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Experimental Investigation of Surface Wear and Induced Damage Evaluation under Dry Sliding Conditions in Medium Carbon Steel

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Abstract

This study examines dry sliding wear in untreated AISI 1038 and AISI 1045 steels, using hardened AISI 1055 steel as the counterpart. Pin-on-disc tests were run at a constant sliding speed of 0.5 m/s under loads ranging from 5 to 40 N. SEM and EDS analyses were used to identify surface damage and the mechanisms behind it. heat treatment, however, markedly improved resistance by raising hardness. AISI 1045 performed best, showing the smallest wear loss because of its tempered martensitic structure. The microscopy and compositional analyses indicated that low loads mainly produced abrasive wear, while higher loads brought adhesive, oxidative, and delamination wear. Protective oxide films formed on the rubbing surfaces and limited direct metal-to-metal contact. Overall, the findings link the improved dry-sliding performance of these medium-carbon steels to both greater hardness and the microstructural changes produced by heat treatment.

Keywords: Dry sliding wear; tribological behavior; heat treatment; medium-carbon steel; AISI 1038 steel.

1. Introduction

Wear and friction are among the main causes of failure and efficiency loss in mechanical systems operating under sliding contact. On a global scale, tribological contacts have been estimated to account for approximately 23% of the world's total energy consumption. Of that share, about 3% goes toward remanufacturing worn parts and replacement equipment damaged by wear and related failures [1]. In industrial systems—including machine tools, guide rails, bearings, and CNC mechanical components—repeated motion between contacting surfaces gradually damages the material. Dimensions drift, and service life shortens [2]. The contact zones may deform, exchange material, oxidize, heat up, and steadily lose material over time [3], [4]

Engineering materials resist wear according to both their mechanical properties and internal microstructure. Medium-carbon steels are widely used in mechanical sliding systems because they balance strength, hardness, machinability, and cost. Their performance during sliding still varies with hardness, carbon content, alloying additions, heat treatment, and the surrounding conditions. Studies generally find that harder materials wear less because they undergo less plastic deformation, which limits material loss at the contact surface [5]–[8]. Archard's classical equation describes the same relationship: wear volume increases with normal load and sliding distance, but decreases as the hardness of the softer surface rises [8]

Several studies have assessed how hardening treatments affect wear and damage in medium-carbon steels. Ceschini et al. [9] compared dry-sliding wear in an induction-hardened, high-silicon medium-carbon microalloyed steel with wear in a conventional quenched-and-tempered steel, using the same hardening conditions for both. The microalloyed steel wore less and produced steadier friction. When the test conditions became more severe, it remained in the mild oxidative-wear regime longer before shifting to severe adhesive wear. Its higher bulk hardness and the stronger tempering stability of its strengthening precipitates helped preserve the protective oxide layers.

Areitioaurtena et al. [10] studied the residual stresses generated during induction hardening of 42CrMo4 steel through both experiments and numerical analysis. They developed a coupled multiphysics finite-element model that reproduced the process's microstructural changes, hardness development, and residual-stress distribution. The hardened surface layer's compressive residual stresses markedly increased fatigue resistance by slowing crack propagation. Accounting for transformation-induced plasticity also improved the model's residual-stress predictions, especially beneath the surface.

Under rolling-sliding contact, Torkamani et al. [11] compared micro-pitting and wear in through-hardened 100Cr6 steel with those in surface induction-hardened C56E2 bearing steel. The induction-hardened material developed high compressive residual stresses, which postponed the shift to severe micro-pitting relative to the through-hardened steel. Their tests revealed three wear stages, progressing from mild wear to severe micro-pitting. Residual stress, hardness distribution, and microstructure all influenced wear resistance and the onset of cracking. Gao and Qin [12] combined finite element simulations with experiments to investigate how feed path and surface curvature shape the continuous

induction hardening of AISI 1045 steel. feed direction had a marked effect on eddy-current distribution, temperature uniformity,. Simulation and experimental results differed by no more than about 5%, can help set induction-hardening parameters and produce more uniform heating. Surface hardening has also been used to improve the dry-sliding wear resistance of En 8 medium-carbon steel [13].

