Comparative Study on Dry Sliding Wear Resistance of Carbon Steel, Alloyed Steel and Cast Iron

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Abstract. The aim of this paper is to study and compare the dry sliding wear resistance of carbon steel, alloyed steel and cast iron, knowing that the sliding wear is a type of deterioration that appears in various practical applications. Experimental research of this study was mainly performed using a tribometer (CSM Tribometer) according to the pin-on-disk method (POD), aiming to determine the coefficient of friction (by graphic representation) and wear rate (by analytical calculation). The tested materials were some iron alloys, namely carbon steels (C25, C45), alloyed steel (34CrNiMo6) and cast iron (EN-GJS-400-15) respectively. The tests were performed complying with ASTM G99 Standard, keeping the same working conditions for all the investigated materials. The results obtained in this study were presented through tables with values, graphs and through characteristic images acquired with a digital microscope and a 3D laser scanning microscope, as well as with the aid of a specialized software (MultiFileAnalyzer) concerning the wear track profiles of the counterbody and tested specimens. The investigations revealed a lower friction coefficient for the cast iron, correlated with a reduced wear rate of the material, which leads to the fact that this type of material has a better resistance to sliding wear resistance compared with the other analysed materials.

1. Introduction

Fe-C alloys (steels and cast irons) present a great importance due to their high produced quantity and their variety of applications [1]. Steels are used in various applications like automotive industry, machinery and components subjected to wear [2]. Moreover, cast irons are used due to their relatively low costs and improved tribological performance [3].

In the case of non-alloyed and low-alloyed steels, higher carbons content in the structure (due to perlite and free secondary cementite) increases also the tensile strength, hardness and wear resistance [4]. In the case of gray cast irons, although these have good characteristics for exploitation (like vibration priming capacity), the presence of graphite in their structure causes their characteristics to decrease, but for the gray cast irons with nodular graphite, the spherical shape reduces the negative effects of its presence in the metallic mass, so that the mechanical characteristics of these castings are closer to those of steels [5].

The behaviour of steels and cast irons against wear and corrosion is usually investigated through many tests with professional laboratory equipment like: tribometer, scratch tester, vibratory apparatus

or others [6-16]. With the aid of the obtained experimental results, the wear resistance of these ferrous materials can be estimated. For example, by testing the materials using a tribometer through the pin-on-disk method (POD), the mass loss, volume loss, coefficient of friction (COF) and wear rate can be calculated/estimated [17].

In this way, regarding the dry sliding wear resistance of steels and cast irons, various tests were performed to investigate the influence of carbon content of steels on the most important mechanical properties of the materials [18]. Generally, it was found that the wear resistance was affected by the applied load (in the current case the load has been varied between 5 - 25 N) and moreover, it was revealed that a lower content of carbon provides less friction [19]. The friction coefficient as well as the wear rate increases when a higher sliding rate is applied [20], but the effect of load shows greater influence on wear in comparison to sliding speed [21]. Heat treatments like laser surface hardening process (in the case of the C45 alloyed steel) has been found to have a positive influence on the dry sliding wear resistance. The significantly enhanced wear resistance is attributed to the refined microstructure and to the presence of a mechanically metastable austenite phase obtained through the laser treatment [22]. Moreover, through tempering and cryogenic treatments (in case of spring steel), the results have revealed that the material condition has a significant influence on the wear performance [23]. The addition of alloying elements like manganese [24] or titanium and chromium induced a significant effect on the behaviour of cast iron wear process [25].

In the evaluation of the dry sliding wear resistance of materials with the aid of a tribometer, a significant interest it is shown regarding the surface deposition application technologies, like thermal spraying, vapor deposition or fluoropolymer coatings [26, 27]. Working with a tribometer, the testing parameters like load, speed or distance can be successively varied and different relations or new equations between these parameters can be found [28].

Accordingly, various studies present a great interest to investigate the sliding wear behavior of materials used in gears manufacturing and of different type of coatings applied on these materials respectively [29-35]. The study of dry sliding wear behaviour of steels in comparison to other systems is essential for their performance evaluation in different applications, where the wear mechanism involves adhesion, oxidation, strain hardening, or other structural changes [36].

