

Heat treatment of steel using Carboxymethyl Cellulose (CMC) as a green quenching medium: effect of concentration on microstructure evolution and wear resistance

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ABSTRACT. Quenching has always been an important heat treatment that alters the mechanical and morphological properties of various types of steel. Different quenching media have been used depending on the operating conditions and desired properties, as each quenching medium affects the resulting properties and microstructure. Various types of quenching media have been used to study their effects, including oils, polymers, and water-based mixtures. In this study, an environmentally friendly, water-soluble polymer quenching medium (Carboxymethyl cellulose sodium salt (CMC)) in different concentrations was used to investigate its effect on the morphology and the mechanical properties of 1020 steel as a quenching medium in future industrial and engineering applications. 0.1% wt CMC polymer as a green quenchant enhances wear resistance despite lower hardness, confirming that microstructure and adhesive wear mechanism affect the tribological behavior rather than hardness alone.

KEYWORDS. Heat treatment, CMC solution, Wear resistance, 1020 Steel, Polymer quenchants.

INTRODUCTION

Heat treatment is one of the most crucial factors affecting the performance of different metals, especially steel and iron-based alloys. It is commonly used to modify the microstructure and enhance its physical and mechanical properties, and also to relieve residual stresses generated from manufacturing processes such as forging and



welding [1]. Quenching followed by tempering is widely used for steel alloys as a heat-treatment to improve the mechanical properties through the formation of martensite phase [2]. Low-carbon steel such as AISI 1020 is used in various fabrication processes, constructional structures, and automobiles because of its ductility and toughness, moderate strength in tension, compression, and shear [3]. However, its relatively low hardness and wear resistance limit its use in tribological engineering applications. Therefore, heat treatment, usually quenching, is applied to enhance its mechanical performance [4]. The effectiveness of quenching treatment is governed by two important factors: quenchant type and immersion speed. Regarding immersion speed, one study on AISI 1020 steel reported that higher mechanical properties can be obtained by lowering immersion speeds [5]. Z. Pan et al found that Direct quenching and tempering methods of low-carbon steels improved the balance between strength and ductility by controlling the transformation to martensite and nano-precipitation[6]. N. A. Özbek and E. Saraç confirm that higher tempering temperatures cause a reduction in hardness and strength but improvement in toughness. Regarding the other factor, many studies have examined the use of different cooling media, such as sand-water and oil, which are found to prevent the formation of martensite and lead to a significant reduction in hardness[7]. Saline solutions were also used as a cooling medium, causing a remarkable increase in hardness by 457BHN compared to 248BHN caused by oil quenching [8]. Recently, polymer-based quenching media have gained considerable attention because they can reduce distortion and cracking compared with water quenching while avoiding the fire hazards associated with oil quenching [9]. The aqueous polymer solutions showed more stable cooling behavior and reduced quenching distortion because of the suppression of the vapor blanket stage. Roshan et al. developed a quenching polymer protective solution (QPPS) that promotes the formation of martensite, hence improving wear and corrosion resistance [10]. Both Nejneru et al. and Perju studied the physicochemical properties of carboxymethyl cellulose (CMC) solutions as a quenching medium. Nejneru et al. studied different properties of a 2.5% CMC solution, such as wettability, degradation, cooling efficiency, and corrosion resistance, while Perju investigated the physicochemical characteristics of this solution in order to highlight the opportunity of using it as an alternative quenching medium for water or oil [11][12]. Although studies have explored the use of the same material as a cooling medium, they have primarily focused on its physical, chemical, and thermal properties. To our knowledge, the direct effect of this medium on the tribological response of low-carbon 1020 steel cooled in low-concentration CMC solutions remains insufficiently investigated. In particular, the relationship between cooling behavior, phase transformation, and grain size evolution has not been thoroughly investigated. Therefore, this study focuses on evaluating CMC as a cooling medium from a metallurgical perspective, emphasizing its impact on phase formation, microstructure enhancement, and its effect on the tribological behavior of this type of steel.

MATERIALS AND METHOD

Sample preparation and heat treatment

AISI 1020 steel with the chemical composition listed in Tab. 1 was cut into cylindrical specimens of 10 mm dia. and 25 mm length for wear testing, in addition to standard tensile test specimens machined according to ASTM E8/E8M.

element	C%	Si%	Mn%	P%	S%	Cr%	Fe%
%	0.181	0.222	0.342	0.0009	0.0018	0.0170	Bal.

Table 1: Chemical composition of the 1020 steel used in the study.

The samples were heat treated using an electrical furnace (KJ-MC-1200-4 .5LZ) by austenitizing at 850°C in ambient air for 15 min with 10°C/min heating rate, then some of them were water quenched, and the other were quenched in different concentrations of the aqueous Carboxymethyl cellulose sodium salt (CMC) polymer solutions (see Tab. 2). Carboxymethylcellulose sodium salt (CAS No. 9004-32-4) was obtained from AVONCHEM Ltd. (UK). The material was supplied as a research-grade powder with an assay purity of 99.9% and a molecular weight of approximately 90,000 g/mol. All quenched samples were tempered at 250 °C for 15 min, followed by air cooling. The heat treatment parameters were chosen according to the recommended processing conditions available in the standard 1020 steel data sheets. Austenitizing at 850°C ensures complete austenitization before quenching, while water quenching provides the reference high-severity standard cooling medium. Tempering was performed to reduce residual stresses and brittleness while maintaining the required mechanical properties. The CMC concentrations were chosen to provide a gradual variation in cooling severity, enabling a systematic evaluation of their influence on microstructure and mechanical properties. Preliminary preparation trials indicated that concentrations above 0.4 wt% resulted in difficulties in achieving complete dissolution and higher



viscosity that hindered heat extraction during quenching, as will be discussed in the results section. The ferrite grain size was measured according to ASTM E112 linear intercept method.