Hardness alone does not determine friction and wear., martensitic transformation, pearlite form, [14], [15]. Steel microstructures are commonly adjusted through quenching both mechanical performance and tribological behavior [16], [17]. strength help limit wear damage under load [18]. Researchers have extensively documented how these tribo-oxide layers form, can shift wear from mild to severe [19]–[21] microstructure, and applied load on dry sliding wear still need clearer definition. This matters when machine parts must withstand repeated contact. Direct comparisons between untreated and heat-treated medium-carbon steels under identical working conditions would also help guide material choices for commercial use.

heat-treatment-driven microstructural changes together affect the dry-sliding wear of AISI 1038 and AISI 1045 steels against hardened AISI 1055 steel. Its specific objectives are:

- i. Measure the mass loss of untreated and quenched-and-tempered AISI 1038 and AISI 1045 pins under normal loads ranging from 5–40 N, using a pin-on-disc tribometer at a constant sliding speed of 0.5 m/s;
- ii. Determine how quenching and tempering affect the hardness and wear resistance of both steels;
- iii. to connect the measured wear behaviour with the ferrite–pearlite structure in the untreated steels and the tempered martensitic structure produced by heat treatment; and
- iv. Use scanning electron microscopy (SEM) to determine which wear mechanisms dominate and what surface damage appears under low and high loads. Energy-dispersive spectroscopy (EDS) will then examine oxide tribofilms formed on the worn surfaces.

Unlike earlier studies, which generally focused on one medium-carbon steel or a single heat-treatment condition, this work compares untreated and quenched-and-tempered AISI 1038 and AISI 1045 steels under the same dry-sliding conditions. Wear was measured with a pin-on-disc tribometer in air, and SEM and EDS were used to examine the resulting wear mechanisms and surface damage.

2. Materials and Methodology

The pins were AISI 1038, with an as-received hardness of 185 HV, and AISI 1045, which measured 210 HV and 20 mm long; each had a flat contact area 2 mm across. 10 mm-thick disc made from heat-treated AISI 1055 steel. Its hardness was 52 HRC, and its microstructure was martensitic. they are widely used in machine parts subject to friction and wear.

AISI 1045 pins were each tested against a hardened AISI 1055 disc. The study examined how heat treatment and hardness affected wear. at 500 °C, the AISI 1038 reached about 30 HRC, while the AISI 1045 reached roughly 35 HRC. held near $R_a = 0.06 \mu\text{m}$ for both pins and discs so that the contact conditions remained comparable.

Dry sliding wear tests were run at room temperature and atmospheric pressure on a TE91 pin-on-disc tribometer (Figure 1). The pin was fixed vertically to a loading arm, then pressed against the rotating disc with dead weights, as shown in Figure 2. Tests ran for 60 min at normal loads between 5 N and 40 N. The sliding speed remained at 0.5 m/s, giving a total sliding distance of 1800 m per test. Wear was determined by weighing each pin before and after the test and calculating its mass loss..



Figure 1. TE91 pin-on-disc tribometer used for the dry sliding wear tests.

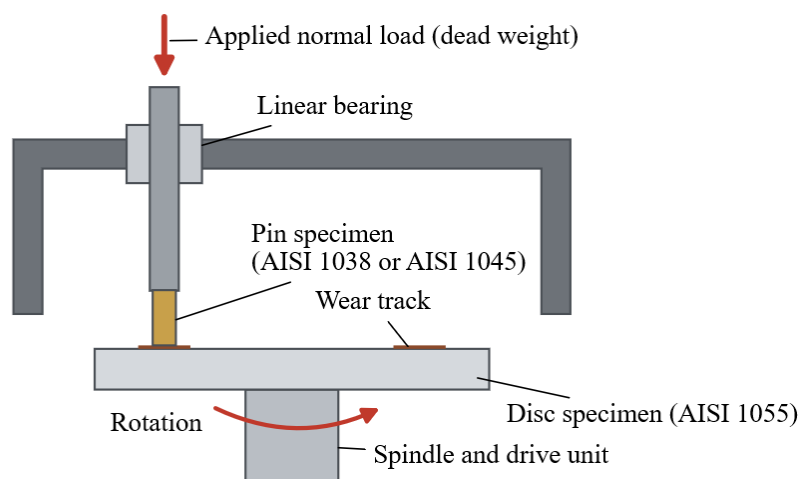


Figure 2. Schematic of the pin-on-disc contact configuration.

SEM was used to examine the worn surfaces and tracks, with particular attention to the dominant wear mechanisms and patterns of surface damage. EDS then identified the chemical composition of these regions and verified the formation of oxide films and other tribological reaction products during sliding.

Each wear test was repeated working conditions. The results were then averaged to limit random error and improve accuracy, while the standard deviation was calculated the consistency and spread of the measurements. (1):

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (1)$$

The SEM observations of repeat similar surface features and wear processes, supporting the repeatability and stability of the experimental results.

