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EFFECTS OF HOT ROLLING ON MICROSTRUCTURES, WEAR AND CORROSION RESISTANCE OF Mo-Ni-W P/M ALLOYED STEELS

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Abstract

This study analyzes how hot rolling changes microstructure, tensile strength, wear, and corrosion behavior of Fe-0.55C-3Mo-10Ni-0.5W alloy steel. The metal powders were pressed at 750 MPa pressure, and the cold-pressed samples were sintered for two hours at 5°C/min up to 1400°C in a mixed-gas environment of 90% nitrogen and 10% hydrogen. The steels produced were then hot rolled at 40% and 80% deformation rate. The microstructures demonstrate that MoC(N), WC(N), and MoWC(N) were produced and that the steels exhibited finer microstructures and better mechanical properties as the deformation rate increased. Wear decreased as the deformation rate increased. Furthermore, the the hot rolling method improved the corrosion resistance, as shown by the Tafel curve analysis. The greatest factor supporting the corrosion resistance was the increase in density value throughout the rolling process.

Keywords: *Hot rolling; Powder metallurgy; Characterization; Alloy steels; Wear; Corrosion*

1. Introduction

The performance of materials under varying environmental conditions is becoming increasingly critical due to advancements in science and technology. Alloyed steels are renowned for their exceptional weldability, durability, toughness, and corrosion resistance, achieved through various strengthening mechanisms and thermomechanical techniques [1]. While steels contain carbon, the addition of alloying elements such as Mo, Ni, W, Nb, Cr, and Si significantly enhances their mechanical properties [2, 3].

Molybdenum and molybdate compounds are effective in improving steel's passive film stability. These compounds act as anodic corrosion inhibitors and are used in applications such as airplanes and ground vehicles due to their non-toxic nature and effective corrosion prevention [4]. Molybdate chemicals work through mechanisms of adsorption, oxidation, and deposition. Mo can also serve as a coating material for other metals, offering additional protection [5, 6]. Research has shown that Mo increases steel hardness and enhances precipitation-hardening in high-strength low-alloy (HSLA) steels. Mo positively affects the microstructure and mechanical properties of steels, making them suitable for demanding applications [7–9]

Nickel (Ni) is crucial for improving the strength, ductility, and oxidation resistance of steel. Ni stabilizes the ferrite phase, reduces grain size, and improves hardness and fatigue resistance, especially when combined with chromium [10–12]. Nickel and chromium are vital in heat-resistant steels used in high-temperature applications across industries such as petrochemicals, aviation, and power generation [13–15]. Tungsten (W) is another important alloying element due to its high strength, density, and melting point. Its combination with other metals enhances corrosion resistance and mechanical properties, making it suitable for high-speed engine components and tool steels [16–18].

Despite these advancements, there is limited research on Mo-Ni-W-containing alloy steels, particularly regarding how different deformation rates and cooling processes affect their microstructure and properties. This study aims to address this gap by investigating the impact of hot rolling on Mo-Ni-W alloyed steel produced via powder metallurgy. The study will involve developing various steel compositions through powder metallurgy and cold pressing, followed by hot rolling to 40% and 80%

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deformation. The resulting microstructures, hardness, wear, and corrosion resistance of both deformed and undeformed samples are analyzed in detail [19–22].

Additional studies are necessary to fully understand how these alloying elements interact under different conditions. This research will provide insights into the optimal conditions for enhancing the performance of Mo-Ni-W alloyed steels, thereby contributing valuable information to the field [23–28]. The results will help in developing advanced materials for applications requiring high strength, durability, and resistance to wear and corrosion [29–33].

By exploring these aspects, the study aims to contribute to the development of more effective and reliable materials for various industrial applications [34–38]. The findings will be significant for improving the performance and longevity of components made from Mo-Ni-W alloyed steels, addressing current gaps in knowledge and practice [39–42]

Summary: This research focuses on investigating the effects of hot rolling on Mo-Ni-W alloyed steel produced via powder metallurgy. By examining various deformation rates and their impact on microstructure, hardness, wear, and corrosion resistance, the study aims to provide a comprehensive understanding of how these alloying elements perform under different conditions. The findings are expected to offer valuable insights into optimizing the properties of Mo-Ni-W steels, ultimately contributing to advancements in materials used in demanding industrial applications.

2. Materials and methods

In order to use the powder metallurgy technique, alloyed steel samples with the chemical composition Fe-0.55C-3Mo-10Ni-0.5W were created for this study. Table 1 lists the powders' sizes and purities. The powders were weighed to a precision of 0.0001 g using a RADWAG AS-60-220 C/2 scale, then mixed and compacted into molds before being sintered to form the final samples.

Table 1. *The sizes and purities of the powders*

	Elemental powders	size (μm)	Purity %	Supplier
1	Iron	≤180	99.9%	Höganas, USA
2	Graphite	<20	96.5%	Höganas, USA
3	Molybdenum	<150	99.9%	Aldrich, Germany
4	Nickel	<44	99.7%	Aldrich, Germany
5	Tungsten	<44	99.95%	Nanografi, Türkiye

Each Fe-0.55C-3Mo-10Ni-0.5W powder composition was generated and blended using a TURBULA T2F (Willy A. Bachofen AG, Muttenz, Switzerland) for many hours. It enhanced 3D motion. The particles were compressed using a 750 MPa hydraulic press (Hidroliksan, Konya, Türkiye). The samples were sintered for two hours at 5°C per minute up to 1400°C in a mixed-gas (90% nitrogen/10% hydrogen) atmosphere. After that, it was cooled to room temperature at 5°C/min.