Sample	Condition	Average grain size(μm)	Hardness(HV)	Standard deviation for Hardness
Ar	As received	26	264	23.41
A	Water quenched+ tempering	43	178	9.51
B	0.1% wt CMC quenched+tempering	44	177	18.38
C	0.25% wt CMC quenched+tempering	36	154	13.67
D	0.4% wt CMC quenched+tempering	59	172	25.57

Table 2: Heat treatment of samples, average grain size, and hardness values.

Mechanical tests

A tensile test was done using computer control electronic universal testing machine (UE 2450, Laryee Technology Co., Ltd). Vickers microhardness testing of the samples was done using a digital microhardness tester (Model: MMV-SA, LARYEE INSTRUMENT) under 4.9 N load and 15 s dwell time. The abrasive wear test was carried out on a universal pin-on-disk tribometer locally made in agreement with ASTM G99, the disk made of 1045 steel with 63 HRC. The rate of wear (g/Nm) was calculated using a modified equation (Eqn. (1)) used by the researchers Das and Biswas [13][14]. In general, the reported results were obtained from the average of 5 samples for the polymer quenching conditions, and for hardness measurements, the average of at least 8 readings was taken to ensure the reliability of the results. The wear test parameters are presented in Tab. 3.

Parameter	Value
Load	0.4 Kg
Sliding diameter	15.8 cm
Sliding distance	1109 m
Sliding velocity	3.7 m/s
Rotating speed	447 rpm
Temperature	Room temperature
Time	5 min

Table 3: Wear test parameter.

$$\text{Wear rate} = \frac{\text{weight loss}}{\text{Normal load} \times \text{sliding distance}} \quad (1)$$

RESULTS AND DISCUSSION

Microstructure and XRD

Fig. 1 shows the microstructure of the samples in different conditions, while Tab. 2 shows the approximate grain size values of ferrite measured for each condition. Fig. 1-AR shows the microstructure of the as-received sample, whose microstructure consists of light-colored ferrite and dark-colored pearlite, with the smallest grain size ($\sim 26 \mu\text{m}$) compared to the other samples. This is attributed to the fact that these samples were cold-drawn, where plastic deformation increases the density of crystal defects and promotes the formation of a fine microstructure and fine ferrite grains. Fig. 1-A shows the water-quenched samples, whose microstructure consists of ferrite and pearlite phases, in addition to lath-tempered martensite [15] resulting from the tempering process after quenching. Such a microstructure was also found by [1]. An increase in grain size to approximately $43 \mu\text{m}$ was observed, which is attributed to grain growth during the austenitization prior to rapid quenching. Fig. 1-B shows samples quenched in a (0.1% CMC) polymer solution, where the microstructure consists of ferrite, pearlite, and lath tempered martensite, with a grain size similar to that of water-quenched samples ($\sim 44 \mu\text{m}$). This behavior is attributed to the low polymer concentration, resulting in a cooling rate close to that of water quenching and a limited effect on grain growth restriction. In contrast, Fig. 1-C shows samples quenched

in a (0.25% CMC) polymer solution, which consists of ferrite, lath tempered martensite, and pearlite phases, with a relatively small grain size of approximately $36 \mu\text{m}$. This indicates that this polymer concentration provides a moderate cooling rate that contributes to higher grain growth compared to water quenching. Fig. 1-D represents the samples quenched in a (0.4% CMC) polymer solution. The higher polymer concentration resulted in a lower cooling rate compared to the other cases, allowing for a longer interval, leading to grain growth during the phase transition. The CMC concentration of 0.4% may have formed a layer around the sample, slowing the rate of heat exchange between the quenching medium and the sample, thus slowing the cooling process and leading to greater grain growth. This was clearly reflected in the increased ferrite grain size, reaching its highest recorded value ($\sim 59 \mu\text{m}$). Overall, these results confirm that the type of quenching medium and its concentration play a crucial role in controlling the cooling rate, which directly impacts the development of the microstructure and grain size, as illustrated in Fig. 1 and Tab. 4.

