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Tribological Evaluation of Additively Manufactured Steels for Applications in Fuel Environments

by A Macknoja, C McCoy, VL Montoya, E Cairns, N Murthy,
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<p>The incorporation of traditional steels in combustion engines poses challenges in adapting to evolving manufacturing designs, repair requirements, and performance demands. However, the emergence of additive manufacturing has provided a promising solution by enabling the integration of new steel compositions for mechanical systems. This study focuses on evaluating the tribological performance of three additively manufactured steels containing 8–20 wt% carbides and carbonitrides dispersed in a steel matrix to determine their suitability for diverse fuel environments, specifically resembling conditions encountered in high-pressure diesel fuel pumps. The selection of these steels was based on their properties. Through a comprehensive tribological analysis, we investigated the behavior of these additively manufactured steel candidates in terms of friction and wear across different fuel environments. Our results unveiled distinct performance variability among the investigated additively manufactured steel candidates, depending on the specific fuel environment. We summarize the additively manufactured candidate steel behavior in ethanol and decane fuel surrogates to support informed decision-making regarding implementation of different fuel chemistries in practical scenarios. This research contributes to the ongoing efforts to advance additive manufacturing techniques and novel steel compositions to enhance the adaptability and performance of mechanical systems within fuel systems for combustion engines.</p>					
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Contents

List of Figures	iv
List of Tables	v
Acknowledgments	vi
1. Introduction	1
2. Experimental Procedure	2
2.1 Materials	2
2.2 Tribological Testing	3
2.3 Characterization	4
3. Results and Discussion	5
4. Conclusions	14
5. References	16
List of Symbols, Abbreviations, and Acronyms	19
Distribution List	20

List of Figures

- Fig. 1 (a) Schematic illustration showing HFRR reciprocating ball-on-disk sliding experiments in a fuel environment. (b) Summary of the results obtained by nanoindentation analysis on the surface of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel. (c) Table summarizes the average hardness and average elastic modulus of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel. 5
- Fig. 2 Coefficient of friction behavior showing the performance in an ethanol-lubricated environment of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (a) alumina counterbody and (c) 52100 counterbody under high-frequency reciprocating rig at frequency of 20 Hz under 10 N as function of cycles. (b and d) Surface morphology of sliding paths and counterface ball surfaces. The scale bar is 200 μm . . 8
- Fig. 3 Coefficient of friction behavior showing the performance in a decane-lubricated environment of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (a) alumina counterbody and (c) 52100 counterbody under high-frequency reciprocating rig at a frequency of 20 Hz under 10 N as a function of cycles. (b and d) Surface morphology of sliding paths and counterface ball surfaces. The scale bar is 200 μm 9
- Fig. 4 Summary of steady-state friction values of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (a) alumina counterbody and (d) 52100 counterbody under high-frequency reciprocating rig at a frequency of 20 Hz under 10 N load in ethanol and decane environment. Counterbody wear rate for (b) alumina counterbody and (e) 52100 counterbody after sliding the same cycles against 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel under ethanol and decane. The flat wear rate of 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (c) alumina counterbody and (f) 52100 counterbody under ethanol and decane environment. 12
- Fig. 5 Surface profile of 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel, 20 wt% carbides/nitrides steel against (a) alumina counterbody and (c) 52100 counterbody, after sliding in ethanol environment. Surface profile of 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel, 20 wt% carbides/nitrides steel against (b) alumina counterbody and (d) 52100 counterbody, after sliding in decane environment. 13

List of Tables

Table 1	Steel composition.....	2
Table 2	Average roughness and Vickers hardness of AISI 52100 and additively manufactured steels specimens	3
Table 3	Tribological testing parameters in fuel environments	4

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1. Introduction

High-pressure fuel systems in combustion engines are subjected to extreme conditions due to the poor viscosity and lubricating properties of fuels, tight tolerances to prevent leakage of high-pressure fuel, and high local contact pressures. These systems rely on effective lubrication to minimize wear and prevent failures. However, conventional lubrication mechanisms often fail to provide sufficient protection due to the low viscosity of the fuels involved. As a result, reciprocating contacts within the fuel system experience high wear rates and are prone to scuffing failure, particularly after prolonged operation.¹⁻⁴ Despite the use of additives to enhance fuel lubricity, sliding steel surfaces remain susceptible to wear and degradation.⁵⁻¹⁰ The current design for fuel pumps typically utilizes hardened AISI-52100 tool steel, a widely employed material known for its strength and wear resistance properties.^{6,11-15} However, the increasing emphasis on zero-carbon emission goals has led to the exploration of low-viscosity fuels like ethanol and gasoline-ethanol blends^{8-10,16} and lower lubricity synthetic jet fuels.^{17,18} Unfortunately, mechanical interfaces of AISI-52100 steel exhibit high wear rates and are prone to scuffing failure when lubricated with such fuels,³ compromising the reliability of fuel delivery systems. To address this challenge, alternative strategies for material modification must be considered. Additive manufacturing (AM) techniques offer the opportunity to develop steel compositions with tailored properties, presenting potential improvements in tribological performance and adaptability to changing manufacturing designs and repair requirements, and performance demands.