3. Results and Discussion

Figure 3 shows how pin wear changes. Across all pins, wear rises almost linearly as the load increases. This agrees with Archard's wear model [8], the real contact area and raises the pressure between the sliding surfaces. The interface also becomes hotter, which strengthens contact with the counterface, encourages material transfer,; as a result, more material is removed from the pin surface. Ceschini et al. Rajput and Das [22] reported the same trend as [9]: wear volume rises substantially with increasing normal load, while greater hardness lowers wear. those findings. Heat-treated AISI 1045 steel showed the least wear loss, attributable to its higher hardness and refined microstructure..

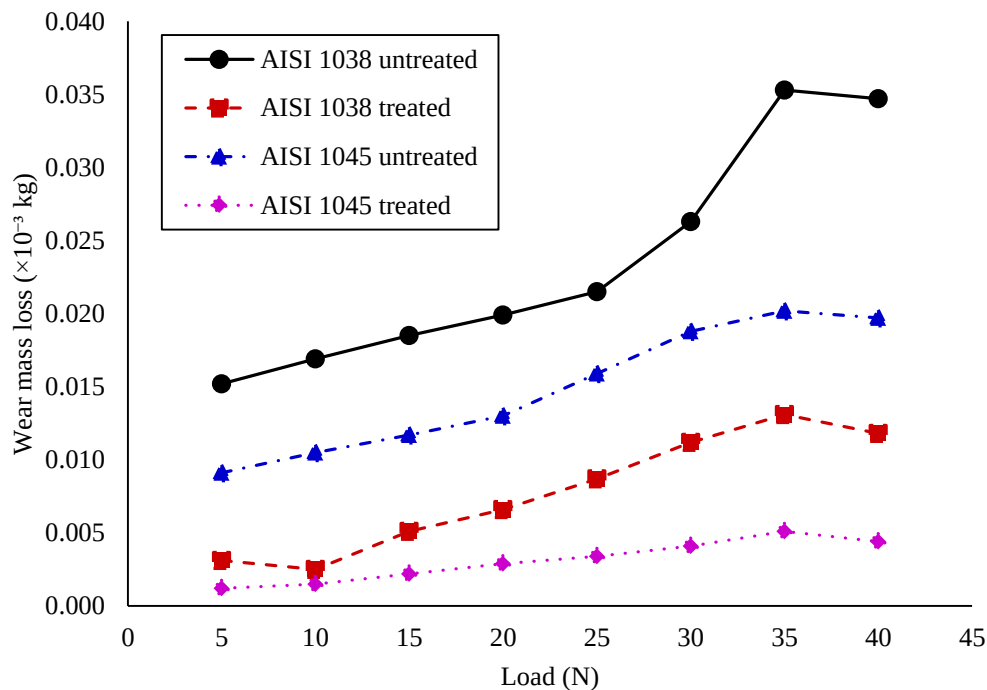


Figure 3. Wear mass loss versus applied load for untreated and treated AISI 1038 and AISI 1045 pins.

Under identical working conditions, untreated AISI 1038 lost more mass than untreated AISI 1045. The difference stems mainly from their microstructures and hardness. Both steels consisted of ferrite and pearlite, but AISI 1045 contained more pearlite, while AISI 1038 contained more ferrite. Since ferrite is softer, AISI 1038 offered less resistance to wear and plastic deformation.

AISI 1045 also had higher carbon and alloying-element contents, particularly manganese and chromium. That composition increased its hardness and improved its wear resistance, as shown in Figure 4(a, b). Gündüz et al. [14] likewise examined how microstructure affects dry-sliding wear in forging steels. Ceschini et al. [9] and Singh et al. reported similar microstructural strengthening mechanisms. [23] examined dry-sliding wear in Nb–V microalloyed martensitic steel and found that heat-treated AISI 1045 lost far less material than untreated steel. Its tempered martensitic structure resisted deformation at the sliding surface..

