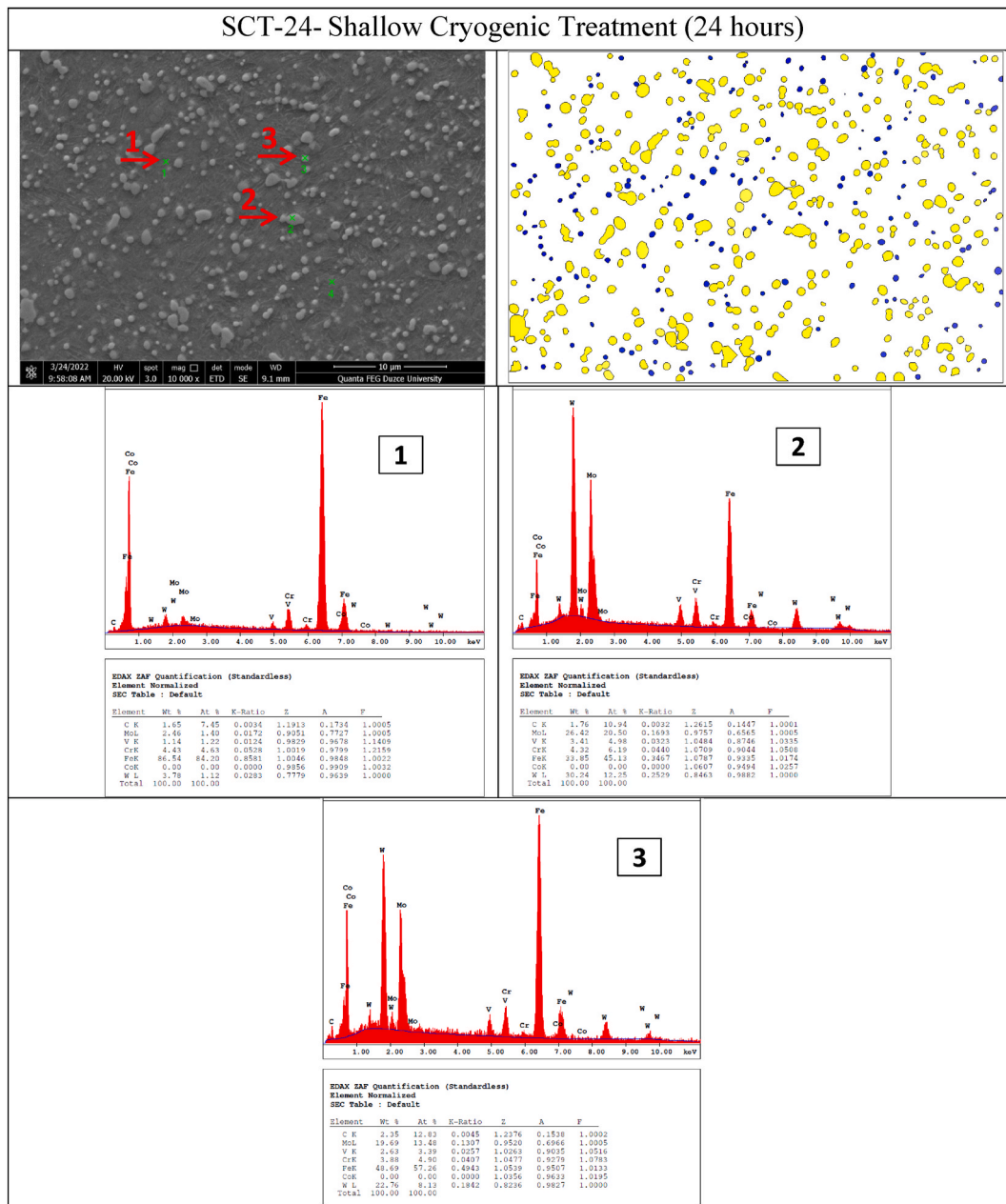


Fig. 6. SEM-EDX analysis of the microstructure of the SCT-24 sample.

martensite aligns parallel to (111) of retained austenite, confirming adherence to the Kurdjumov-Sachs (K-S) relationship. Fig. 9(c)&(d) elaborate on the microstructure and diffraction spots of the specimens subjected to DCT + T. Even after DCT, it is evident that the retained austenite remains, indicating incomplete transformation. The small layer of preserved austenite between the martensite laths is thought to have been challenging to change. The explanation is that at low temperatures, lattice shrinkage causes the carbon atoms to diffuse into the retained austenite, increasing the retained austenite's carbon content. As a result, the austenite that was kept was comparatively stabilized and brought back to room temperature. The transition of retained austenite was hindered by this stage, which was often known as the thermal stability of austenite [26].