Therefore, this work aims to study and compare the dry sliding wear resistance of three types of iron alloys which have different carbon content and which can be used in gears manufacturing. Also, through this comparative study, the authors understand better the sliding wear process by using a tribometer according to the pin-on-disk method (POD).

2. Materials and methods

The tested materials are two carbon steels C25 (1.0406) and C45 (1.0503), an alloyed steel 34CrNiMo6 (1.6582), which was heat treated especially for the armament industry and a gray cast iron with nodular graphite EN-GJS-400-15 (0.7040).

The chemical composition of these materials is presented in table 1.

Table 1. The chemical composition of the investigated materials (wt.%).

Alloys type	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Mg	Fe
C25	0.24	0.27	0.61	0.007	0.005	0.26	0.13	0.16	0.02	-	97.91
C45	0.46	0.28	0.73	0.008	0.008	0.05	0.03	0.06	0.01	-	97.67
34CrNiMo6	0.32	0.27	0.50	0.002	0.005	0.21	1.5	1.4	0.18	-	95.2
EN-GJS-400-15	3.5	2.06	0.22	0.050	0.015	0.04	0.03	0.04	0.01	0.038	93.99

The arrangement of the tribometer was a 100Cr6 steel ball with a diameter of 6 mm for the pin holder (static friction partner) loaded against as the testing specimens. According to the instructions of

the ASTM G99 Standard, all tests should be made in the same working conditions regarding the tribological environment (temperature: 20ºC; atmosphere: air and humidity: 50%).

The testing parameters are presented in table 2.

Table 2. Parameters for the dry sliding wear investigations.

Load (N)	Linear speed (cm s⁻¹)	Motor speed (rpm)	Radius (mm)	Distance (m)	Distance (lap)	Test duration (s)
10	15	474.3	3	750	39525	5000

The coefficient of friction was monitored and registered as a graphic representation during the tests and the wear rate was calculated according to equation 1 [17]:

$$K = \frac{2\pi r \cdot h\left(3h^2 + 4s^2\right)}{6 \cdot L \cdot d \cdot s}$$

(1)

where: K is the wear rate; h - wear track depth; s - wear track width; L - applied force and d - distance.

Additionally, microhardness measurements were also considered for the investigated specimens, following the ISO 6507 standard. The microhardness was measured in 5 different areas using the Vickers method on a Zwick-Roell ZHVµ-S instrument with an applied force of 0.3 kgf.

3. Results and discussions

The variation of the coefficient of friction of the four tested specimens is presented in figure 1.
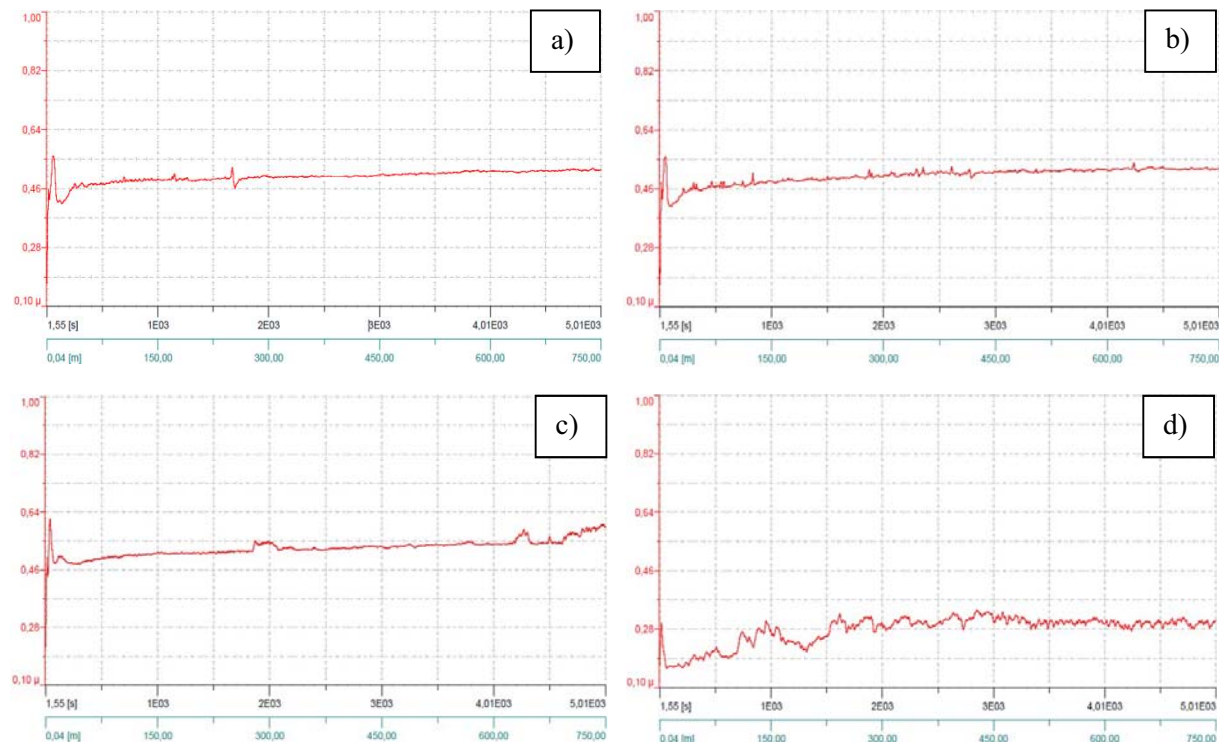