Table 2. *Chemical compositions of the PM steels*

Sample	C	Mo	Ni	W	Fe
(sample-1) Fe-0.55C-3Mo-10Ni-0.5W Undeformed	0.55	3	10	0.5	Rest
(sample-2) Fe-0.55C-3Mo-10Ni-0.5W 40% Deformed	0.55	3	10	0.5	Rest
(sample-3) Fe-0.55C-3Mo-10Ni-0.5W 80% Deformed	0.55	3	10	0.5	Rest

The sintered samples were hot-rolled using different passes. A reduction ratio of 20%, a preheating temperature of 1150°C, a holding period of 30 minutes, and ultimate rolling temperatures above 950°C were used during rolling. Samples were continuously rolled under the same rolling specifications until 40% deformation was removed to cool at room temperature The remaining samples were returned to the furnace for heat preservation for hot rolling after each rolling pass at 1150°C and a holding time of 30 minutes in a Protherm heat treatment furnace until 80% deformation. They were then also removed to cool to room temperature. The roller diameter used in the rolling process is 200 mm. The number of rolling cycles is 20 cycles/minute. The hot-rolled and unrolled samples are visually distinguishable based on their surface characteristics. The material with an initial thickness of 12.32 mm was reduced to 2.76 mm through 80% cold deformation, while the sample with 40% cold deformation was reduced from 12.41 mm to 6.85 mm.

A Radwag density kit (ASTM B 328-96) (Bruker Alpha, Bursa, Türkiye) was used to determine the specimen densities (according to Archimedes principle) [43]. Before examining the materials under an optical microscope, their surfaces were cleaned, abrasive papers with the different mesh sizes were used. After that, polishing with a 0.3μm Al_2O_3 suspension was done, and $1HNO_3$+3HCl etching was the next. Later, ethyl alcohol and distilled water were applied to clean them all, and air drying was conducted.

A Nikon ECLIPSE L150 optical microscope (Melville, NY, USA), was used for the research. SEM and XRD were used to analyze the microstructural and the wear-and-corrosion surface using a Zeiss microscope and a Rigaku Ultima IV diffractometer. XRD was used to qualitatively analyze the structural changes in the alloys after adding Mo, Ni, and W.

A (HMV-Shimadzu, Tokyo, Japan) micro hardness tester was employed under an HV0.5 load for a duration of 15 seconds. The hardness value was calculated by averaging five hardness tests of each sample.

Before the corrosion test, a copper wire was soldered to the samples to ensure the conductivity of the samples with the corrosion unit. Then, they were molded with epoxy resin to provide insulation. Additionally, ethyl alcohol was used to clean the surface after abrasive papers with different mesh sizes up to 1200 were used. On the surface of the specimen, a thick adhesive tape was applied with a hole of 0.25 cm in diameter. In order to avoid any potential negative consequences, the corrosion tests were conducted on all specimens in the same location. The potentiodynamic polarization tests were done at room temperature in 3.5% NaCl utilizing a Gamry model PC4/300mA potentiostat/galvanostat with computer-controlled DC105 corrosion analysis. A three-electrode electrochemical cell was used for the corrosion tests, with graphite as the counter electrode and a saturated calomel electrode as the reference electrode. In this setup, a classical corrosion cell configuration was employed, where the working (sample) electrode, counter electrode, and calomel electrode were positioned in close proximity to one another.

The samples for the wear test were prepared using 400, 600, 800, 1000, 1500, 2000, and 2500 meshes of coarse-to-fine abrasive paper. The 4D-ECN (in Türkiye) tribometer was used for the wear tests. The dry wear test was performed at room temperature with 20N and 40N loads, a 10mm stroke, 100 meters of sliding distance per load, and 0.04 m/s sliding speed. For the wear test, AISI 52100 6mm chrome steel balls were used. A profilometer (Mitutoyo SJ-410, Tokyo, Japan) was used to measure the alloy steel surface's wear markings after the wear test. Then, wear-line SEM pictures were taken.

3. Results and discussions

Fig. 1. illustrates the microstructure of undeformed Mo-Ni-W steel, In Fig. 1, it was observed that bainite, martensite, and austenite, were formed in the microstructure.

Furthermore, Fig. 2 illustrates how the grain size decreases with increasing deformation. It was discovered that the addition of Mo and W reduces the grain size. The formation of MoC(N), WC(N), and