3.2. Evaluation of macro and micro hardness

Hardness tests are preferred more in defining mechanical properties

because they are simple and less destructive compared to other tests. It is easier to interpret mechanical properties in a material with a known hardness value. Hardness value is an important factor affecting other tests. In tests such as abrasion, tensile, impact, material hardness affects the result in parallel or inversely.

Macro and micro hardness values of conventional heat treated samples and cryogenically treated samples are shown in Fig. 10. When hardness values are examined, it is seen that the highest values are listed as DCT-36, SCT-24, SCT-12. The highest hardness increase after cryogenic treatment in DIN 1.2344 tool steel was seen in DCT-36 sample at a rate of 1.79%. This situation is explained by the transformation of the soft phase austenite in the DIN 1.2344 tool steel into a harder phase martensite structure after cryogenic treatment [27–29]. Yi et al. (2013) reported that there was a 22% increase in hardness after deep cryogenic treatment [29]. In another study, Altan Özbek and Özbek (2022) obtained an improvement of approximately 11.75% in hardness values after deep cryogenic treatment applied to Sverker 21 tool steel [30].

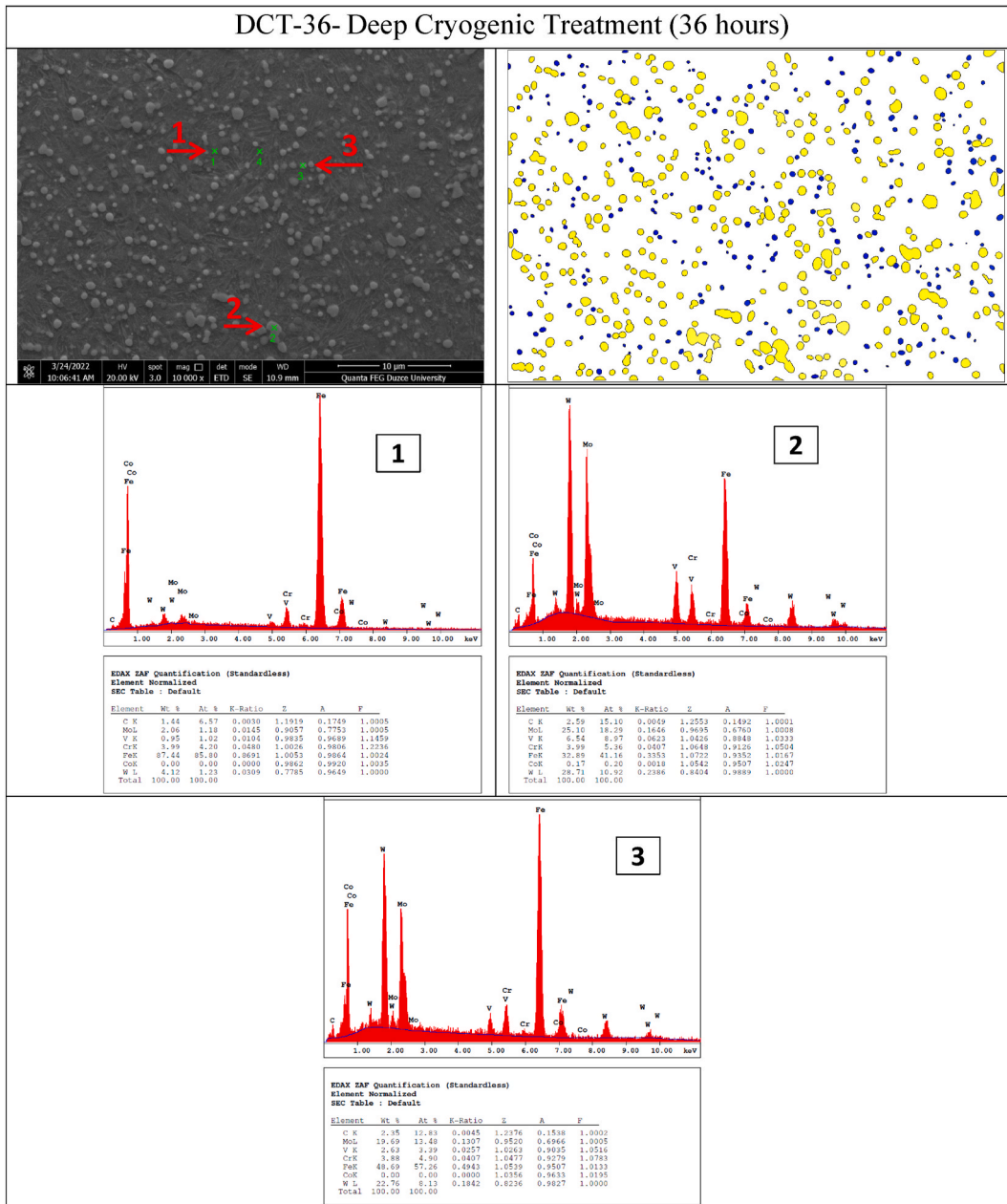


Fig. 7. SEM-EDX analysis of the microstructure of the DCT-36 sample.