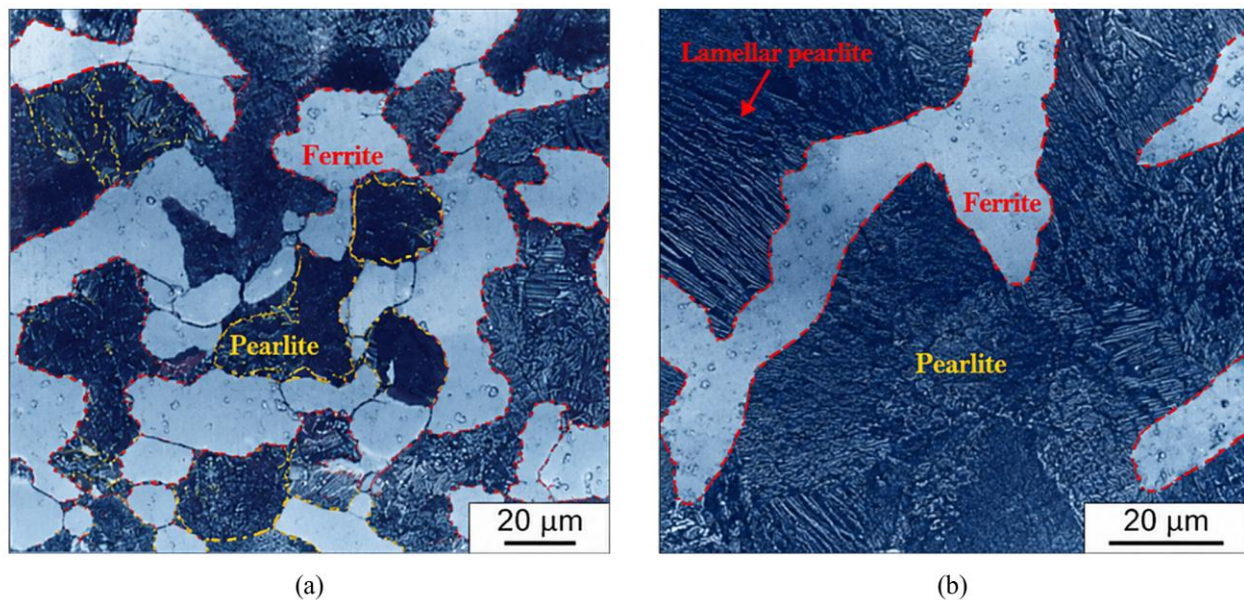


Figure 4. Optical micrographs of the untreated steels showing ferrite (light) and pearlite (dark): (a) polygonal ferrite with pearlite colonies; (b) lamellar pearlite colonies surrounded by ferrite.

At the relatively low loads of 5–20 N, wear remained slight because only a small portion of the two sliding surfaces actually touched. Adsorbed films and oxide layers covered the contact points, limiting direct metal-to-metal interaction between asperities and providing a lubricating barrier [19], [20]. Figure 5(a, b) presents SEM images of the surfaces worn under a 20 N load. [4]. Hard asperities and loose wear particles likely produced the grooves by sliding between the two surfaces—a pattern also reported by Ceschini et al. [9] and Singh et al. [23].

At the higher load of 40 N, wear became substantially more severe. As shown in Figure 6(a, b), the damaged surfaces exhibited pronounced plastic deformation, adhesion, delamination, and material loss. This delamination likely resulted from cracks forming and spreading beneath the surface under repeated plastic shear [24]. Frictional heating also raised the contact temperature enough to promote oxidation.

Once detached, the oxidised fragments remained between the sliding surfaces as hard third-body particles, intensifying abrasion and further damaging the surfaces. Dense oxide layers offered some protection, however, by reducing severe adhesion metal-to-metal contact. This agrees with previous findings to severe wear depends on the stability of tribo-oxide layers [15], [21]. Figure 6(c,d) shows EDS spectra for untreated AISI 1038 and AISI 1045 steels. In both cases, the strong Fe peak indicates that by the steel substrate. iron oxide tribofilms formed during dry sliding, as frictional heating under. Carbon comes mainly from the steel matrix, although a small amount may have come. Weak Mn and Si signals match. Small Cr peaks may also appear, depending on detector resolution; the alloys themselves or from limited transfer of material from the hardened AISI 1055 counterface., AISI 1038 produced a noticeably stronger oxygen peak than AISI 1045. to more extensive oxidation during sliding,: the AISI 1038 surface showed greater plastic deformation, heavier material transfer,. AISI 1045, being harder, resisted plastic deformation more effectively and took longer to develop severe surface damage.. Ceschini et al. [9] and Li et al. [25] reported similar findings, showing that wear resistance depends not only on hardness but also on how the carbides are distributed...