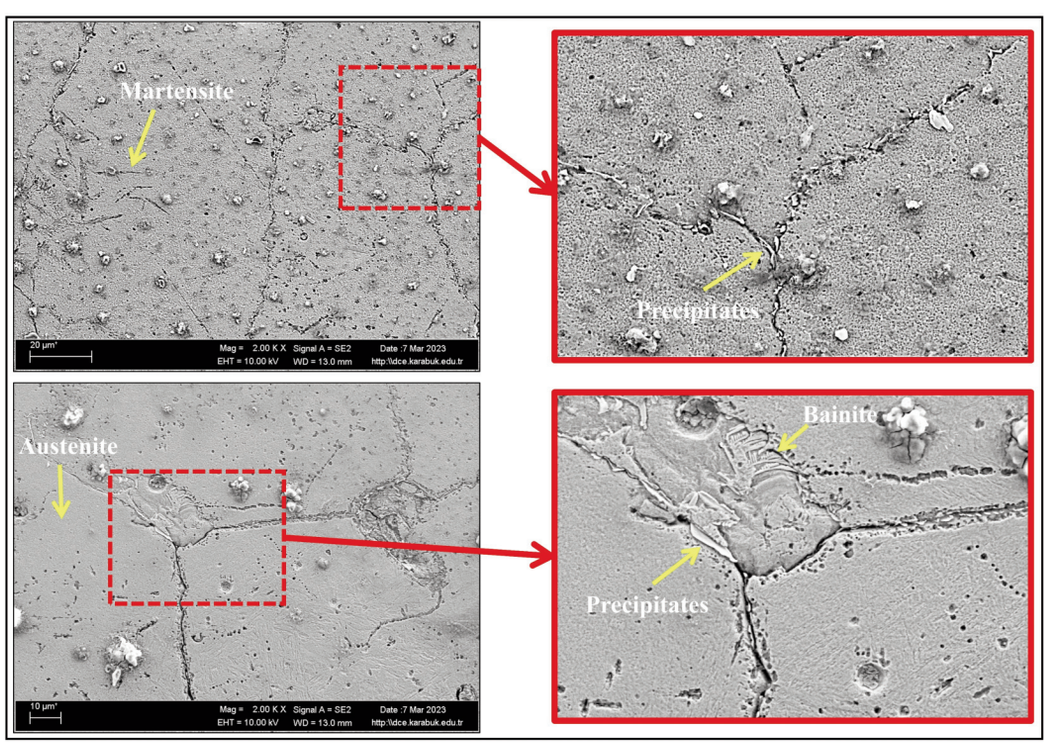

Figure 1. *Microstructure details for undeformed sample (2000x-5000x)*

MoWC(N) precipitates in grains and grain borders might cause grain refining [44, 45]. On the other hand, many studies in the literature show that deformation refines grain size [41, 46–48]. For instance, according to Inagaki [47], ferrite nucleation and subsequent grain refinement are enhanced by adding highly stressed patches at grain borders or close to the boundaries of annealing twins. This suggests that the deformation in the non-recrystallizing zone of austenite accelerates the nucleation rate and ferrite formation. Little ferrite particles are created as a result, and the structure's ferrite volume rises [48]. In addition, the results obtained from this study showed that 80% of the deformed samples exhibited smaller grains than sintered materials. Li [46] investigated how the forging rate affected the microstructure of H13 steel and found that as the forging rate increases, the grain size reduces, providing more nucleation points and storing energy for grain recovery and recrystallization. Therefore, it was observed that this promotes grain thinning.

Fig. 2 presents SEM point EDS analysis and mapping images of 40% deformed samples, while Fig. 3 shows the same for 80% deformed samples. Microstructural analysis revealed that heat deformation reduced pores and grain size. The solution-based alloying had little impact on the austenite recrystallization, while precipitated particles strongly inhibited grain boundary movement [49]. Hong et al. investigated the effects of tungsten addition to 9Cr–Mo steels (M10, W18, W27) on the microstructure and high-temperature tensile strength.

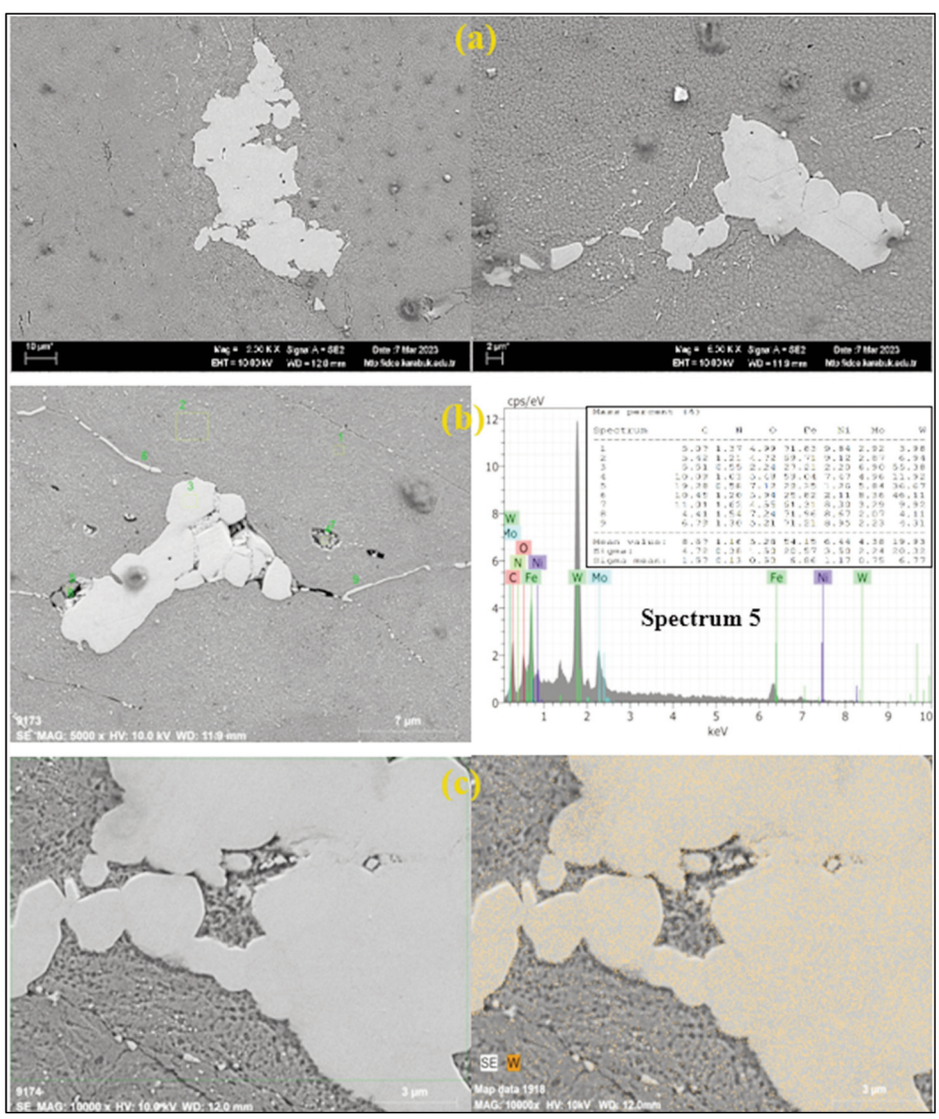

Figure 2. *Mo-Ni-W steel 40% Deformed (a) SEM Microstructure images (2000x-5000x), (b) SEM point EDS analysis (5000x), (c) SEM mapping images (10000x)*

Tungsten improved the tensile strength by increasing the Cr/Fe ratio, which led to lattice expansion and dislocation glide pinning. The M23C6 carbides were fine and homogenous in tungsten-treated 9Cr steels, while they agglomerated in M10 steel. The high tensile strength of the tungsten-added 9Cr steels was attributed to the stable M2X and M23C6 carbides and the reduced iron self-diffusivity after tempering, which hindered dislocation recovery.

Adding W to 9Cr steels demonstrably delays phase transformation processes and stabilizes their microstructure. The incorporation of tungsten to these steels results in the formation of M2X carbonitrides and homogeneous M23C6 carbides, alongside the retarded dislocation recovery, thus improving the material's mechanical properties [50]. As shown in Figs. 3 and 4, EDS analysis of both sintered and 80% deformed materials reveals the presence of precipitates in various sizes, including Fe3C, MoC, MoC(N), WC, and WN. These precipitates form due to the interactions between Fe, C, Mo, and W elements. The EDS results further indicate that deformation accumulation plays a crucial role in initiating the precipitation of carbonitrides in steels, a phenomenon that is influenced by the alloying elements such as Mo and W, which enhance precipitation during deformation [51, 52].