According to the results obtained, it is seen that the results obtained in the literature are in parallel direction. It was seen that the highest hardness value after cryogenic treatment was 56.6 Hrc in the DCT-36 sample. It is also seen that there is an increase in SCT samples compared to conventional heat treatment. The result is related to the transformation of austenite in the microstructure into martensite after cryogenic treatment.

According to the microhardness results, the highest hardness value was observed to be the DCT-36 sample with a value of 713.9 HV. In other samples, the average microhardness values of SCT-24, SCT-12 and CHT samples were ranked from highest to lowest at 699.7 HV, 690.7 and 678.8 HV, respectively. When the results are examined, the change rates in microhardness values are parallel to the macrohardness values. The DCT-36 sample has the highest hardness value with a 5.17% improvement rate in microhardness value as in macrohardness.

3.3. Evaluation of impact resistance

Cryogenic treatment significantly affects the impact resistance of materials [31]. In order to examine the effect of cryogenic treatment on the mechanical properties of DIN 1.2344 tool steel, impact tests were applied to 4 different samples. The average values of the results obtained by applying the impact test 3 times to each sample were taken. The impact resistance results of the samples are given in Fig. 11.

Impact energy values are 38.9 J, 38.3 J, 38.1 J and 38 J, respectively, in DCT-36, SCT-24, SCT-12 and CHT samples, ranked from largest to smallest. It is seen that DCT-36 sample has the highest fracture energy. It is seen that there is a 2.37% improvement in the cryogenically treated DCT-36 sample compared to the conventionally heat treated sample. As can be understood from the graph, it was determined that there was an improvement in the impact strength of the cryogenically treated samples compared to the conventionally heat treated sample. In their study, Çakır and Çelik determined that there was an improvement in impact

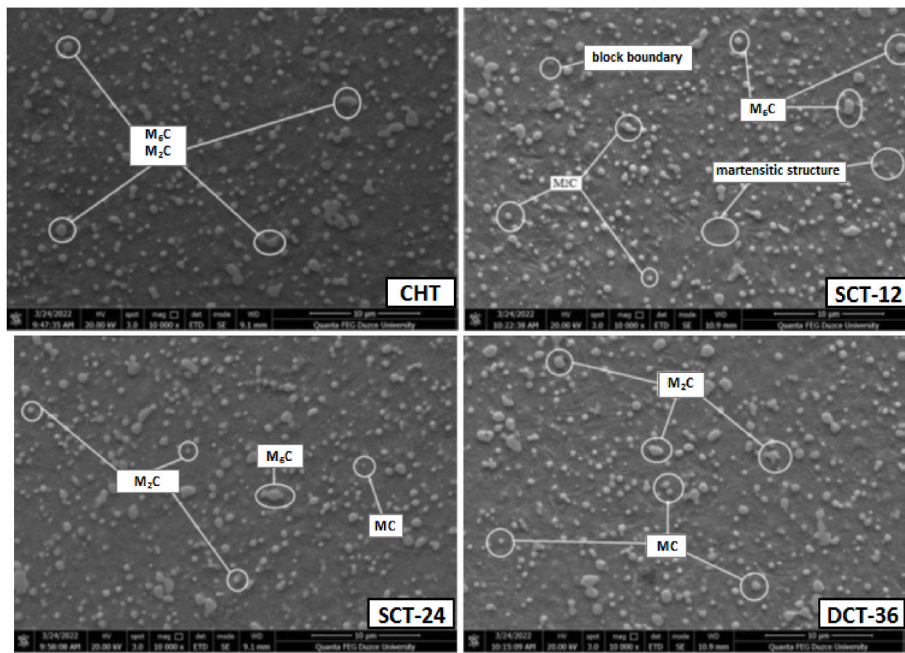


Fig. 8. Microstructure images showing carbide types.