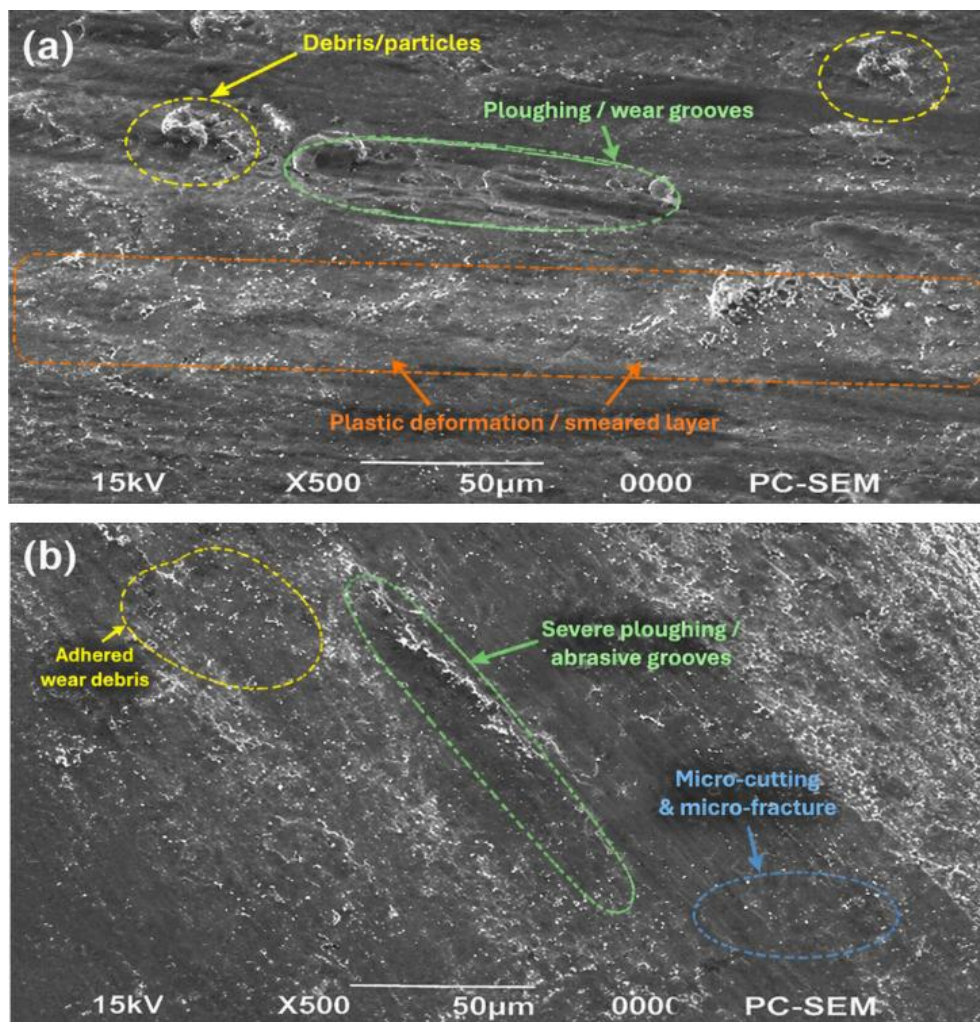


Figure 5. SEM micrographs of worn pin surfaces at 20 N: (a) ploughing grooves and wear debris; (b) deeper grooves, adhered debris, and micro-fracture.