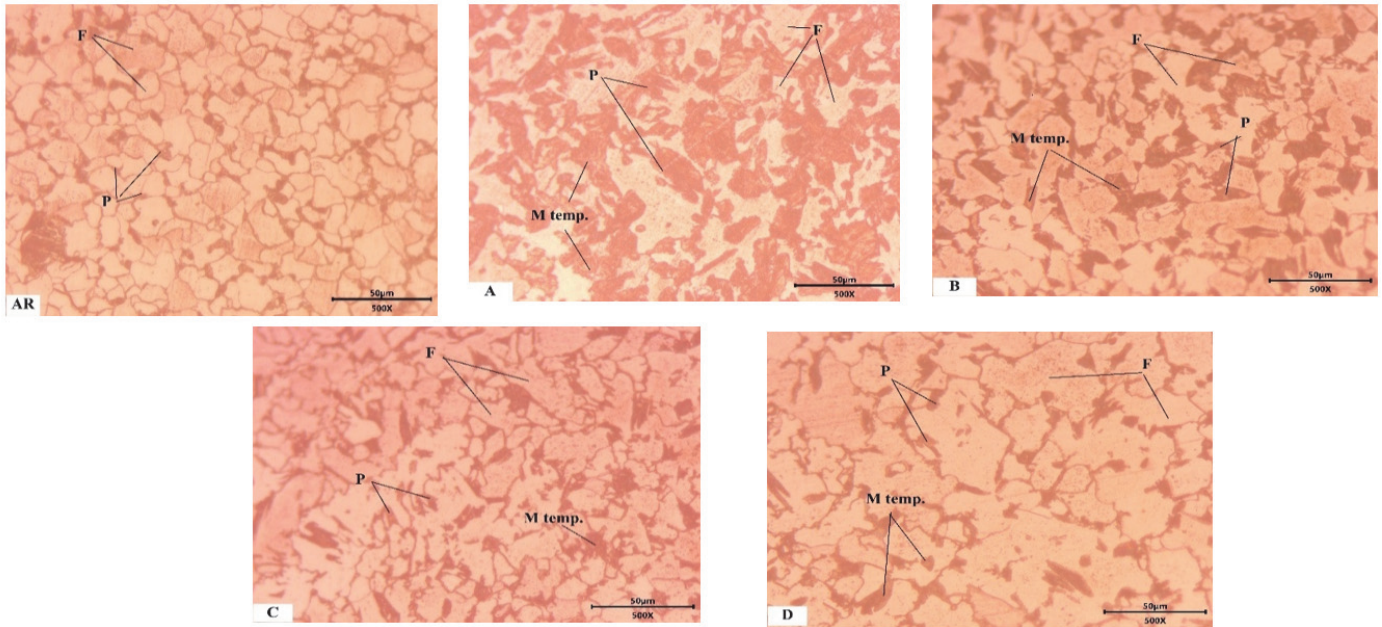
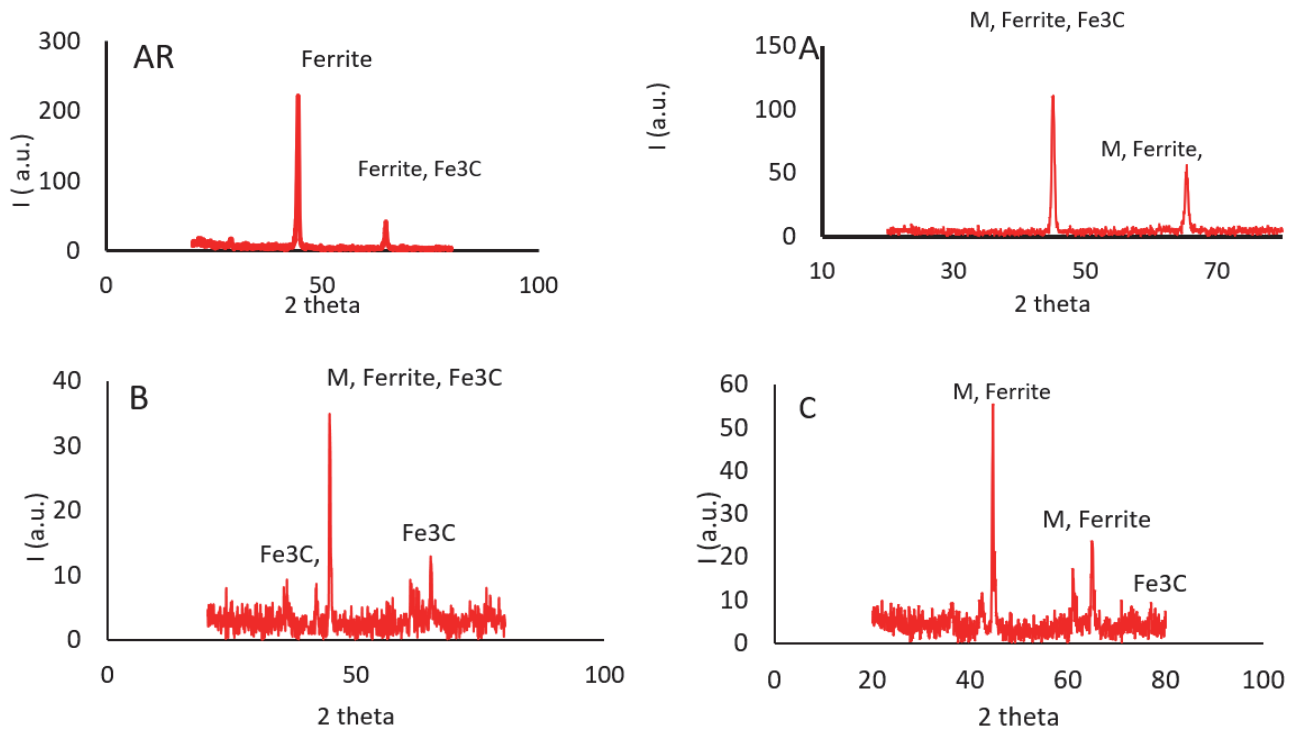


Figure 1: Microstructure of samples: AR) as-received, A) water quenched, B) 0.1%CMC, C) 0.25% CMC, D) 0.4% CMC.



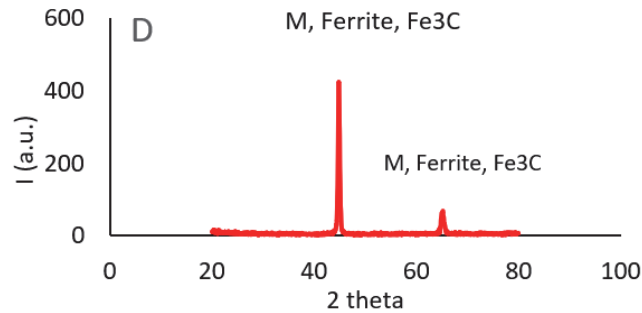


Figure 2: XRD pattern of the different samples with the phases generated.