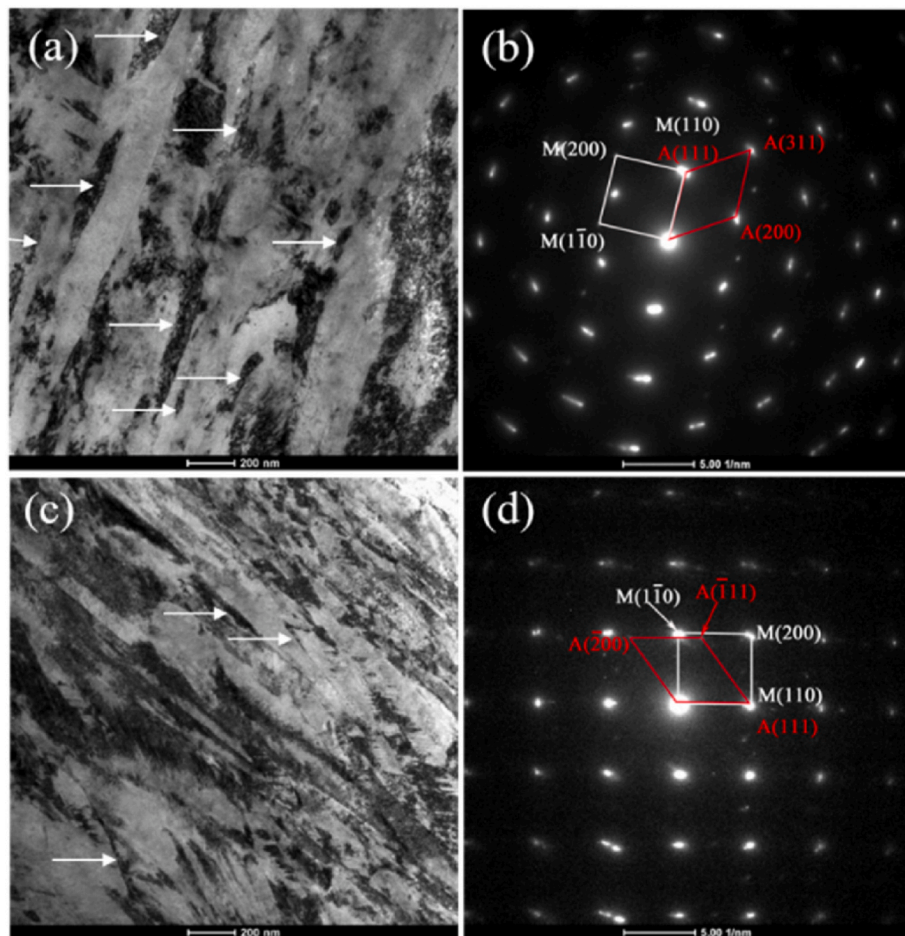


Fig. 9. TEM of the retained austenite between martensite laths after different heat treatments: (a) Microstructure of Q + T; (b) diffraction patterns of the retained austenite and martensite after Q + T; (c) Microstructure of DCT + T; (d) diffraction patterns of the retained austenite and martensite after DCT + T [26].

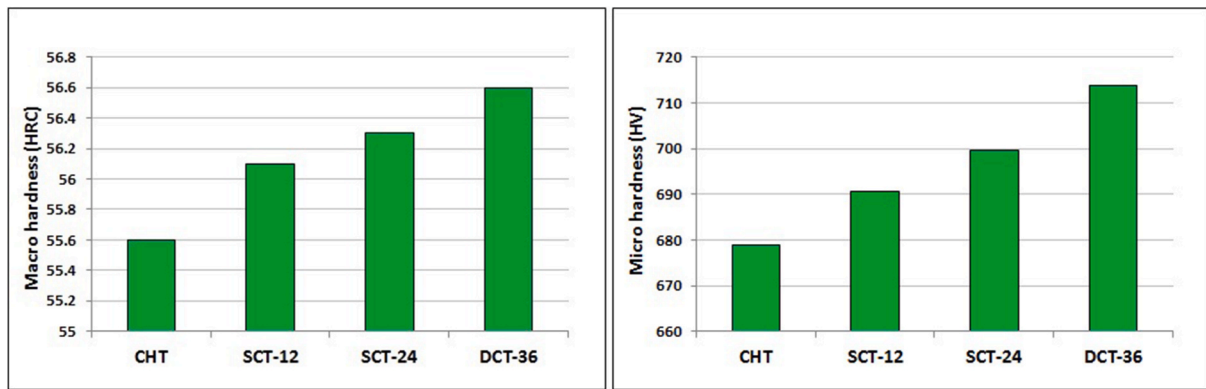


Fig. 10. Change in macro and micro hardness values.