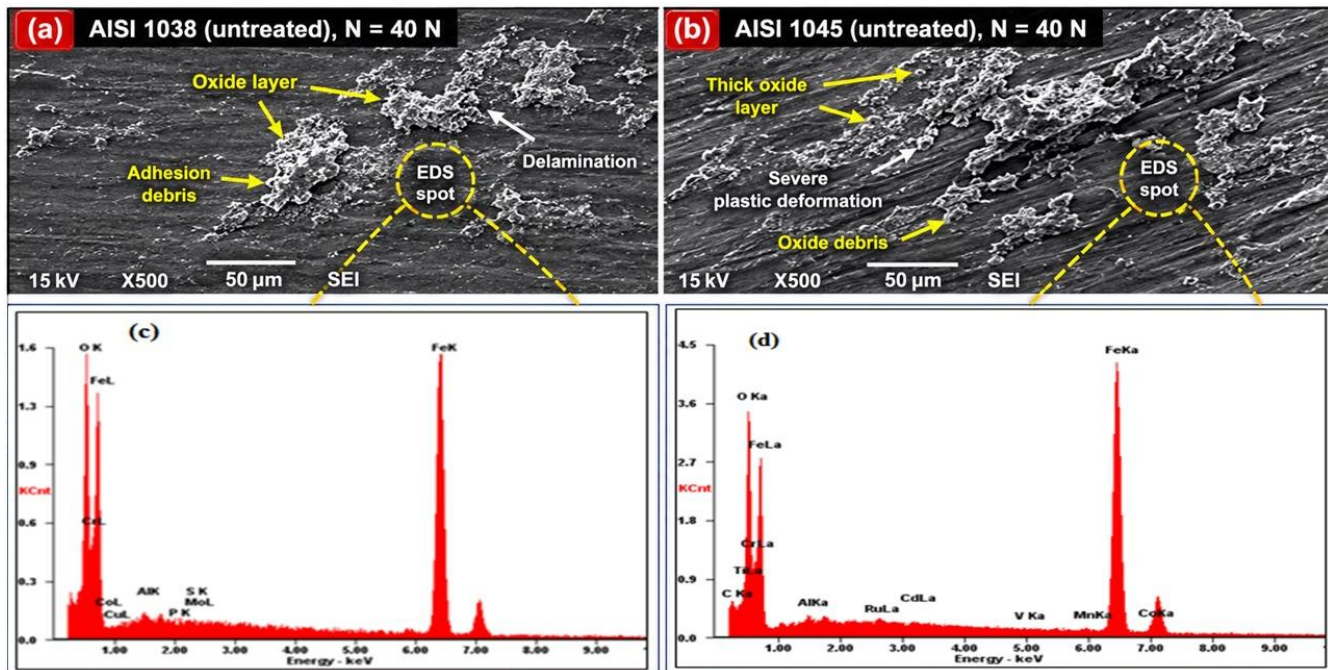


Figure 6. Worn surfaces of untreated pins at 40 N and corresponding EDS spectra: (a, c) AISI 1038; (b, d) AISI 1045.

Figure 3 shows that the heat-treated pins. Quenching and tempering raised the hardness of AISI 1038 to about 30 HRC and AISI 1045 to roughly 35 HRC. treated AISI 1045 performed best, recording the lowest wear rate.. Quenching produced martensite, a very hard structure made up of lath- or needle-like phases [16]. Martensite can be brittle, so tempering followed improve structural stability [17]., more closely spaced pearlite lamellae in AISI 1045 steel than in AISI 1038 steel. resistance. Jiang et al. [26] likewise found that refining the microstructure improves the mechanical stability of medium-carbon steels.

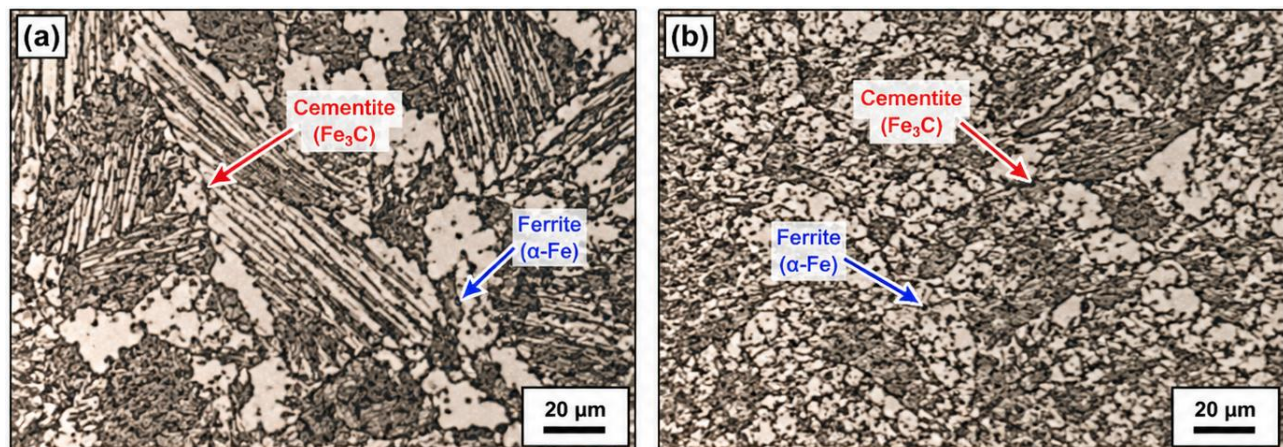


Figure 7. Microstructures after quenching and tempering: (a) AISI 1038 (30 HRC); (b) AISI 1045 (35 HRC).

Quenching a harder tempered-martensitic matrix, which reduced severe plastic deformation and repeated oxide-film fracture; the stronger matrix [18],

Among the heat-treated steels, AISI 1045 maintained. The oxide film therefore stayed intact for longer during sliding, limiting direct metal contact and reducing adhesive wear.

These results are consistent with Ceschini et al. [9], -carbon steels retain more stable oxide layers during dry sliding and delay adhesive wear. Li et al. [25] similarly showed that suitable hardness limits plastic deformation the formation of wear debris. Singh et al. [23] also reported that martensitic microstructures restrict subsurface deformation. Taken together, the SEM and EDS results indicate that heat treatment improves wear resistance it also supports the formation and persistence of protective oxide films, which limit direct metal-to-metal contact during dry sliding..