Fig. 3 illustrates SEM images, including line EDS and point EDS analysis of precipitates formed within the grains and at the grain boundaries, along with mapping images of Mo and W in the 80% deformed steel. EDS analysis results from this work, and prior studies show that alloyed PM steels can include MoC(N) and WC precipitates. Microscopic precipitates such as MoC, WC, MoN, WCN, MoCN, and WMoCN may form during 1400°C sintering or post-sintering cooling. EDS showed Mo and W precipitated as grains/grain boundaries (Fig. 3). The EDS line analysis showed that the alloy comprised a diversity of components in both kind and quantity along the matrix-precipitate line (Fig. 3). Mo is abundant in the spherical precipitate. In contrast, iron is abundant in the matrix phase. The concentration of Mo increases significantly when the analytical line and the precipitates converge. The PM steel samples have precipitates (confirmed by SEM and EDS studies) that are known to substantially affect austenite recrystallization and grain development [9, 12].

Small ferrite grains are created when precipitates that do not dissolve at the sintering temperature stop the growth of austenite grains [31, 53–55].

The SEM microstructure and EDS results obtained from Mo-Ni steel after deformation (Fig. 3 and Fig. 4) reveal the formation of nano-sized precipitates on both the grain and grain boundaries, consistent with previous studies [56]. These precipitates, primarily composed of Mo, contribute to the stabilization of the microstructure. Tracey [50] and Reyes et al. [51] observed bainite and martensite phase formation in similar steels, while Alharthi [52] showed that the transformation to bainitic structures is facilitated by C and Mo, even in the absence of Ni in the Fe particle center. The EDS analysis indicates the presence of Ni-rich austenitic regions, which transform into

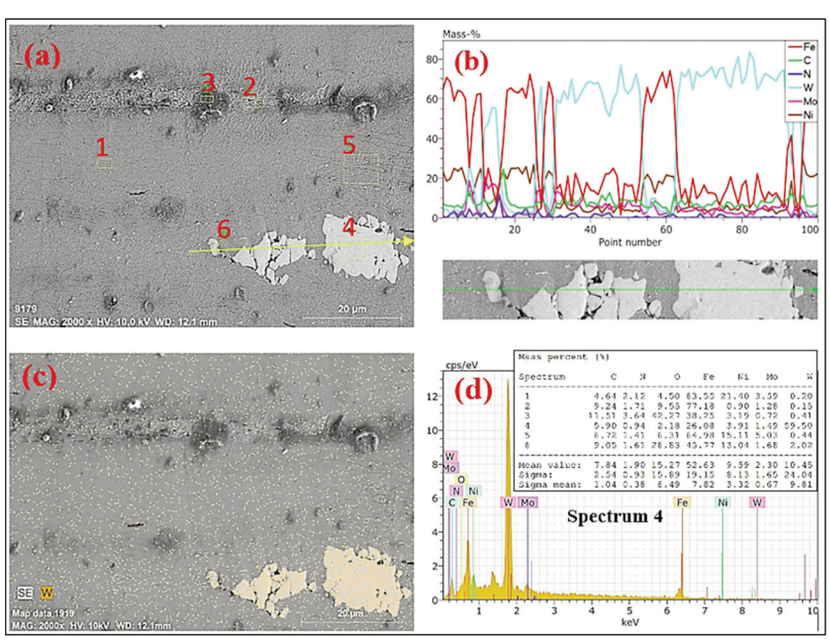

Figure 3. *Mo-Ni-W steel 80% Deformed (a, b, and d) SEM point EDS images, and line EDS analysis (2000x), (c) SEM mapping images (2000x)*

martensite over time, with longer sintering times increasing the amount of Ni-rich martensite. Additionally, Fig. 4 highlights martensite phase formation, with Mo playing a key role in preventing grain growth by forming precipitates such as MoC, MoN, and MoCN, as supported by [55, 60, 61]. These findings underline the significant role of Mo and Ni in phase formation and microstructural stabilization, aligning with previous research.

Fig. 5 XRD shows the patterns of Mo-Ni-W steel. Depending on the alloy type, the XRD patterns and the predictions of what compounds may have formed in the pattern peaks are shown in Fig. 5. Considering the XRD pattern of the Fe+0.55C+3Mo+10Ni+0.5W alloy, where all elements and compounds are seen together, it is approximately 38° for the MoN compound, 44° for Fe_3Ni_2, and WMoC compounds, 48° for WN compound, 68° for MoWCN compound, 76° for WMoC compound and 82° for WC compound.

The hardness test results indicate that the hardness values of Mo-Ni-W steels increased as the rate of deformation increased. Specifically, the hardness values of Mo-Ni-W steel were 283.8 Hv for sintered, 378.6 Hv for homogenized, 40% deformed, and 573 Hv for 80% deformed samples, respectively.

The increased number of precipitates that form in alloyed steel, such as MoN, MoC, WC, and WN, as well as the grain refinement that occurs in steel with a rising deformation rate, are both responsible for this rise in hardness. The production of these precipitates was verified by the XRD data. In contrast to undeformed steel, alloyed steel had a harder grain structure and reduced grain size due to precipitates that hindered grain growth and dislocation movement. The impact of alloy elements on grain boundary movement and recrystallization is due to precipitates