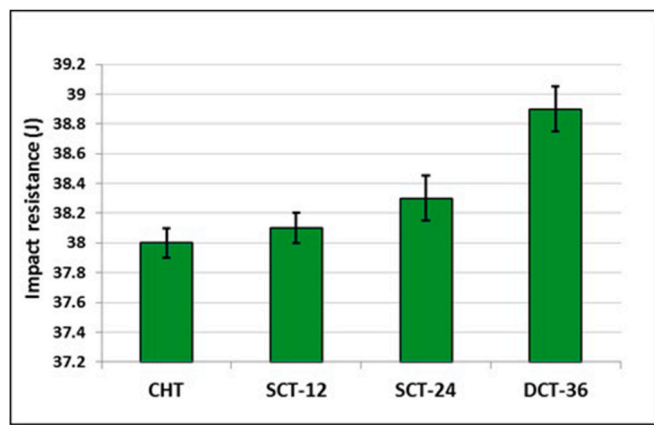


Fig. 11. Impact strength of samples.

resistance as a result of the deep cryogenic treatment applied to the high-speed-train railway material during the 36-h waiting period [32].

3.4. Evaluation of tensile strength

In the studies, it is observed that there are improvements in the mechanical properties of the materials after cryogenic treatment [33, 34]. Tensile tests were applied to four different samples to investigate the effect of cryogenic treatment on the mechanical properties of DIN 1.2344 tool steel. The average values of the tests repeated three times for each sample were taken. The tensile test results and tensile diagram of each grouped sample were given in Fig. 12 and Table 3. The improvement rates in yield strength were determined as 24.73%, 19.14%, 3.76% in DCT-36, SCT-24, SCT-12 samples, starting from the highest value. The highest tensile strength and yield strength were observed in DCT-36 sample. As mentioned before, this situation is related to the transformation from austenite structure to martensite structure. With the martensite structure formed after cryogenic treatment, homogeneous distribution of carbide grains and decrease in toughness, improvements were provided in yield and maximum tensile strengths [34,35]. An increase in yield and tensile strengths was observed in SCT and DCT samples as a result of the increase in hardness after cryogenic treatment compared to CHT sample.

A graph is seen in the opposite direction of yield and tensile strength in the elongation amounts. The elongation amount is related to the ductility and brittleness of the material. When the elongation amounts between the samples are examined, if the order is made from the lowest value, it is seen as DCT-36, SCT-24, SCT-12 and CHT, respectively. The CHT sample has elongated more than the DCT-36 sample due to its more ductile and brittle structure. It is known that residual austenites are

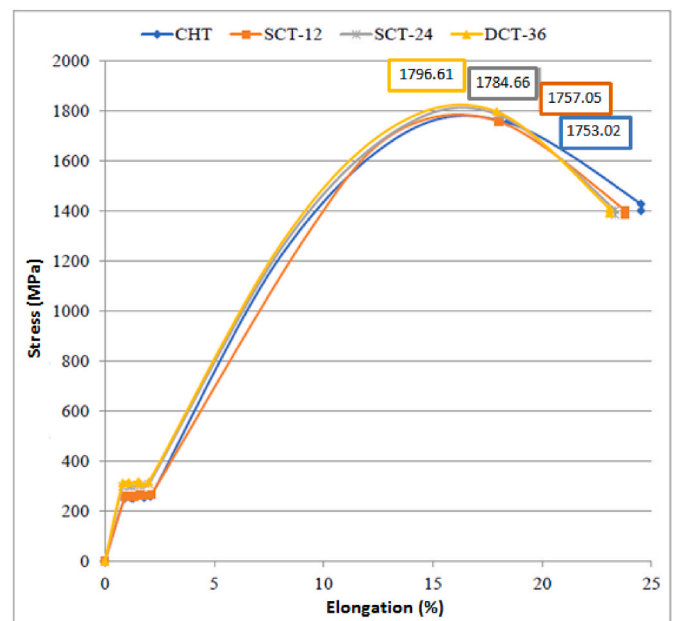


Fig. 12. Stress strain diagram.

Table 3

Results of tensile tests at room temperature for DIN 1.2344 steel.

Samples	Yield strength (MPa)	Maximum tensile strength (MPa)	Elongation (%)
CHT	250.46	1753.02	24.52
SCT-12	259.87	1757.05	23.79
SCT-24	298.4	1784.66	23.34
DCT-36	312.4	1796.61	23.08

formed during the transformation of austenite in the microstructure to martensite in steels where the temperature value is rapidly reduced. As a result of the decrease in the austenite volume, the ductility property decreased in the DCT-36 sample in relation to the transformation to martensite structure and it broke with less elongation compared to the other samples. It has been recorded that the martensite structure is less ductile than austenite and has a higher tensile strength [36]. It was determined that the cryogenic treatment applied to N52 and 21-4 N valve steels resulted in an improvement in tensile strength of 7.84% and 11.87%, respectively, and a decrease in elongation [37]. Parallel results were observed between this study and literature studies [34,35].