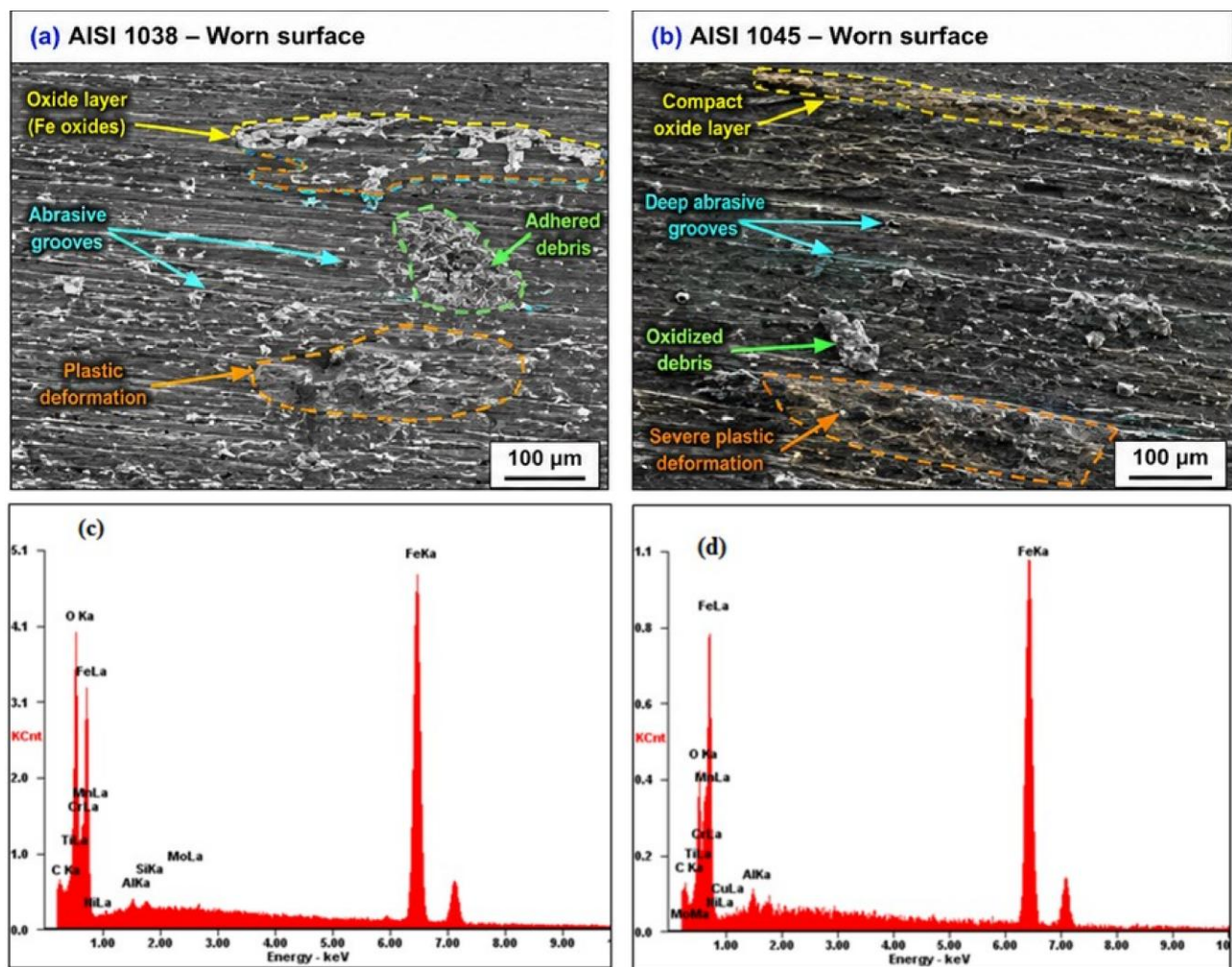


Figure 8. Worn surfaces of heat-treated pins at 40 N and corresponding EDS spectra: (a, c) AISI 1038; (b, d) AISI 1045.

4. Conclusions

This study examined by heat treatment affect dry sliding wear in untreated and quenched-and-tempered AISI 1038 and AISI 1045 medium-carbon steels, the counterface. Earlier research generally examined one steel grade or a single heat-treatment route. compared under the same dry-sliding conditions, with their wear behaviour related to microstructure, hardness, and damage at the sliding surface. Wear loss rose steadily as the normal load increased. The greater contact pressure, together with frictional heating, promoted plastic deformation. Heat treatment made both steels more resistant to wear: it changed the ferrite–pearlite structure which increased hardness and limited adhesive deformation. Quenched-and-tempered AISI 1045 with the highest hardness and the lowest mass loss.