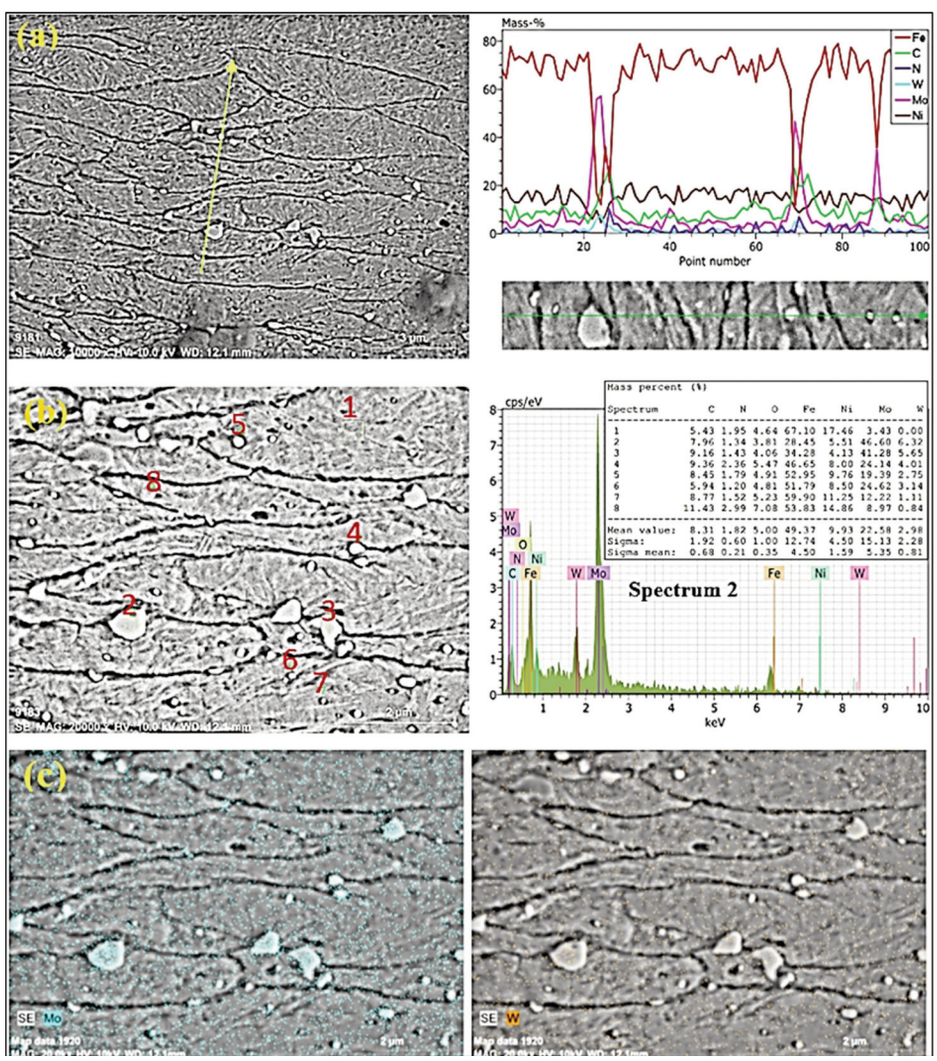

Figure 4. *Mo-Ni-W steel 80% Deformed (**a**) SEM. Line EDS images (10000x), (**b**) SEM point EDS analysis of precipitates formed in the grain and grain boundaries (20000x), and (c) mapping images of Mo and W*

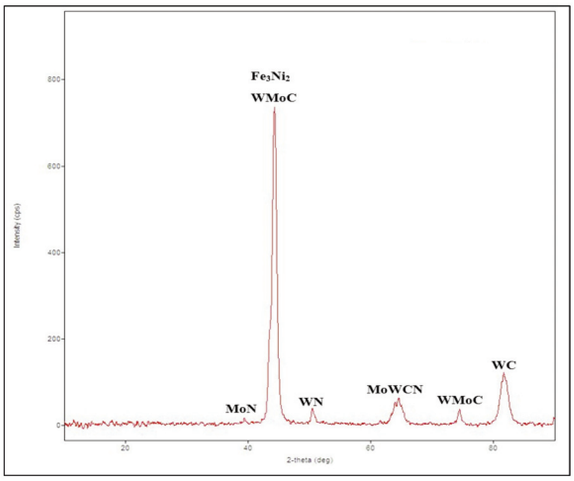

Figure 5. *XRD patterns of Mo-Ni-W steel*

of carbonitride that either developed during cooling or remained undissolved in austenite. Furthermore, as plastic deformation (strain-induced precipitation) increases, so does the rate of precipitation. The grain diameters were reduced, and the strength increased when the precipitated particles prevented grain boundary movement [62, 63]. Earlier micro hardness studies [64, 65] on ferrite grains revealed that precipitation hardening is primarily responsible for the micro-alloyed steels' increased hardness.

Changes in density and porosity were noted in addition to precipitates and refinement of grain size. There are fseveral actors that influence the porosity of powder metallurgical steels. These include the deformation rate, the alloying, the sintering temperature and duration, and the pressing methods (e.g., warm, hot, and cold). In general, alloying makes porosity higher [66]. However, sintering time and temperature reduce porosity [66, 67]. The relative densities (%) of the alloyed and unalloyed steels are displayed in Table 3. It is found that when the deformation rate increases, both steels' relative densities increase, and the porosity percentage decreases in tandem. It is thought that the porosity level of specimens made via powder metallurgy also has an impact on their hardness values. Pores can contribute to the propagation of fractures if their shape is not aligned, as they can function as stress raisers and start cracks where stress is concentrated [68]. It was found that as deformation rates increase, the amount of porosity decreases. Steels that were alloyed became harder as a result.

Tastemur et al. [68] investigated the 40% and 75% thickness reduction processes used to manufacture powder metallurgy-produced unalloyed steel and micro-alloyed steel with 0.15% Nb. They discovered that in both steels, the grain size progressively shrank

Table 3. *Density and porosity of samples*

Alloys	Experimental Densities (g/cm3)	Porosity (%)
(sample-1) Undeformed	69.948	13.38
(sample-2) 40% Deformed	74.762	7.42
(sample-3) 80% Deformed	78.957	2.22

with the rate of deformation. The grain size study corroborated that the tiny grains resulted from a full recrystallization process at a 75% deformation rate. The increase in deformation rate resulted in a rise in the density and hardness values. Under sintered conditions, the micro-alloyed steel's density and hardness were 89.46% and 75 HV, respectively. However, in a 75% deformed state, the same values were 98.51% and 231 HV.

The wear depth results for all samples under a 40N load indicate the impact of the applied load on the wear depth. It was observed that as the degree of deformation increased, the wear depth decreased. The lowest wear track depth was found in the sample with 80% deformation, while the highest depth was observed in the sample without deformation. According to morphology obtained from the surface roughness device, the undeformed sample exhibited adhesive wear, whereas the 80% deformed sample showed abrasive wear. This suggests that increased deformation significantly enhances wear resistance, reducing surface wear.