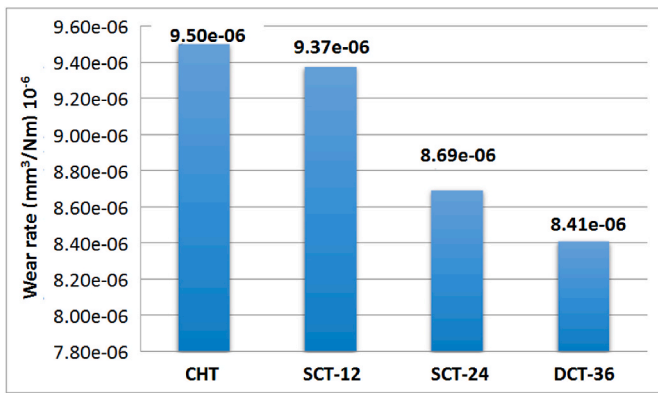


Fig. 13. Wear rates.

3.5. Evaluation of wear performance

In Fig. 13, the wear rates calculated depending on the wear losses obtained after the wear test are given. It is observed that the wear rate decreases with the increase in the hardness ratio of the materials after the cryogenic treatment. The wear rate decreases from shallow cryogenic treatment to deep cryogenic treatment in the cryogenically treated sample. Das et al. 2009 determined an increase in wear resistance as a result of the deep cryogenic treatment applied on AISI D2 steel. The best result was obtained with the cryogenic treatment applied in 36 h of waiting time [38].

In Fig. 14, the friction coefficients formed on the surfaces of the samples subjected to abrasion test under 20 N load are given. The friction coefficients of the samples were determined as 0.51, 0.54, 0.58 and 0.59 for DCT-36, SCT-24, SCT-12 and CHT, respectively, from smallest to largest. It is seen that the highest friction coefficient among these values is in the CHT sample. It is seen that the friction coefficient is parallel to the hardness values. It was determined that the wear rate improved by 1.34%, 9.31% and 13% in the SCT-12, SCT-24 and DCT-36 samples, respectively. The relationship between the wear rate and hardness is similar to the studies in the literature [39].

Fig. 15 shows the weight losses of the samples after 1000 and 2000 m after the wear test. According to the wear losses, it is seen that the wear volume loss is less in the cryogenically treated sample due to the resistance. Accordingly, the samples with the highest wear loss were determined as CHT, SCT-12, SCT-24 and DCT-36, respectively. Wear loss in the DCT-36 sample improved by 0.02% at 2000 m distance compared to the conventionally heat-treated sample. In their study, Yildiz and Altan Ozbek applied deep cryogenic treatment to X17CrNi16-2 martensitic stainless steel for 12, 18 and 36 h, and the highest mechanical properties

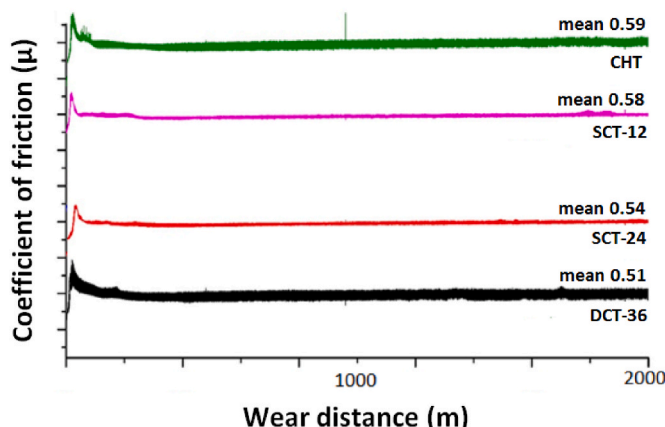


Fig. 14. Friction coefficients for 20 N.