VBN Components AB has developed steels optimized for AM processing and containing large amounts of dispersed carbides and carbonitrides (<https://vbncomponents.com/materials>). These additively manufactured steels offer increased hardness, toughness, and corrosion resistance, which are vital for withstanding the demanding conditions encountered within fuel systems. This study focused on the concept of replacing conventional AISI 52100 steel with additively manufactured steels, evaluating their tribological performance and suitability for fuel pump applications. Through a comprehensive tribological analysis encompassing friction and wear investigations, the performance variability of several AM steel candidates across various fuel environments was explored. The unique composition of the AM steels demonstrated increased durability in mechanical interface in fuel environment versus AISI 52100 steel. Tribometer measurements, coupled with the examination of wear rates under different fuel environments and counterbody materials, offered valuable data to understand the tribological properties of the additively manufactured steel samples and their

potential applications in various operating conditions. By contributing to the understanding of fuel-lubricated behavior in sliding mechanical interfaces with novel steel compositions produced through AM techniques, this research aims to drive advancements in the design and functionality of mechanical systems within combustion engines.

2. Experimental Procedure

2.1 Materials

The additively manufactured steels used in this study were obtained from VBN Components AB (Sweden). Three different types of steel samples were analyzed, each with a distinct composition. Table 1 provides a summary of the composition of these additively manufactured steels in comparison to 52100 steel. The three additively manufactured steel types examined are designated as 8 wt% carbides steel, 20 wt% carbides steel, and 20 wt% carbides/nitrides steel. The 8 wt% carbides steel is composed of a higher chromium and vanadium content and exhibits a higher hardness than 52100 steel. The 20 wt% carbides steel has elevated levels of molybdenum, tungsten, vanadium, and cobalt, leading to the highest hardness of the three materials. Lastly, 20 wt% carbides/nitrides steel displays increased chromium and vanadium content, contributing to increased corrosion resistance. The comparison to 52100 steels served as a reference point to evaluate the distinctive characteristics and performance of these additively manufactured steel samples. The 52100 steel, a widely used bearing steel, possesses well-established composition and mechanical properties, providing a benchmark for comparison in this study. By investigating the unique compositions of the different additively manufactured steel samples, we aimed to understand the influence of varying alloying elements on the material's properties and performance.

Table 1 Steel composition

Material (Composition)	Fe wt. %	C wt. %	Cr wt. %	Mo wt. %	W wt. %	V wt. %	Co wt. %	Mn wt. %	S wt. %	Si wt. %	P wt. %	Carbides %	Carbide/Nitrides %
AISI 52100 Steel	Bal	1.1	1.6	-	-	-	-	0.45	0.025	0.30	0.025	6%	-
8% Carbides AM Steel	Bal	1.5	4.0	2.5	2.5	4.0	-	-	-	-	-	8%	-
20% Carbides AM Steel	Bal	2.30	4.2	7.0	6.5	6.5	10.5	-	-	-	-	20%	-
20% Carbides/Nitrides AM Steel	Bal	1.9	20	1.0	-	4.0	-	-	-	-	-	-	20%

Specimens underwent a specific process by VBN (the company responsible for their fabrication). Initially, the specimens were printed using the AM technique. Following printing, a heat treatment process was applied to enhance the material's properties. Once the printing and heat treatment were completed, the specimens were further polished to achieve a mirror-like finish.

To evaluate the surface roughness of the additively manufactured steel samples and provide a quantitative comparison, average roughness measurements were performed using a white light interferometer from Filmetrics Profilm3D manufactured by KLA Instruments. The white light interferometer is a noncontact optical measurement instrument that provides high-resolution surface topography data. Table 2 summarizes the average roughness values obtained for all the additively manufactured steels, as well as for 52100 steel. The roughness values ranged from approximately $51\text{--}55 \pm 14$ nm for both 52100 steel and all additively manufactured steel samples.

The bulk mechanical properties of the additively manufactures steels is shown in Table 2. The Vickers hardness (HV) of the steels was obtained from an average of 10 measurements using a Mitutoyo HM-200. Additional properties of the additively manufactured steels were studied by Hammond et al.¹⁹

Table 2 Average roughness and Vickers hardness of AISI 52100 and additively manufactured steels specimens

Material (composition)	Average roughness (nm)	Hardness (HV)
AISI 52100 steel	51 ± 12	809.6 ± 26.1
8 wt% Carbides additively manufactured steel	51 ± 9	741.5 ± 14.9
20 wt% Carbides additively manufactured steel	53 ± 11	1059.5 ± 17.4
20 wt% Carbides/nitrides additively manufactured steel	55 ± 14	664 ± 14.3

2.2 Tribological Testing

The specific wear rate of each sample was evaluated using a high-frequency reciprocating rig (HFRR) tribometer, specifically the Phoenix TE-77 model. The tribometer allowed for controlled testing in two different fuel environments: ethanol and decane. The effect of a chemically inert counterbody was investigated by conducting tests in ethanol and decane fuel environments using two different counterbody materials: a 10-mm AISI 52100 ball and a 10-mm Al₂O₃ ball.

The HFRR tribometer is a widely used instrument for studying the friction and wear behavior of materials under realistic operating conditions. It provides precise control over testing parameters and enables accurate measurement of wear rates.