Fig. 2 represents the XRD pattern of the different samples with the phases generated. X-ray diffraction (XRD) patterns show that ferrite is the dominant phase in all cases, as evidenced by the strong diffraction peaks observed near $2\theta \approx 45^\circ$. Additionally, peaks consistent with martensite (M) and cementite (Fe_3C) are present in the quenched-tempered samples, indicating the formation of a mixed microstructure after heat treatment. Sample B exhibited relatively more pronounced diffraction characteristics related to Fe_3C , suggesting increased carbide precipitation during tempering, while samples A and C mainly showed ferrite and martensite peaks with weak carbide presence. Sample AR showed mainly ferrite peaks with limited Fe_3C peaks. Samples A, B, and C exhibited several additional weak peaks, suggesting the possible deposition of transition carbide phases (Fe_2C) formed during low-temperature tempering. These phases lead to martensite decomposition in the quenched-tempered low-carbon steel before the formation of stable cementite (Fe_3C), as described in reference [16]. The appearance of these weak peaks in samples A, B, and C may indicate differences in the tempering response and carbide decomposition behavior after quenching. However, definitively identifying the presence of these carbides requires high-resolution characterization techniques such as transmission electron microscopy (TEM). In contrast, sample D (0.4% CMC) did not exhibit similar diffraction characteristics, likely due to the effect of the higher polymer concentration on the cooling behavior during rapid quenching. The increased CMC concentration likely reduced the heat transfer rate by forming a thicker insulating layer around the sample surface, thus affecting martensite decomposition and subsequent carbide decomposition during tempering. This behavior may have suppressed the formation of detectable transition carbide deposits or reduced their size to below the detection limit by X-ray diffraction.

Tensile test

Fig. 3 shows the tensile strength results for the samples under different conditions. Fig. 4 represents the typical stress-strain curves for all conditions. Sample as supplied (AR) exhibited relatively high yield strength and tensile strength, attributed to the cold drawing process applied during manufacturing. Cold drawing leads to an increase in both dislocation density and residual internal stresses, as well as an improved grain structure. These factors enhanced both of σ_y and σ_{uts} and decreased plastic deformation. For sample A (water quenched), σ_y and σ_{uts} were the highest among all conditions. This is basically attributed to the fast cooling rate of water compared to polymer solution, that lead to a martensite-rich microstructure with the precipitation of fine carbides. The fast cooling rate of water decreased the diffusional transformations and increased the dislocation densities inside the martensite phase, which resulted in the impediment of dislocation motion. The tempering treatment, which followed the quenching process, also helped to minimize the brittleness by relieving the internal stresses, thus enhancing the strength. For CMC solution quenched samples (B, C, and D), σ_y decreased compared to sample A. The reason may be attributed to the slower cooling rate of the polymeric solution. During cooling, the CMC formed a viscous, polymer-rich coating layer around the hot samples. This layer lowered the cooling rate, hence reducing the heat extraction efficiency. This leads to promoting the diffusional transformations, retarding the martensitic transformation, and causing grain growth compared to the AR sample. Compared to all quenching conditions, sample B (0.1% CMC quenched) showed a good balance between strength and ductility. This is due to the moderate cooling rate of this solution, which leads to a more homogenous microstructure and lowered residual internal thermal and localized stresses. In samples C and D (higher CMC concentration), no major changes were noticed in tensile properties because these concentrations showed similar cooling rates, resulting in similar microstructures and mechanical properties.

In Fig. 4, the stress-strain curves illustrate that the quenching medium had a significant effect on the mechanical properties of 1020 steel. The AR sample exhibits the lowest tensile strength, which indicates that the ferrite-pearlite microstructure provided limited resistance to plastic deformation. Sample A showed the highest ultimate strength, reaching approximately

660MPa. This behavior can be attributed to the higher cooling rate of water that promotes the formation of martensite phase and increases resistance to dislocation movement, but this increment was accompanied by a reduction in ductility compared to polymer-quenched samples. Samples B, C, and D, which were polymer quenched, showed a lower tensile strength compared with AR and A but noticeably greater elongation before rupture. This was attributed to the lower quenching severity of the CMC polymer, which reduced internal stresses and promoted a more balanced microstructure that results in enhanced ductility. Among these samples, B and D provided the best combination of strength and ductility, with sample C exhibiting the highest elongation, hence the best plastic deformation ability. These results confirmed the traditional trade-off between ductility and strength in heat-treated iron-based alloys. While water quenching elevates strength, polymer quenching produces a more balanced mechanical performance, which may be advantageous for applications that require both load-bearing ability and resistance to premature rupture.

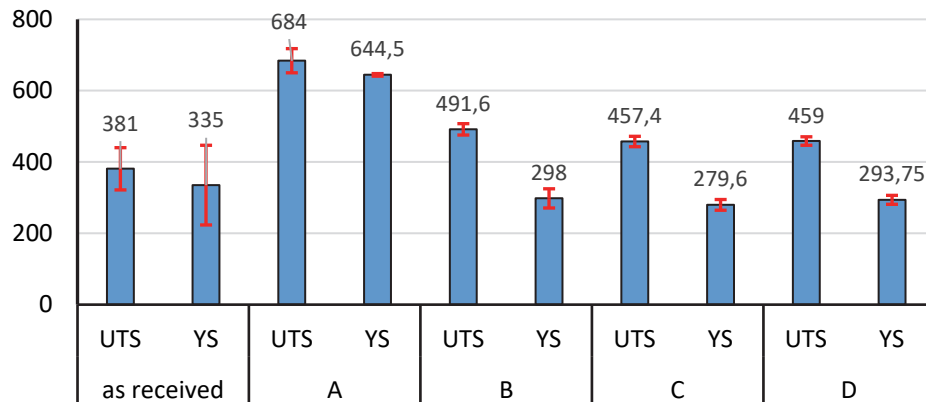


Figure 3: σ_{uts} and Y for the different samples.