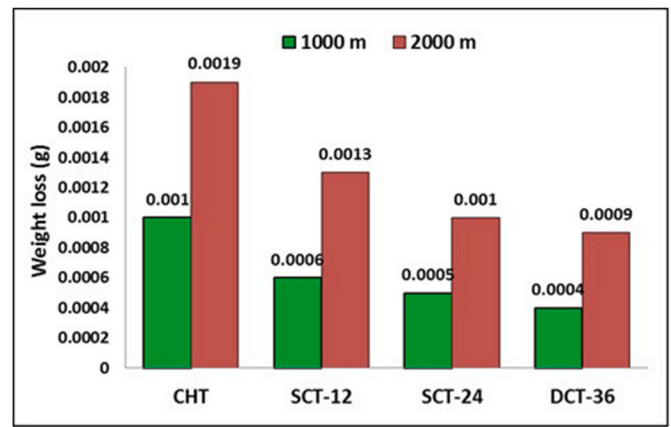


Fig. 15. Weight losses resulting from wear tests.

were obtained with the longest holding time of 36 h of cryogenic treatment. Compared to the CHT sample, the DCT36 sample has a higher microhardness, tensile strength and yield strength of approximately 5.87%, 1.87% and 8.17%, respectively, and has 88% less wear rate [40]. This situation was associated with the martensite structure formed after cryogenic treatment providing improvement against wear resistance.

Surface profiles were measured in different directions and wear areas were calculated. Three-dimensional scanning device images of the wear areas of CHT and SCT-12, SCT-24 and DCT-36 samples are given in Fig. 16. Three-dimensional images of the surface wear areas of the samples subjected to abrasion test with 20 N load of CHT, SCT-12, SCT-24 and DCT-36 samples were taken. When the wear areas are examined, it is seen that the highest value belongs to the CHT sample. As a result of the test, the surface values (Ra) obtained as a result of wear were measured and the highest surface Ra value was obtained in the CHT sample. The Ra values were measured as 0.07, 0.072, 0.086, 0.090 in DCT-36, SCT-24, SCT-12 and CHT samples, respectively. It was determined that the surface quality was improved with the cryogenic treatment application. Fig. 16 shows the line EDAX images taken from the worn surfaces. In the wear test, the elements on the surface are displaced or broken with friction. For this reason, the element line between the non-worn surface and the worn surface was examined. As a result of the analysis, it is seen that the line belonging to the elements C, O, Mo and V increases during the transition from normal surfaces to the worn surface. Although the C and O amounts show a low increase as a result of the analysis of the CHT and SCT-12 samples, significant increases are seen in the SCT-24 and DCT-36 samples.

It is observed that wear losses decrease depending on hardness in cryogenically treated samples. This situation shows similar results with the deformation formed in SEM images of the wear surfaces. It is observed that the deformation in the CHT sample, which has a softer structure, is higher in the SEM image. After wear, there is burr smearing on the surface of the CHT sample and this shows that the material has a softer structure than the other samples. Similarly, the homogeneous image formed in the DCT-36 sample is attributed to the homogeneity of the carbide distribution in the microstructure. The carbides formed as a result of the element distribution analysis lead to a decrease in other elements in the microstructure. The increasing amount of carbide with the cryogenic process caused the other elements to change in the direction of decrease as seen in the element distribution analysis results.

4. Conclusions

In this study, the effects of shallow and deep cryogenic treatment on wear and impact performance of X40CrMoV5 1 hot work tool steel were investigated. In addition, the effects on mechanical properties and microstructure were investigated with different holding times (12 and