Table 3 contains detailed information regarding the specific testing parameters used in this study. These parameters include load, sliding distance, frequency, temperature, and lubrication conditions, among others. During the testing process, each additively manufactured steel sample was subjected to reciprocating sliding motion against the selected counterbody material, with the fuel environment serving as the lubricating medium. Two distinct counterbody materials were used to assess the influence of surface chemistry and hardness on the wear behavior of the additively manufactured steels.

Table 3 Tribological testing parameters in fuel environments

Operating parameter	Value
Applied load	10 N
Maximum contact pressure	1.01–1.18 GPa
Stroke length	10 mm
Temperature	40 °C
Frequency	20 Hz
Average sliding velocity	400 mm/s

To determine the specific wear rate, the material loss of each sample after testing was measured and normalized by considering the sliding distance and applied load. This normalization allowed for a direct comparison of the wear rates among different samples and under varying test conditions. By conducting tribological tests in both ethanol and decane fuels, we aimed to assess the performance of the additively manufactured steels samples in chemically different lubricating environments similar to those found in fuels. Ethanol provided a polar alcohol environment similar to E-85, and decane provided an alkane environment similar to the main components of gasoline and kerosene jet fuel. Additionally, comparing the wear behavior with different counterbody materials, namely AISI52100 steel and Al₂O₃, provided insights into the tribological compatibility and wear mechanisms of the additively manufactured steels.

2.3 Characterization

Nanoindentation testing was performed on each sample to determine their hardness and elastic modulus. The KLA Nanoindenter was used to conduct the indentations. To analyze the wear tracks on the flat sides and the ball wear scars formed after the tribological tests, the Zeiss optical microscope was used. After the completion of the tribological testing, wear volumes were estimated by averaging three cross-sectional profilometry scans taken with a Filmetrics Profilm 3D profilometer. The wear volume of the entire wear track was obtained, allowing for the calculation of the predicted wear rate for each set of testing conditions. Additionally, the wear

volumes of the counterbody materials were determined using optical measurements taken with a Zeiss LSM 700 Optical Microscope. The wear scar diameter, as per the ASTM D6079 standard,⁶ was measured and used to calculate the average wear volume of each counterbody.

By employing a combination of nanoindentation testing, optical microscopy, and profilometry, a comprehensive characterization of these steel's mechanical properties, wear features, and wear volumes was achieved. This detailed analysis provides crucial information to understand the performance and durability of these additively manufactured steels under tribological conditions.

3. Results and Discussion

Figure 1 presents key information regarding the HFRR and the mechanical properties of the samples investigated in this study.

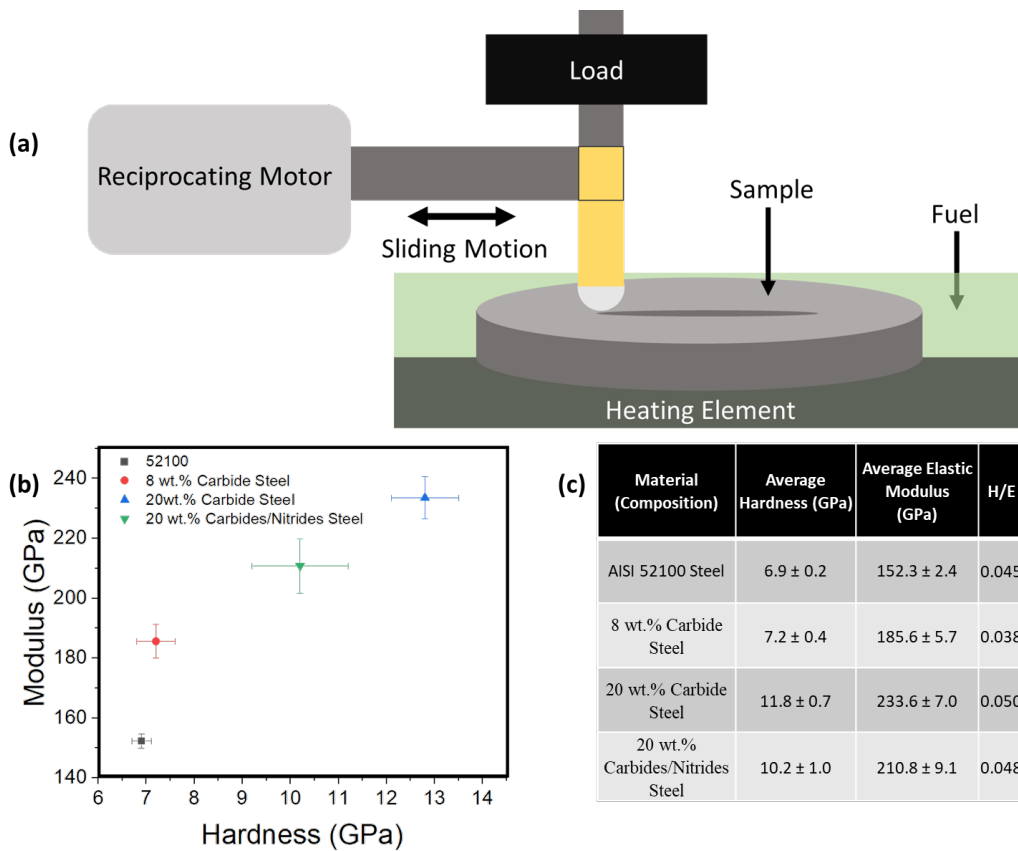


Fig. 1 (a) Schematic illustration showing HFRR reciprocating ball-on-disk sliding experiments in a fuel environment. (b) Summary of the results obtained by nanoindentation analysis on the surface of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel. (c) Table summarizes the average hardness and average elastic modulus of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel.