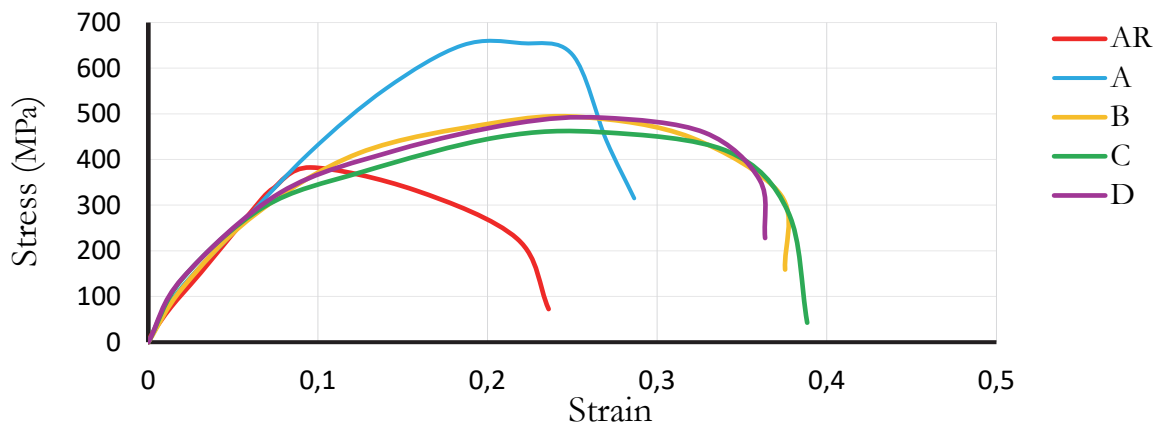


Figure 4: Stress –strain curve for the different samples.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3809.7	2	1904.8	1.013	0.39	3.88
Within Groups	22545.2	12	1878.7			
Total	26354.9	14				

Table 4: ANOVA for Ultimate Tensile Strength(UTS).

One-way ANOVA calculations from Tab. 4 and 5 indicated that the differences in tensile properties for polymer quenched samples (B, C, and D) were not statistically significant ($p > 0.05$). This result may be due, at least in part, to the relatively narrow concentration range used in this study(0.1,0.25 and 0.4 wt%CMC), so the resulting cooling characteristics may not

have differed sufficiently to produce statistically distinguishable data in tensile strength. Nevertheless, the observed variations in hardness and microstructure suggest that the CMC solutions did influence the steel performance. It is therefore reasonable to make an assumption that a wider concentration CMC range leads to more significant differences in mechanical properties, since the viscosity will get higher with increasing concentration.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3100	2	1550	1.41	0.28	3.88
Within Groups	13134	12	1095			
Total	16234	14				

Table 5: ANOVA for Yield Stress (YS).

Fig. 5 illustrates the fracture surface of all samples. The fracture mechanism is ductile for all conditions with generation, growth and coalescence of microvoids. The presence of these voids, along with the absence of cleavage surface or intergranular cracks indicates to a great amount of plastic deformation prior to failure. These findings agreed well with the fracture nature shown in Fig. 5. From Fig.5, the size of the dimples for samples (A and AR) looks similar despite the differences in the cooling conditions and mechanical properties. The reason for that is attributed to the ability of the two samples to withstand the plastic deformation before failure. On the other hand, the size of the dimples in samples (B, C, and D) looked smaller and denser than their counterpart (A and AR). This indicates that the controllable cooling behavior of the polymeric solution impedes the growth of the voids before fracture, resulting in a homogenous deformation all over the samples, in addition to the minimization of the thermal degradation and the localized stresses. The absence of brittle fracture characteristics such as cleavage or intergranular cracks indicates that the heat treatment process and the different quenching conditions didn't cause brittleness despite the differences in cooling rates.