The wear test and the volume loss results of the samples reveal that, similar to the area loss findings, the volume loss decreases with increasing deformation. Specifically, the undeformed sample exhibited a volume loss of 2.58 mm^3 under a 20N load and 3.12 mm^3 under a 40N load. In contrast, the sample with 40% deformation showed a reduced volume loss of 1.1 mm^3 at 20N and 1.99 mm^3 at 40N. The sample with 80% deformation experienced the lowest volume losses, with only 0.5 mm^3 under 20N and 0.9 mm^3 under 40N. These results suggest that higher deformation levels significantly improve wear resistance, as seen in the consistently lower volume losses at both load levels for more deformed samples.

The average friction coefficient values observed during the wear test show a decrease as the level of deformation increases. For the undeformed sample, the friction coefficient was 0.79 under a 20N load and decreased slightly to 0.69 under a 40N load. In comparison, the sample with 40% deformation exhibited reduced friction coefficients of 0.55 at 20N and 0.50 at 40N. The sample with 80% deformation recorded the lowest friction coefficients, with values of

0.43 under 20N and 0.49 under 40N. This trend suggests that increased rolling deformation leads to a smoother surface and enhanced contact stability, likely due to a more compact and refined microstructure, ultimately lowering the friction coefficient. Erden and Aydin [69] mentioned that they successfully used powder metallurgy to create AISI 8620 steel, which they then carburized for four hours at 925°C. They discovered that as carburization proceeds, the average friction coefficient tends to decrease. An analysis of worn surfaces revealed the presence of oxidative wear at 15 N of load. At greater loads, oxidative wear transforms into abrasive wear. An investigation was conducted by Zhou et al. to determine how the microstructural development of carburized G20CrNi2MoA-bearing steel was influenced by the surface friction characteristics and the complete forming process [70].

The wear rate significantly decreased as hot rolling distortion increased, with a rapid early wear period followed by a stable wear stage. The friction coefficient also decreased with hot rolling deformation, dropping by 45% compared to the raw material, and 50% in total [71, 72]. High friction, especially in dry conditions, causes material accumulation and cracks. AISI 52100 chrome steel balls accumulate on the workpiece surface under high friction or dry conditions, with material deposition visible only in dry environments [73, 74].

Fig. 6 illustrates the worn surface images of all samples subjected to both 20N and 40N loads, providing a detailed insight into the wear patterns and surface damage that occurred under varying loading conditions.

Dry sliding wear tests remove components from the contact surfaces, causing abrasive wear, while others accumulate in the wear channels, fracture, and deform the surface. The powdered metal steel samples lost material through various wear mechanisms, as shown by the surface morphological changes. At low weights (20 N), scuffing, cracks, and potholes appeared. The friction force pressed worn debris into the surface, causing material loss and fractures. The frictional heat caused the material to adhere between the ball and the workpiece at high loads, favoring

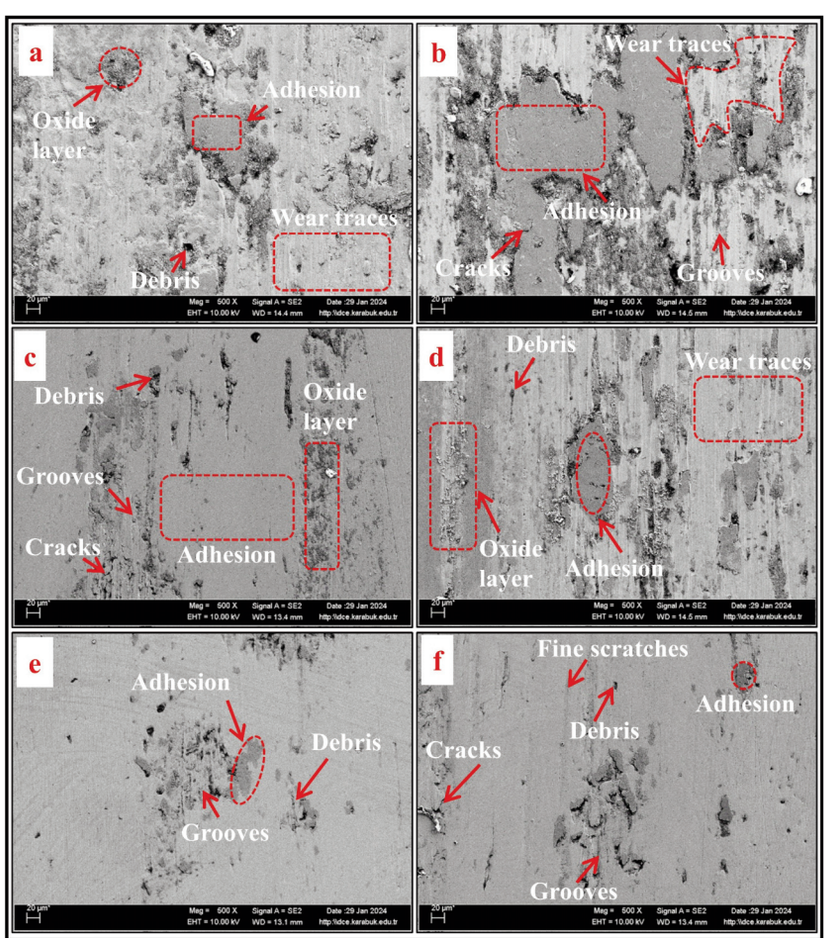

Figure 6. *Worn surface images of alloys: a) undeformed 20N, b) undeformed 40N, c) 40% Deformed 20N, d) 40% Deformed (40N), e) 80% Deformed (20N), and f) 80% Deformed (40N)*

shedding and adhesion in dry conditions.

Fig. 7 shows SEM images and EDX results of the worn surface of all samples under 20N and 40N load. Small pits were also observed forming in the wear SEM images, as shown in Figs. Powdered metal's strain-hardening properties boost steel's wear resistance, and wear debris cuts through the substrate and creates microscopic grooves. During wear testing, sliding friction heats the powder metal steel surface, reacting with air oxygen to produce substantial oxide.