Figure 1a illustrates a schematic representation of the HFRR used for tribological testing. This rig plays a crucial role in simulating real-world operating conditions and evaluating the performance of materials under sliding contact. Its design and functionality ensure controlled and repeatable testing, allowing for an accurate assessment of friction and wear behavior. Figures 1b and 1c provide detailed insights into the mechanical properties of the samples, obtained through nanoindentation testing. Figure 1b displays the relationship between the elastic modulus and hardness for the samples, including 52100 and additively manufactured steels. This plot offers a comprehensive view of the materials' mechanical response and their relative hardness and stiffness.

From Fig. 1b, it can be observed that the elastic modulus tends to increase with increasing hardness. This trend indicates that the materials with higher hardness values exhibit enhanced stiffness and resistance to deformation. Among the samples, additively manufactured 20 wt% carbides steel demonstrates the highest hardness and elastic modulus, indicating better mechanical properties for protecting the surface in fuel-lubricated mechanical interfaces, such as higher hardness and elastic modulus, as compared to the other materials. Figure 1c presents a summarized table of the average hardness, elastic modulus, and hardness/elastic modulus values for 52100 and additively manufactured steels. It is evident from the table that the additively manufactured steels exhibit higher hardness and elastic modulus values compared to 52100 steels.

The observed differences in mechanical properties among the selected samples can be attributed to their unique compositions and microstructures. The presence of alloying elements, such as chromium, vanadium, molybdenum, tungsten, and cobalt in the additively manufactured steels contributes to their higher hardness and stiffness. In additively manufactured 8 wt% carbides steel, the carbon content is relatively low at 1.50 wt%. As a result, the formation of carbon-rich phases will be limited. Additively manufactured 20 wt% carbides steel has a higher carbon content of 2.30 wt%, indicating a greater potential for the formation of carbon-rich phases. Lastly additively manufactured 20 wt% carbides/nitrides steel had a similar carbon content to the 8 wt% carbides steel, but with the addition of nitrides. Each of these steels contains fine carbides according to the manufacturer (Company-provided datasheets, 2017: Vibenite 150 Material Datasheet,²⁰ Vibenite 280 Material Datasheet,²¹ Vibenite 350 Material Datasheet²²). Overall, the percentage of carbon phases in the additively manufactured steels varies based on the carbon content and additional alloying elements. The 8–20 wt% carbide and 20 wt% carbides/nitrides steel are expected to have carbon phases, including cementite, martensite, and potentially retained austenite. The 20 wt% carbides/nitrides steel contains finely

structured carbides of Cr_{23}C_6 , Cr_7C_3 , and vanadium carbide (VC), (Vibenite 350 Material Datasheet²²); however, it may also contain carbon-nitride phases.

The results presented in Fig. 1b and c highlight the potential of the additively manufactured steels, particularly additively manufactured 20 wt% carbides steel, as promising materials for applications requiring high mechanical strength and stiffness. The mechanical properties such as higher hardness and elastic modulus of additively manufactured 20 wt% carbides steel as compared to 52100 steel makes it a suitable candidate for demanding tribological applications, where resistance to deformation and wear is crucial.

The friction behavior of the tested materials in different fuel environments (ethanol and decane) and with two distinct counterbody materials (alumina and 52100) was examined in this study. Figure 2 provides insights into the frictional behavior observed during tribological testing in ethanol, while also showing the wear morphology on the flat and counterbody surfaces. In Fig. 2a, the frictional behavior of additively manufactured 20 wt% carbides steel was found to have similar frictional properties to that of 52100 steel, which were slightly lower in friction than additively manufactured 8 wt% carbides steel and 20 wt% carbides/nitrides when using alumina as the counterbody in the ethanol environment. On the other hand, when using 52100 as the counterbody material (Fig. 2c), 52100 steel flat surfaces had a lower coefficient of friction than all the additively manufactured steels. The optical micrographs in Fig. 2b and d provide a visual representation of the wear scars on the flat and counterbody surfaces. Comparing the wear scars formed when using alumina as the counterbody (Fig. 2b) with those formed when using 52100 as the counterbody (Fig. 2d), it can be observed that the wear scars on the ball and wear tracks appear significantly smaller when alumina is used as the counterbody material.