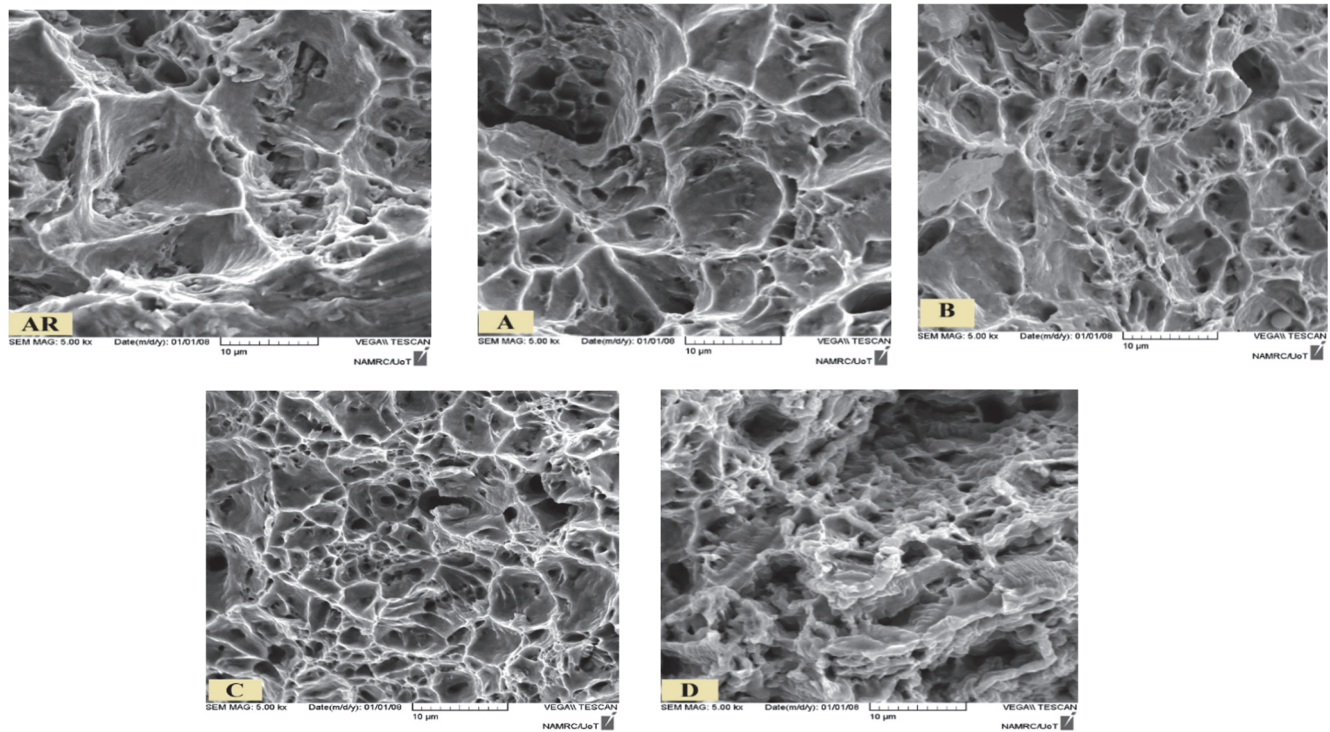


Figure 5: Fracture surface: AR) as received, A) water quenched, B) 0.1%CMC quenched, C) 0.25%CMC quenched, D) 0.4%CMC quenched.

Hardness and wear test

Hardness values for all conditions are listed in Tab. 2. Fig. 6 represents the wear rate of all conditions with a total sliding distance of 1109 meters. From Fig.6, the sample (AR) showed the lowest wear resistance among all conditions, despite its higher hardness. The contradiction between its hardness and wear resistance indicates two reasons. First, the wear behavior

doesn't solely rely on the hardness values, but also on different factors such as the homogeneity of the microstructure, work hardening during sliding, and the ability of the tribolayer to accommodate the progressive plastic deformation caused by wear. Similar findings were also recorded by [17], in which harder samples showed lower wear resistance. Second, since the AR sample was already cold drawn, it suffered from severe plastic deformation, that cause higher residual stresses and higher dislocation density, hence leading to the crack and separation of material during sliding. In contrast, Sample A revealed better wear resistance compared to AR because of the following reasons: the stability of its surface layer during the sliding was enhanced by the martensitic transformation resulting from fast cooling, and the homogenous distribution of the harder phases throughout the matrix minimizes the localized deformation. Samples (C and B) showed better wear resistance compared to AR despite their lower hardness. The good balance between the ferrite, martensite, and carbides for these samples enhances the ability of their surface layer to withstand plastic deformation and material removal during sliding. Sample B represents the concentration of the polymeric solution that gives the best balance between hardness, wear resistance, and strength. Sample D showed similar wear behavior to AR due to the higher concentration of the CMC (0.4%), hence the viscosity that lowered the cooling efficiency, minimizing martensite formation and more heterogeneous distribution of phases across the microstructure. Overall, wear behavior is a sophisticated mechanism that depends on numerous factors, microstructure nature, distribution of phases across the microstructure, residual stresses, deformation characteristics of the surface layer during sliding, and the nature of the tribolayer. These factors lead to a large scatter in wear rate results. However, the overall wear trend remains clear.

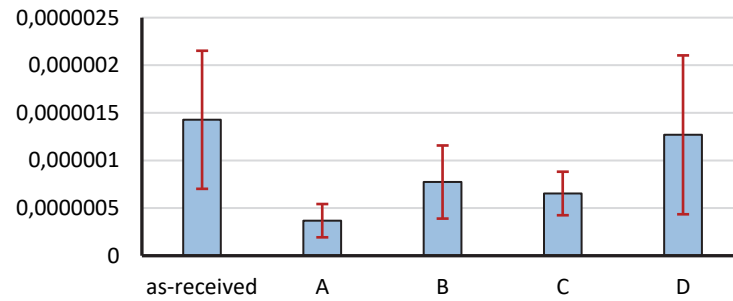


Figure 6: Wear rate of all samples after 1109 m sliding distance.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.32×10^{-12}	4	5.8×10^{-13}	2.1	0.17	3.47
Within Groups	2.90×10^{-12}	10	2.9×10^{-13}			
Total	5.22×10^{-12}	14				

Table 6: ANOVA for wear rate.

Despite the scatter observed in the wear rate measurements, the overall trend refers to the fact that quenching in the CMC solutions improved the wear performance compared to the as-received sample. ANOVA results shown in Tab. 6 revealed that the differences between the investigated CMC concentrations were not statistically significant ($p > 0.05$), which suggests that the tribological response became stable within the examined concentration range. This finding should not be interpreted as an absence of the CMC effect. Rather, it may indicate that even the lowest investigated concentrations were sufficient to alter the cooling performance and produce useful microstructural changes that improved tribological behavior. Therefore, the combination of tribological and microstructural results indicates that the CMC quenching medium was effective in enhancing 1020 steel performance.