SEM images showed a clear transition in wear mechanisms as the applied load increased; mild abrasion dominated at low loads, whereas severe adhesive wear and three-body abrasion were prevalent at higher loads. Energy-dispersive X-ray spectroscopy (EDS) area analysis revealed oxygen-rich tribofilms on the worn surfaces. These protective oxide layers played a crucial role in limiting direct metal-to-metal contact and enhancing overall wear resistance, particularly in the heat-treated specimens. By preserving these intact oxide films, the treated steel surfaces were able to support significantly higher mechanical loads. Furthermore, the observed relationships between hardness, applied load, and wear behavior strongly aligned with established predictive trends, confirming the effectiveness of heat treatment in optimizing tribological performance.

Limitations of the study

This study has several limitations. at ambient temperature in air, so the results may not apply directly to industrial settings involving lubrication, contaminated environments. The experiments also covered only a narrow range of sliding speeds, leaving other conditions common in mechanical systems unexamined.

Suggested future work

Future work should test these steels different sliding speeds, including lubricated tests that better reflect industrial conditions. surface coatings reduce friction and limit wear. X-ray diffraction (XRD) (TEM), and 3D surface profilometry would reveal subsurface deformation, residual stresses, and how cracks begin, giving a clearer picture of wear progression. Analytical.

Declaration of generative AI and AI-assisted technologies in the writing process

-None

Disclosures

The authors have no conflicts of interest to declare in relation to this manuscript.

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دراسة تجريبية لبلى السطح وتقييم الأضرار الناجمة تحت ظروف الانزلاق الجاف في الفولاذ متوسط الكربون

الخلاصة: تُبين هذه الدراسة مدى مقاومة الفولاذات متوسطة الكربون للبلى الانزلاقي الجاف، وهي مواد تُستخدم على نطاق واسع في مكونات مثل المفاصل المتحركة وقضبان التوجيه في ماكينات التحكم الرقمي بالحاسوب (CNC). أُجريت اختبارات البلى باستخدام جهاز الديوس على القرص (Pin-on-Disc) تحت ظروف بيئية اعتيادية لتقييم سلوكي فولاذي AISI 1038 و AISI 1045 عند احتكاكهما بفولاذ AISI 1055 المقسى. كما تم التحقيق في تأثير المعالجة الحرارية والحمل المطبق على مقاومة البلى. تم تقييم العينات في حالتها الأصلية (كما استلمت) وكذلك بعد عمليات التقسية والمراجعة الحرارية (Quenching and Tempering). على بيانات فقدان الكتلة تحت أحمال تراوحت بين 5 و 40 نيوتن وعند سرعة انزلاق ثابتة مقدارها 0.5 م/ث، تم حساب أداء البلى. كما استُخدم كل من المجهر الإلكتروني الماسح (SEM) ومطيافية تشتت الطاقة للأشعة السينية (EDS) لدراسة آليات البلى والأضرار السطحية. أظهرت النتائج أن معدل البلى ازداد مع زيادة الحمل المطبق، في حين أن زيادة الصلادة أدت إلى تحسين مقاومة البلى. كما ساهمت المعالجة الحرارية في تعزيز متانة كلا النوعين من الفولاذ من خلال إحداث تغييرات في البنية المجهرية. ومن بين المواد المختبرة، أظهر فولاذ AISI 1045 المعالج حرارياً أفضل أداء من حيث مقاومة البلى وأقل فقدان في الكتلة. وقد ارتبط هذا السلوك ببنية المحسنة المكونة من البيرلايت (Pearlite) والمارتنسيت (Tempered Martensite)، مما ساعد على تقليل الضرر الناتج عن البلى الكاشط وزيادة الصلادة. وأظهرت فحوصات الأسطح أن الأحمال المنخفضة أدت إلى بلى كاشط طفيف، بينما تسببت الأحمال المرتفعة في حدوث الالتصاق والتقشر الطبقي (Delamination) وتلف السطح. كما تبين أن طبقات الأكاسيد المتكونة أثناء الانزلاق عملت كأغشية احتكاكية واقية (Tribofilms) حذت من البلى من خلال تقليل التلامس المباشر بين الأسطح المعدنية. وتؤكد النتائج أن نسبة الكربون، والبنية المجهرية، وظروف المعالجة الحرارية تؤثر بشكل كبير في مقاومة البلى. وقد حقق فولاذ AISI 1045 أفضل مزيج من مقاومة البلى والصلادة عند تطبيق عمليات التقسية والمراجعة الحرارية بصورة محكمة ومضبوطة.

الكلمات المفتاحية: البلى الانزلاقي الجاف؛ السلوك الاحتكاكي؛ المعالجة الحرارية؛ الفولاذ متوسط الكربون؛ فولاذ AISI 1038 .