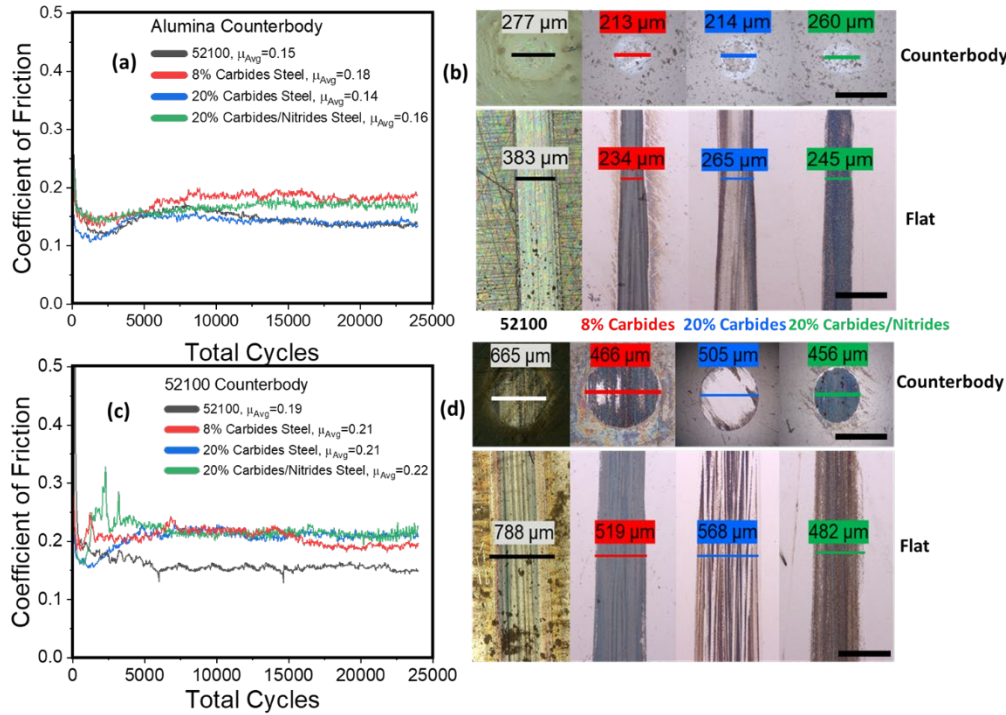


Fig. 2 Coefficient of friction behavior showing the performance in an ethanol-lubricated environment of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (a) alumina counterbody and (c) 52100 counterbody under high-frequency reciprocating rig at frequency of 20 Hz under 10 N as function of cycles. (b and d) Surface morphology of sliding paths and counterface ball surfaces. The scale bar is 200 μm .

The use of alumina as the counterbody appears to result in reduced wear on both the flat and counterbody surfaces compared to using 52100 as the counterbody material. The frictional behavior of additively manufactured 20 wt% carbides steel in ethanol, as shown in Fig. 2a, can be attributed to its composition, microstructure, and higher hardness. The presence of alloying elements, such as molybdenum, tungsten, vanadium, cobalt, and formation of 20 wt% carbides may contribute to improved tribological performance, reducing the friction and wear of the material under these test conditions. The selection of the counterbody material, as well as the fuel environment, significantly affected the frictional behavior and wear characteristics of the tested materials. The observed differences in wear scar size and friction behavior highlight the importance of considering tribological compatibility and the specific conditions in which the materials will be used.

The friction behavior of the additively manufactured steels with different counterbody materials (alumina and 52100) in the decane environment was investigated, and the results are presented in Fig. 3. The performance of the

additively manufactured steels varied depending on the choice of counterbody material.