Figure 1. Variation of the coefficient of friction for a) C25; b) C45; c) 34CrNiMo6; d) EN-GJS-400-15 in time (s) and distance in meters.

The friction coefficient curves for the three steel grades are quite similar, with a maximum friction value between 0.17 - 0.22 at the beginning of the test and during the test, where the COF is fluctuate during the tests between 0.34-0.56 (here the steady state is reached [37]). For cast iron specimen (EN-GJS-400-15), COF reaches a maximum value of 0.24 at the beginning of the test and further, the value is maintained constant between 0.16 - 0.28 for a distance of 225 m and then at the end of the test (750 m) varies in the range of 0.28 - 0.34.

Table 3. Comparison of the friction coefficients values.

| Alloys type	Start	Min	Max	Mean	Std. Dev.
C25	0.170	0.170	0.559	0.496	0.020
C45	0.216	0.169	0.558	0.500	0.025
34CrNiMo6	0.240	0.218	0.619	0.528	0.026
EN-GJS-400-15	0.170	0.158	0.340	0.279	0.042

Images for the specimens and ball wear track profile were acquired with a digital microscope (KEYENCE VHX-600) and with a confocal 3D laser scanning microscope (KEYENCE VKX-260K) respectively, as shown in figure 2-4.
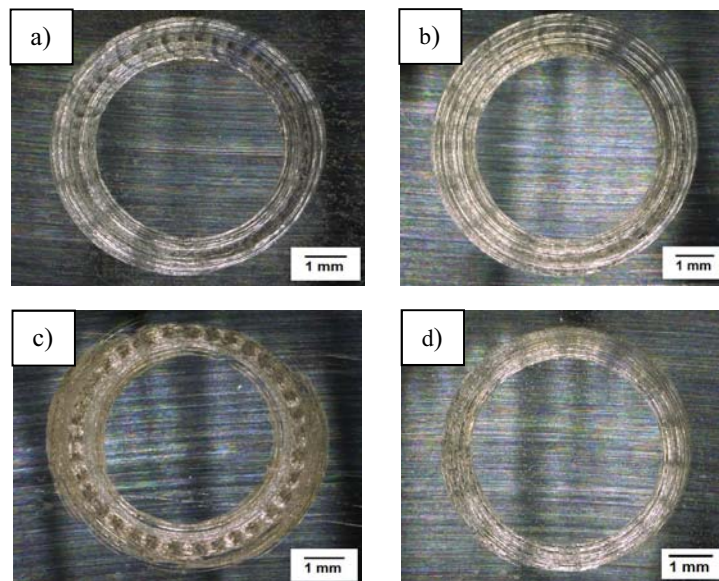
Figure 2. Specimens wear track profiles for a) C25; b) C45; c) 34CrNiMo6; d) EN-GJS-400-15.
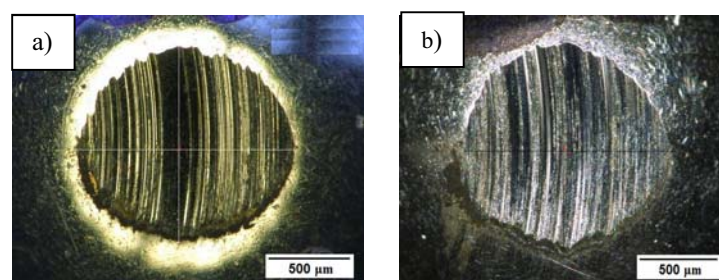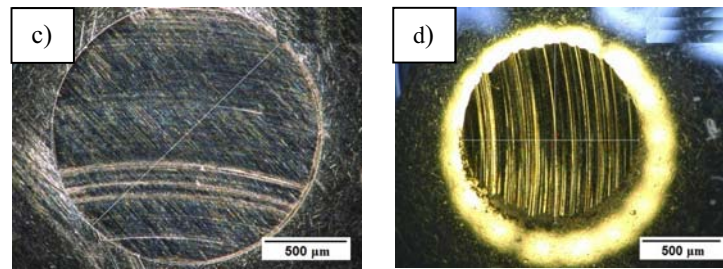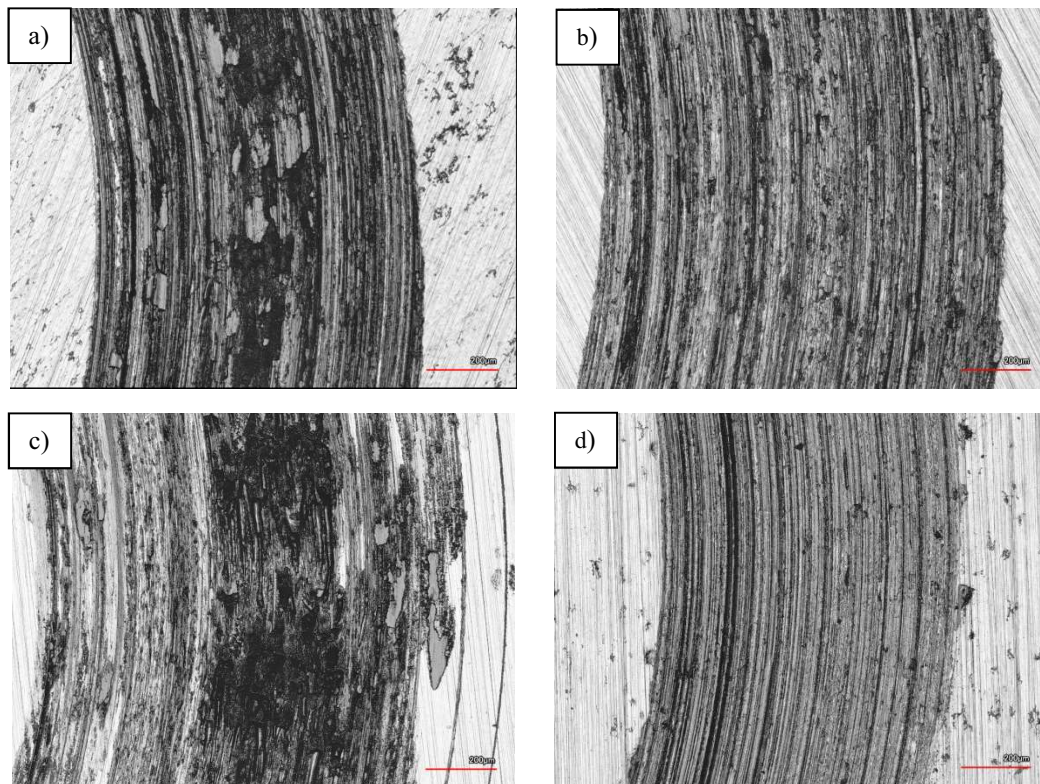
Figure 3. Ball wear track profiles for a) C25; b) C45; c) 34CrNiMo6; d) EN-GJS-400-15.

The characteristic width *s* and depth *h* of the specimens wear track profiles were measured with the MultiFileAnalyzer software and the overall calculated wear rate values are presented in table 4.

The width of the ball track profiles measured with the digital microscope is as follows: 1317 μm (C25), 1317.76 μm (C45), 1600.35 μm (34 CrNiMo6) and 1091.48 μm (EN-GJS-400-15) respectively.

Figure 4. Area of specimens wear track profiles for a) C25; b) C45; c) 34CrNiMo6 and d) EN-GJS-400-15 (100X Magnification).