The profile images of abrasive balls used in wear tests under 40N load show the effect of counter material hardness on the surface profile. High-precision AISI 52100 chrome steel balls were used. The ball against the 80% deformed sample, which had the highest hardness, exhibited a rougher surface. For the undeformed sample, the wear mark depth was 40 microns, width 0.95 microns, indicating adhesive wear. The 40% deformed sample's ball showed a depth of 57 microns and width 1.05 microns, with mainly adhesive wear but abrasive characteristics in deeper areas. The ball opposite the 80% deformed sample had a depth of 48 microns and width 1.25 microns, with almost entirely abrasive wear.

Fig. 8 shows the SEM and EDX analysis of the abrasive balls of the test carried out at 40N load. The test findings showed that the balls were abrasive and sticky depending on the load. The EDS analysis of the

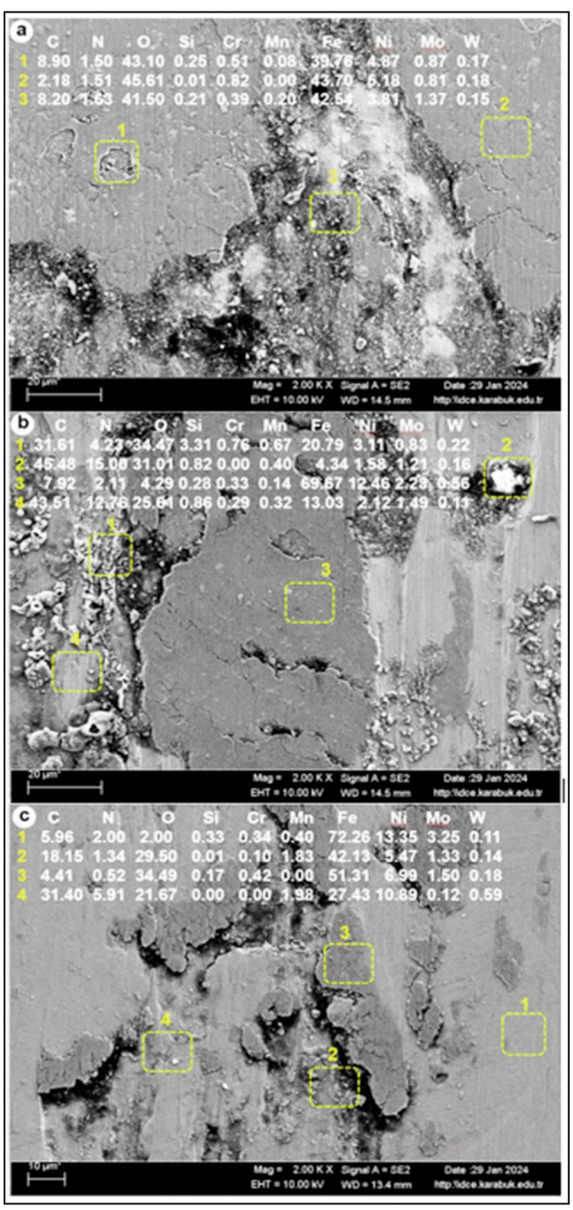

Figure 7. *SEM images and EDX results of the worn surface under 40N load: a) Undeformed samples, b) 40% deformed, and c) 80% deformed samples*

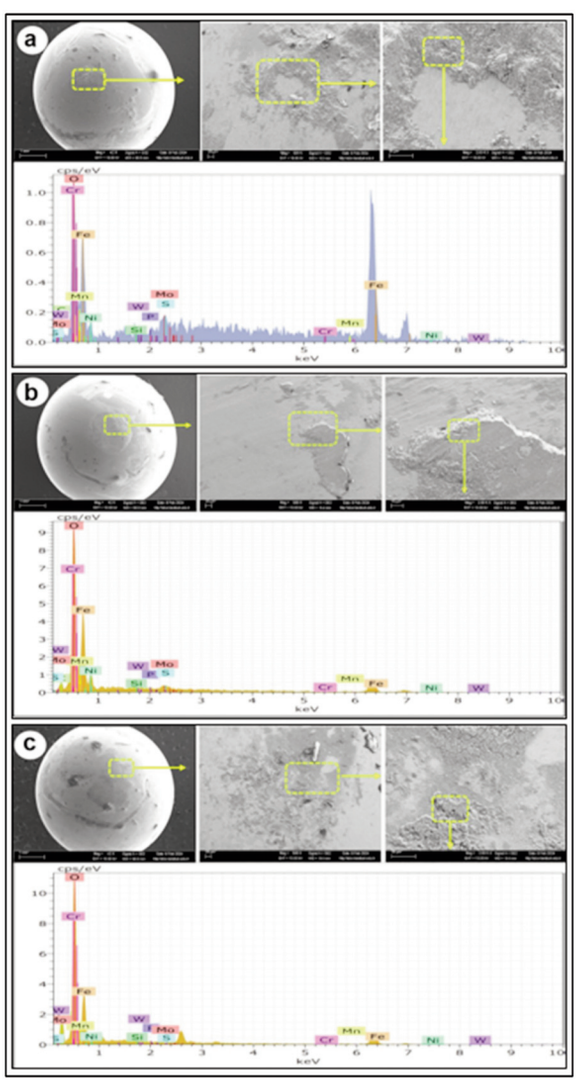

Figure 8. *SEM and EDX analysis of abrasive balls of the test carried out at 40N load: a) Undeformed, b) 40% deformed, and c) 80% deformed*

ball revealed a sticky coating, proving an adhesive mechanism. The ball surface EDX research results are displayed in Fig. 8 [75].