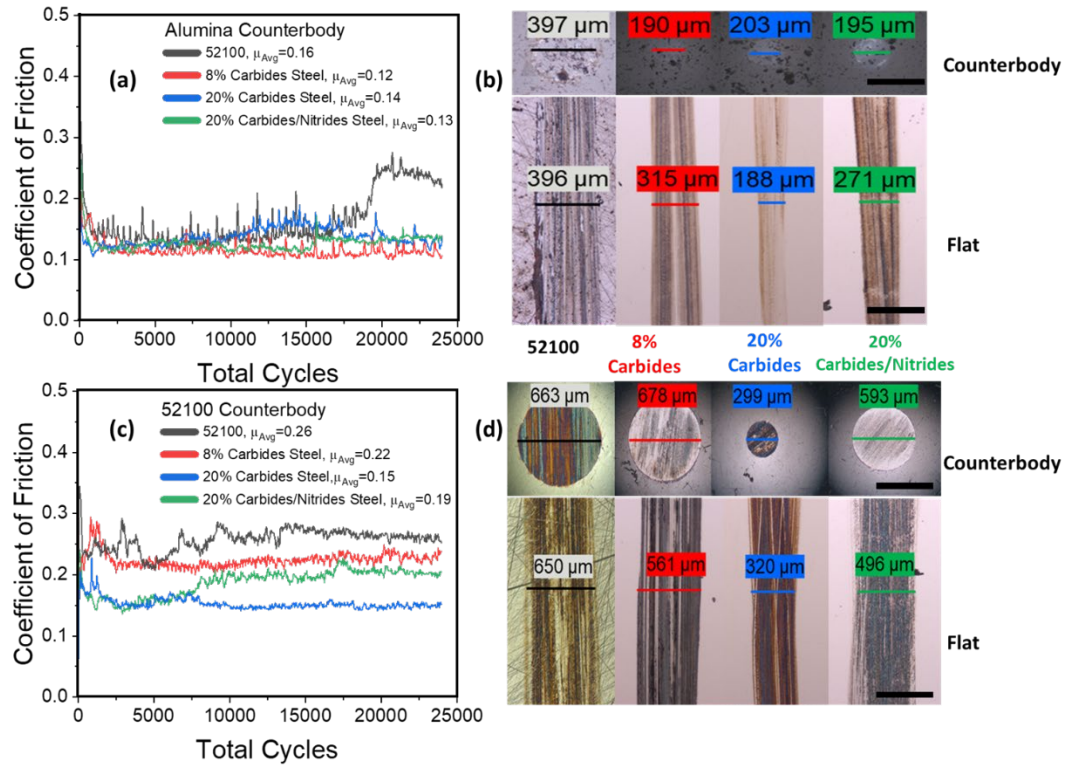


Fig. 3 Coefficient of friction behavior showing the performance in a decane-lubricated environment of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (a) alumina counterbody and (c) 52100 counterbody under high-frequency reciprocating rig at a frequency of 20 Hz under 10 N as a function of cycles. (b and d) Surface morphology of sliding paths and counterface ball surfaces. The scale bar is 200 μm .

Figure 3a demonstrates that when alumina was used as the counterbody material in the decane, 8 wt% carbides steel exhibits a lower friction compared to 52100 and all other additively manufactured steels.

When 52100 was used as the counterbody material in decane (Fig. 3c), additively manufactured 20 wt% carbides steels had a lower friction than the other additively manufactured steels. The contrasting results underscore the significant influence of the counterbody material on the friction behavior and wear performance of the additively manufactured steels. The choice of counterbody material affects the tribological compatibility and the interaction between the materials, leading to distinct frictional responses.

Visual representations of the wear scars on the flat and counterbody surfaces are shown in Figs. 3b and d. Figure 3b illustrates that the wear scar on the alumina counterbody appeared less visible and slightly polished after testing. In contrast,

Fig. 3d demonstrates that when a 52100 counterbody was used, the wear scars on both the flat and counterbody surfaces were more prominent and visible. The contrasting wear scar appearances further emphasize the influence of the counterbody material on the friction behavior and wear characteristics. The use of alumina as the counterbody results in smaller, less pronounced wear scars, indicating potentially reduced wear accompanying the generally lower coefficient of friction. Conversely, the use of 52100 as the counterbody led to more visible wear scars, showing increased wear as compared to alumina.

The wear scars were also different in size among the different steels for the same counterbody. Figure 3b displays the wear scar results when alumina counterbody was tested against different materials. It shows that when alumina was run against 52100 steel, it exhibited a larger wear scar compared to all the additively manufactured steels that contained 8–20 wt% carbide and carbon/nitrides. The wear scar measurements for alumina against 52100 steel, alumina against 8 wt% carbides steel, alumina against 20 wt% carbides steel, and alumina against 20 wt% carbides/nitrides steel are 397, 190, 203, and 195 μm , respectively. The results indicate that the additively manufactured steels with carbide and carbon/nitrides additives wear the alumina less than the reference 52100 steel. In Fig. 3d, the wear scar results are presented when 52100 steel was used as the counterbody against 52100 steel and the additively manufactured steels. The wear scar measurements for 52100 steel against 52100 steel, 52100 steel against 8 wt% carbides steel, 52100 steel against 20 wt% carbides steel, and 52100 steel against 20 wt% carbides/nitrides steel are 663, 678, 299, 593 μm . Interestingly, the wear scar produced on the counterbody was highest when 52100 steel was tested against itself. Among the additively manufactured steels, the 8 wt% carbides steel exhibited the largest wear scar, similar in size to the 52100 counterbody test, indicating that this particular additively manufactured steel had a more significant wear impact on the 52100 counterbody. Conversely, when the 52100 steel counterbody was tested against the 20 wt% carbides steel, it showed a smaller wear scar compared to both the self-mated 52100 and the other additively manufactured steels, implying that the 20 wt% carbides steel wore the 52100 counterbody less compared to the other materials. The 8 wt% carbides steel with alumina counterbody and 20 wt% carbides steel with 52100 counterbody in the decane environment can be attributed to the specific compositions and microstructures of these additively manufactured steels. When selecting materials for tribological applications, it is crucial to consider the environmental characteristics and the choice of counterbody material. The compatibility between the materials and the specific operating conditions significantly influences friction behavior and wear resistance.

The coefficient of friction, ball wear rate, and flat wear rate of the tested materials (52100 and additively manufactured steels: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel) in ethanol and decane environments against alumina and 52100 counterbody materials were analyzed and are summarized in Figs. 4 and 5. Figure 4a provides an overview of the frictional behavior of samples tested against alumina. In the ethanol environment, additively manufactured 20 wt% carbides steel exhibited the lowest coefficient of friction, while in the decane environment, additively manufactured 8 wt% carbides steel had the lowest steady-state coefficient of friction. The ball wear rate (Fig. 4b) and flat wear rate (Fig. 4c) show that the alumina counterbody experienced higher wear against 52100 steel flat when compared to additively manufactured steels in both ethanol and decane environments. When comparing the ball wear rate of alumina against the additively manufactured steels in ethanol, 8 wt% carbides steel showed less wear than 20 wt% carbides steel and 20 wt% carbide nitrides steel. This could be due to the possibility that the flat sample was wearing faster than the ball itself in the ethanol environment. Additionally, 20 w.% carbides steel showed less wear in the ethanol environment (Fig. 4c). The profilometry scan in Fig. 5a confirms that 20 wt% carbides steel exhibited less wear loss than all other samples in the ethanol environment against an alumina counterbody.