Fig. 7 illustrates the SEM images of the worn surfaces of the different conditions, with the adhesive wear behavior being dominant. This type of wear includes the material transfer, layer separation, and debris formation between the sample and the rotating disc. A large amount of plastic deformation, layer fragmentation, and the appearance of debris were observed, indicating repeated adhesion and fragmentation processes. Sample B showed the smoother surface, less layer fragmentation areas, and fewer grooves, which were a sign of its good wear resistance. SEM observation shown in Fig.

7 explains the wear rate results shown in Fig. 6. Although the dominant wear mechanisms in all samples were adhesive and delamination in nature, the severity of these features varied considerably. AR sample exhibited extensive delamination and adhesion regions, referring to severe wear scenarios, which is consistent with its high wear rate illustrated in Fig. 6. Sample A showed less delamination and more uniform worn tracks, corresponding to its lower wear rate among all samples. Samples B and C showed moderate wear behavior with limited delaminated areas, referring to intermediate wear rates as shown in fig. 6. Sample D showed a severe wear track with more delaminated regions and wear debris accumulation, hence a higher wear rate. Therefore, the SEM results are in good agreement with the wear measurements that strongly affected by the worn surface nature and the extent of the delaminations.

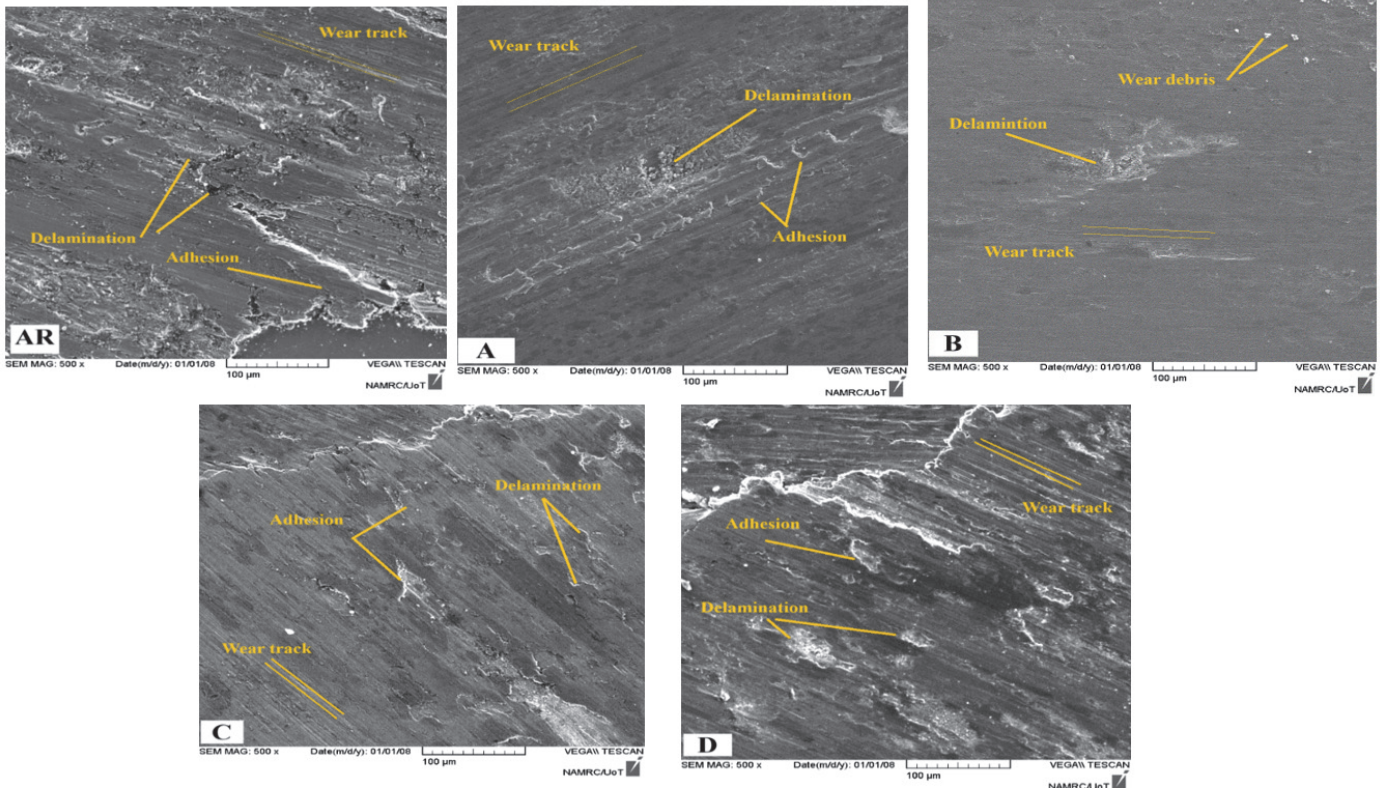


Figure 7: SEM of the worn surface of the different conditions.

These results are consistent with those of Otani et al[18], who described two main patterns of dry adhesive wear: surface deformation and surface fracture. The former involves flattening of protrusions and plastic flow leading to strong adhesion, while the latter involves subsurface cracking and layer separation under increasing shear stress. The transition between these patterns depends on the joint size, with smaller joints favoring plastic deformation, while larger joints promote fracture[19]. Adhesive wear is also strongly influenced by ductility and surface shape [20] as limited plastic deformation accelerates crack formation and debris generation.