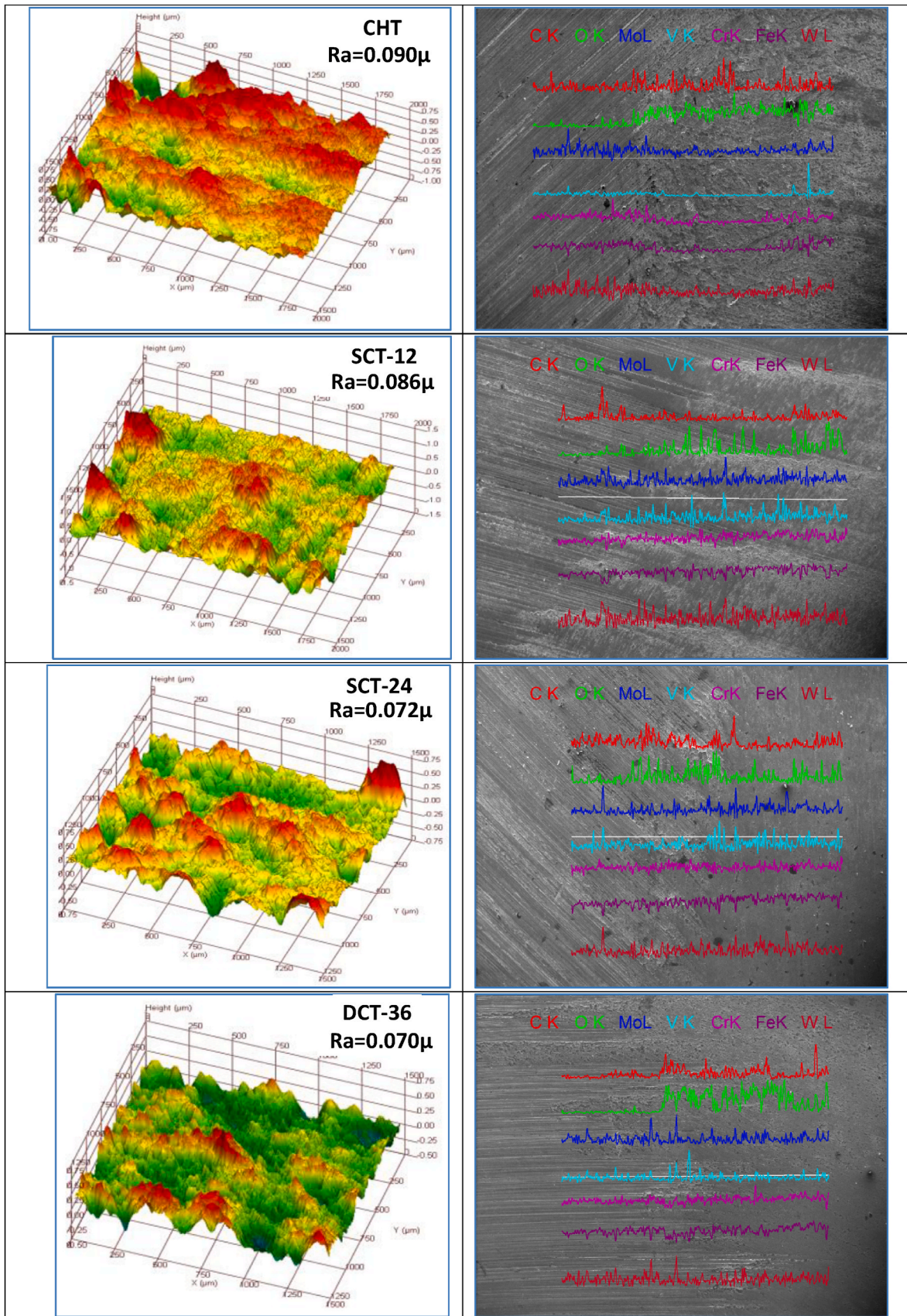


Fig. 16. 3D profilometer images and element distribution analysis for worn surfaces.

24 h, -80°C) and deep cryogenic treatment (36 h -180°C) applications in shallow cryogenic treatment. Based on the experimental results, the following conclusions were drawn.

- In microstructure analysis, it was determined that cryogenically treated samples gave better results than CHT sample. Martensite formation was also seen in the microstructure. After cryogenic treatment, M_2C and MC carbides rich in V and W elements were present compared to M_7C_3 carbides rich in Cr. DCT-36 sample, which has a homogeneous structure with secondary carbide precipitations, was determined as the sample showing the best microstructure properties.
- According to both macro and micro hardness results, the highest hardness values were obtained in DCT-36, SCT-24, SCT-12 and CHT samples, respectively. The DCT-36 sample with the highest hardness due to cryogenic treatment exhibited 1.79 and 5.17% improvement for macro and micro hardness, respectively.
- Impact energy values are 38.9 J, 38.3 J, 38.1 J and 38 J, respectively, in DCT-36, SCT-24, SCT-12 and CHT samples, ranked from largest to smallest. It is seen that DCT-36 sample has the highest fracture energy. It is seen that there is a 2.37% improvement in the cryogenically treated DCT-36 sample compared to the CHT sample.
- The DCT-36 sample exhibited the highest improvement in tensile test results as well as in hardness and impact strength. Compared with the CHT sample, for the DCT-36 sample, 24.73% and 2.45% improvement in yield strength and tensile strength were obtained, respectively.
- In the wear test, it was determined that the wear resistance increased in cryogenically treated samples. Shallow cryogenically treated samples showed 1.34% and 9.31% improvement, respectively, compared to the conventional heat treated sample. The DCT-36 sample provided the highest improvement of 13%. Wear rates were determined from lowest to highest as DCT-36, SCT-24, SCT-12 and CHT. Wear resistance and hardness values exhibited parallel results after cryogenic treatment.

As a result, the study showed that shallow cryogenic treatment and deep cryogenic treatment at different holding times improved the mechanical properties (macro-micro hardness, tensile performance, impact strength, wear performance) and microstructure of DIN 1.2344 hot work tool steel.

Declaration of competing interest

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

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