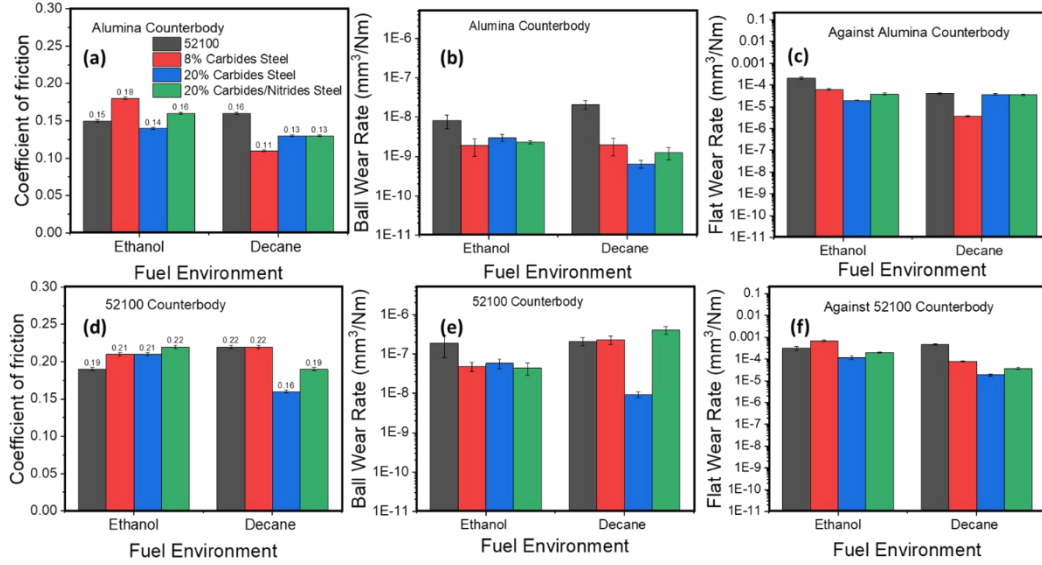


Fig. 4 Summary of steady-state friction values of 52100 and additively manufactured: 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (a) alumina counterbody and (d) 52100 counterbody under high-frequency reciprocating rig at a frequency of 20 Hz under 10 N load in ethanol and decane environment. Counterbody wear rate for (b) alumina counterbody and (e) 52100 counterbody after sliding the same cycles against 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel under ethanol and decane. The flat wear rate of 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel and 20 wt% carbides/nitrides steel against (c) alumina counterbody and (f) 52100 counterbody under ethanol and decane environment.

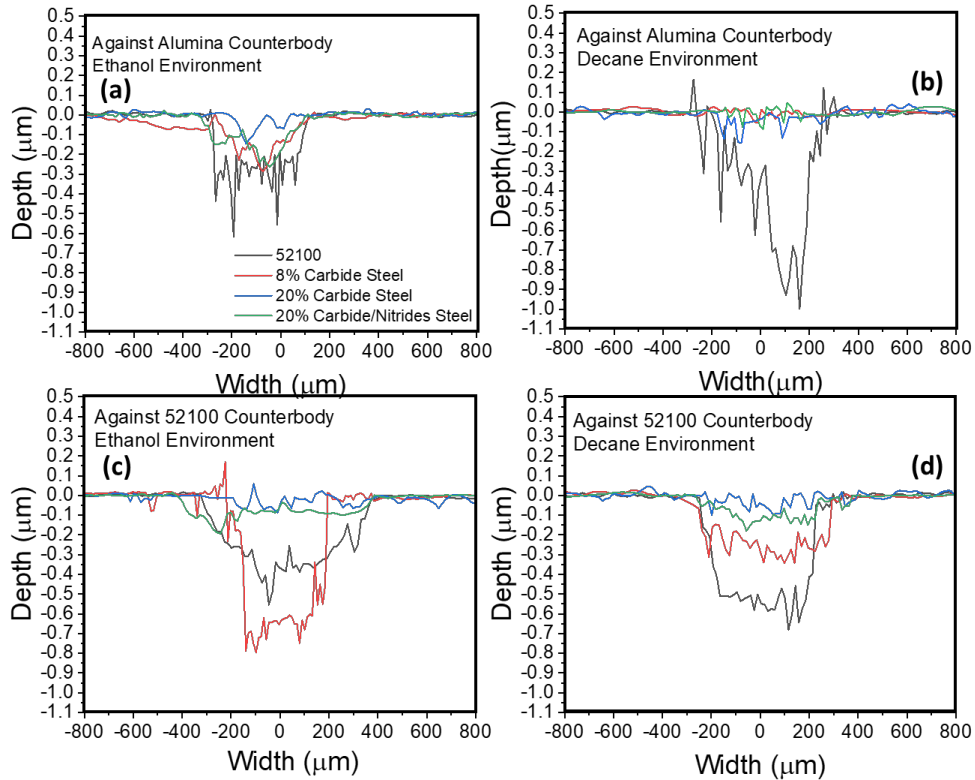


Fig. 5 Surface profile of 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel, 20 wt% carbides/nitrides steel against (a) alumina counterbody and (c) 52100 counterbody, after sliding in ethanol environment. Surface profile of 52100 and additively manufactured 8 wt% carbides steel, 20 wt% carbides steel, 20 wt% carbides/nitrides steel against (b) alumina counterbody and (d) 52100 counterbody, after sliding in decane environment.