Cooling behavior of CMC medium

Carboxymethyl cellulose is a byproduct of the paper manufacturing process. It is an organic polymeric material with the chemical formula $C_8H_{16}O_8$ [21]. It can be dissolved in water in less than 5%. Its cooling rate is considered medium which is suitable to quench parts that are sensitive to cracking or tension concentrators [22]. Fig. 8 below shows the cooling curve of 5% CMC solution compared to water[12]. Since in this study we used CMC concentrations less than 5%, it is expected that the cooling curve for the concentrations used in this study will be between the water curve and the 5% CMC curve,

but closer to water. The cooling rate ($\frac{dT}{dt}$) is expected to decrease with increasing CMC concentration due to the increase in solution viscosity and reduction in heat transfer efficiency. Accordingly, the cooling performance can be qualitatively ranked as:



$$\left(\frac{dT}{dt}\right)_{\text{water}} > \left(\frac{dT}{dt}\right)_{0.1\% \text{ CMC}} > \left(\frac{dT}{dt}\right)_{0.25\% \text{ CMC}} > \left(\frac{dT}{dt}\right)_{0.4\% \text{ CMC}} \quad (2)$$

During the quenching process, the temperature of the CMC solution is increased, leading to its thermal degradation. The thermal degradation starts with the breaking of the H bonds between the macromolecular chain, followed by the breaking of the covalent bonds in the basic chains, that eventually cause a decrease in molecular mass[23]. Depending on the degradation and the fractions of reduced molecular mass, the solutions would have had different viscosities. These differences result in variations in the intermolecular interactions. It is, therefore, understandable why the CMC solutions had a different behavior in terms of surface wetting and contact angle. The contact angle of the CMC solution was generally slightly hydrophilic (around 70°) according to[11], indicating the formation and preservation of cooling through a vapor blanket stage, then the intermittent stage. Because of the gradual cooling method of the CMC solution, the cooling rate is slower than with water, thus leading to the formation of a mixture of pearlite and martensite phases, not just martensite.

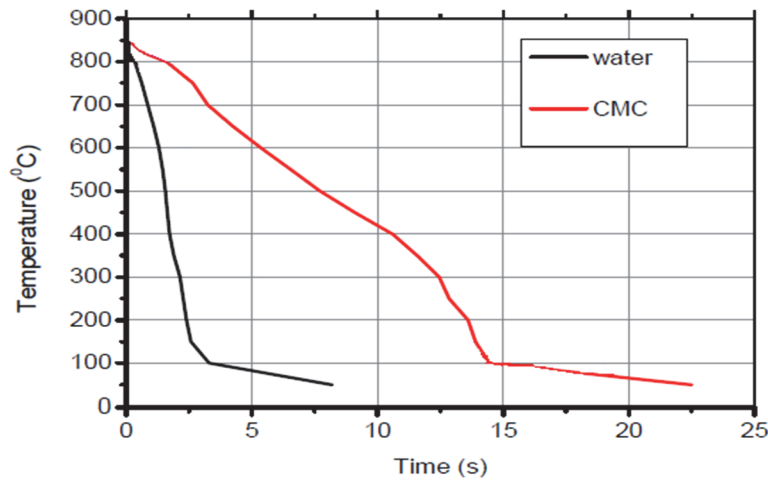


Figure 8: Cooling curve of 5% CMC solution [12].

The wear results can be interpreted in the light of the cooling behavior of the CMC quenching medium, demonstrating that increasing CMC concentration leads to an increase in viscosity of the solution, which will reduce the cooling severity. The Variation in cooling rate/severity influenced the resulting microstructure and consequently affected the wear behavior. Samples quenched in media with lower cooling rates showed different wear responses due to changes in phase transformation and microstructure development. Therefore, the wear Behavior was not governed solely by the sliding conditions but also by the cooling characteristics of the quenching mediums, which ultimately affect the microstructure evolution after heat treatment.

OVERALL DISCUSSION

Using variant concentrations of CMC solutions results in different viscosities, hence different cooling severity/cooling rates. The variations in cooling rate influenced grain size and the resulting microstructure, which subsequently affected tensile response, hardness, and wear performance. The wear behavior was generally governed by the synergistic effect of cooling rate, microstructure changes, and mechanical properties rather than hardness alone. The non-monotonic variations observed in the mechanical behavior of the CMC quenched samples that accompanied the increase in CMC concentration indicate that the relationship between the concentration and the resulting material properties is not linear. Despite the variation in cooling severity associated with the different CMC concentration may have affected the mechanical performance, the lack of direct cooling curve measurements for the investigated quenching solutions precludes establishing a definitive correlation. Consequently, the observed variations may be interpreted as a result of synergistic factors, such as cooling behavior and microstructural evolution, rather than direct relation with CMC concentration alone.



CONCLUSIONS

The present study investigated the effect of using CMC as a cooling medium from a metallurgical perspective, emphasizing its impact on phase formation, microstructure enhancement, and its effect on the tribological behavior of 1020 steel. Based on the obtained results, the following conclusion can be drawn:

- 1- The results showed that water quenching yielded the highest mechanical properties due to the high cooling rate and the resulting martensitic microstructure. However, quenching media with very low concentrations of carboxymethyl cellulose (CMC), particularly 0.1% by weight, achieved a promising balance between mechanical properties and tribological performance.
- 2- The wear behavior of the CMC quenched samples was governed by the combined effect of microstructural evolution and wear mechanisms. SEM observations of the worn surfaces confirmed that the wear performance was correlated more closely with surface damage and delamination rather than hardness alone.
- 3- The use of CMC as a sustainable cooling medium has a promising future due to improving wear performance, reduced deformation and cracking tendency, and eliminating fire hazards associated with oils.

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