The potentiodynamic polarization curves of the samples indicate their electrochemical behavior. Table 4 presents the corrosion potentials (Ecorr), current densities (Icorr), and corrosion rates (CR). Increased deformation raised corrosion potential and reduced corrosion current density, suggesting improved corrosion resistance. The correlation between a lower corrosion rate, higher corrosion potential, and lower current density is significant [76], as pitting corrosion is more active in samples with lower current density [77]. This is attributed to the galvanic effect in the undeformed sample, with coarser grains and fewer grain boundaries, promoting pit formation [78]. The surface images after corrosion are shown in Figure 9, illustrating the formation of iron oxide and hydrochloric acid during the corrosion process, which deepens the pits and accelerates rusting [79].

$$Fe^{+2} + 2NaCl + 2OH^{-} \rightarrow FeCl_2 + 2NaOH \quad (1)$$

$$FeCl_2 + \left(\frac{1}{4}\right)O_2 + \left(\frac{5}{2}\right)H_2O \rightarrow Fe(OH)_3(s) + 2HCl \quad (2)$$

Table 4. *Ecorr, Icorr, and corrosion rate values of the alloys*

Alloys	Ecorr (mV)	Icorr ($\mu A/cm^2$)	Corrosion rate (mm/year)
(sample-1) Undeformed	-174.0	37.4	0.753
(sample-2) 40% Deformed	-127.0	33.4	0.68
(sample-3) 80% Deformed	-96.9	29.1	0.482

4. Conclusion

The Fe-0.55C-3Mo-10Ni-0.5W composition was produced by powder metallurgy and deformed at 40% and 80% by hot rolling. The study concludes:

The microstructure includes martensite, pearlite, austenite, and residual austenite phases. Ni enhances martensite and bainite, while Mo promotes pearlite and bainite.

Deformed PM steels show better mechanical properties, a finer microstructure, reduced grain size, porosity, and increased density and precipitate formation (MoC(N), WC(N), MoWC(N)).

EDS analysis revealed Fe, C, N, Mo, Ni, and W in the iron matrices, with XRD confirming compounds such as Fe_3Ni_2, WMoC, WN, and WC.

Hardness increased with deformation due to precipitate formation and grain refinement.

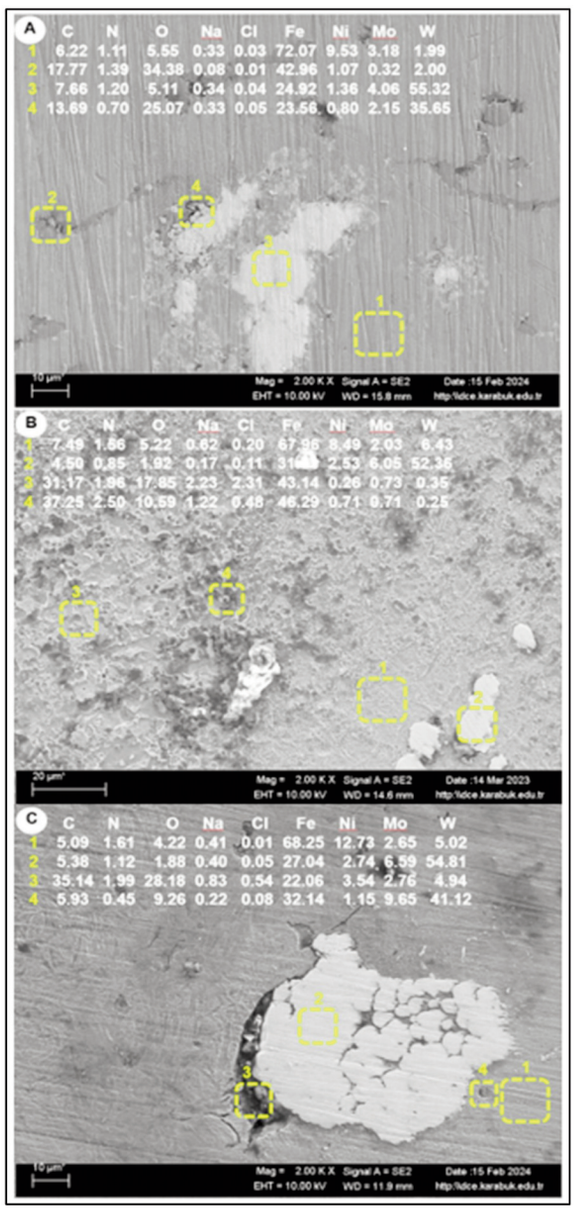

Figure 9. *SEM images and SEM EDX results of the samples after the corrosion test a) 40% undeformed, b) 40% deformed, and c) 80% deformed*

The wear depth was lowest at 80% deformation and highest in the undeformed sample. Wear depth, volume loss, and friction coefficient decreased with increased deformation.

Higher deformation reduced polarization resistance, likely due to increased density and finer grain size. Mo, Ni, and W contribute to corrosion resistance by forming passive films.

The study shows that decreasing wear depth and friction with higher deformation. Further exploration

of deformation ratios and load conditions is needed.

The research highlights dry sliding wear's impact on material loss. Future studies should assess wear in lubricated or humid environments for real-world applications.

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

R.H.R.E., M.A.E., H.Ç., and B.C. designed the experiments; H.A., O.A., and R.H.R.E. performed the experiments. H.Ç., B.C., R.H.R.E., and M.A.E. analyzed the data and wrote the paper. R.H.R.E., M.A.E. B.C., H.A., O.A., and H.Ç. directed the research and contributed to the discussion and interpretation of the results. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data are contained within the article.

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EFEKTI TOPLOG VALJANJA NA MIKROSTRUKTURE, OTPORNOST NA HABANJE I KOROZIJU Mo-Ni-W P/M LEGIRANIH ČELIKA

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Apstrakt

Ova studija istražuje kako toplo valjanje menja mikrostrukturu, zateznu čvrstoću, otpornost na habanje i koroziona svojstva legiranog čelika Fe-0.55C-3Mo-10Ni-0.5W. Metalni prahovi su presovani pod pritiskom od 750 MPa, a hladno presovani uzorci su sinterovani dva sata pri brzini zagrevanja od 5°C/min do temperature od 1400°C u gasnoj atmosferi sastavljenoj od 90% azota i 10% vodonika. Dobijeni čelici su zatim toplim valjanjem deformisani sa 40% i 80%. Mikrostrukture pokazuju prisustvo MoC(N), WC(N) i MoWC(N), pri čemu su čelici imali finiju mikrostrukturu i bolje mehaničke osobine sa povećanjem stepena deformacije. Habanje je opadalo sa povećanjem stepena deformacije. Pored toga, proces toplog valjanja poboljšao je otpornost na koroziju, što je pokazano analizom Tafelove krive. Najveći faktor koji je doprineo povećanoj otpornosti na koroziju bio je porast gustine materijala tokom procesa valjanja.

Ključne reči: *Toplo valjanje; Metalurgija praha; Karakterizacija; Legirani čelici; Habanje; Korozija*