In the decane environment (Fig. 4a), 8 wt% carbides steel had lower friction when compared with all other steel samples. The ball wear rate (Fig. 4b) demonstrates that alumina against 20 wt% carbides steel showed the lowest wear, while the flat wear rate (Fig. 4c) follows the same trend, where a lower ball wear rate corresponds to a higher flat wear rate, and vice versa. Figure 5b supports these findings, showing that additively manufactured 8 wt% carbides steel had lower wear loss than 52100 and all other additively manufactured steels. When comparing the performance of 52100 and additively manufactured steel against the 52100 counterbody in the ethanol environment (Fig. 4d), 52100 steel had the lowest average coefficient of friction. For ethanol and decane, the ball wear rate was higher when the counterbody was 52100 compared to the alumina counterbody. The trend observed in the ball and flat wear rates aligns with previous discussions, where higher ball wear rate corresponds to lower flat wear rate, and vice versa. The profilometry scan of the flats in Fig. 5c confirms that 20 wt% carbides steel exhibited less wear than all other samples in the ethanol environment.

When comparing the decane and ethanol environments, the additively manufactured 20 wt% carbides steel had lower ball and flat wear rates than 52100 and additively manufactured 8 wt% carbides steel and 20 wt% carbide/nitride steel. This is further supported by the profilometry scan of the flats in Fig. 5d, which confirmed that additively manufactured 20 wt% carbides steel exhibited the lowest wear loss. The results highlight the significant influence of the counterbody material and the environmental conditions on the tribological performance of the tested materials. The choice of counterbody material and the specific operating environment play crucial roles in determining friction behavior and wear resistance. Further investigations are necessary to gain deeper insights into the underlying mechanisms responsible for the observed friction behavior and wear performance of the tested materials. Understanding these mechanisms will aid in optimizing material selection and design for specific tribological applications, ensuring enhanced performance and durability.

4. Conclusions

In this study, we investigated the tribological performance and suitability of additively manufactured steels for fuel pump applications, with a focus on replacing conventional AISI 52100 steel. The additively manufactured steels comprised three distinct compositions: 8 wt% carbides steel, 20 wt% carbides steel, and 20 wt% carbides/nitrides steel. Through comprehensive tribological analysis, we evaluated the friction and wear behavior of these additively manufactured steels under different fuel environments (ethanol and decane) and with two counterbody materials (alumina and 52100). The results provided valuable insights into the performance and potential of the additively manufactured steels for demanding tribological applications.

The unique compositions of the additively manufactured steels significantly influenced their mechanical properties and tribological performance. The additively manufactured steels demonstrated higher hardness and elastic modulus values compared to 52100 steel, contributing to higher mechanical strength and stiffness. Among the additively manufactured steels, the 20 wt% carbides steel exhibited the highest hardness and elastic modulus. In terms of friction behavior and wear resistance, the additively manufactured steels demonstrated varying performance depending on the fuel environment and counterbody material. In ethanol, additively manufactured 20 wt% carbides steel exhibited the lowest frictional performance, while in decane, additively manufactured 20 wt% carbides steel had a coefficient of friction lower than other steel samples. The choice of counterbody material also played a crucial role, with alumina showing reduced wear compared to 52100. The observed tribological performance of the additively

manufactured steels can be attributed to their specific compositions and microstructures, as well as the resulting mechanical properties. The presence of alloying elements, such as chromium, vanadium, molybdenum, tungsten, and cobalt, contributed to improved friction behavior and wear resistance under the test conditions. Additionally, the formation of different carbon-rich phases, such as cementite, martensite, and carbides, presumably influenced the material's mechanical properties and tribological performance.

Overall, the results of this study highlight the potential of additively manufactured steels, particularly the 20 wt% carbides steel, as promising materials for applications requiring high mechanical strength, stiffness, and resistance to wear. The additively manufactured steels exhibited frictional behavior and wear resistance under specific fuel environments and counterbody materials that would be favorable for fuel system components. However, for other tribological applications, it is important to consider the specific operating conditions and compatibility between materials when selecting materials. These results demonstrate that for fuel tribological applications, we may leverage the unique capabilities of AM techniques and tailored steel compositions that can lead to significant advancements in the design and functionality of mechanical systems within combustion engines for improving their efficiency, reliability, and sustainability.

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List of Symbols, Abbreviations, and Acronyms

AM	additive manufacturing
ARL	Army Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
HFRR	high-frequency reciprocating rig
HV	Vickers hardness
UNT	University of North Texas
VC	vanadium carbide

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