Table 4. Comparison of the wear rate values.

| Alloys type	Wear track depth, h (μm)	Wear track width, s (μm)	Cross section area, A (μm^2)	Volume loss, V (mm^3)	Wear rate, K (mm^{3}N^{-1}m^{-1})
C25	9.421	941.182	5911.69	0.1114	14.9·10^{-6}
C45	3.861	1161.34	2989.31	0.0563	7.51·10^{-6}
34CrNiMo6	8.52	1161.55	6597.11	0.1244	16.6·10^{-6}
EN-GJS-400-15	2.50	878.08	1465.24	0.0276	3.68·10^{-6}

The occurrence of adhesive wear is highlighted by the removal of the material from the specimen surface, as observed in the wear track profiles presented in figure 4, particularly in the case of C25 (a) and 34CrNiMo6 (c).

The gray cast iron (EN-GJS-400-15) with nodular graphite presents a lower friction coefficient, correlated with a reduced wear rate of the material, which leads to the fact that this type of material has a better resistance to sliding wear compared with the other analyzed steels, due to the self-lubricating graphite character.

Therefore, 34CrNiMo6 suffers the most severe wear rate as compared to EN-GJS-400-15, in the presented tested conditions. The combined effect of adhesive wear is responsible for an inferior wear resistance of the C25 and C45 steels.

Correspondingly, the friction coefficient values obtained in this study for the investigated specimens are in good agreement with the dry sliding wear of steel-steel and steel-cast iron friction value range presented in literature [38-41].

Forwards, the microhardness tests results are highlighted in figure 5 and the microhardness values are presented in table 5.
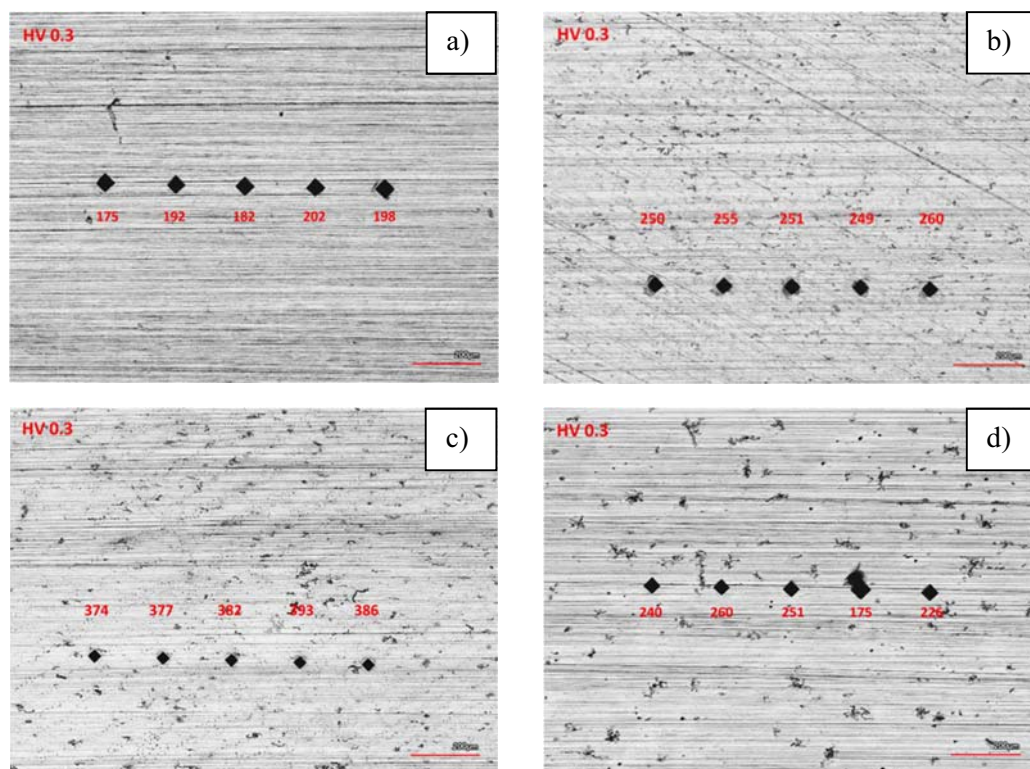
Figure 5. LM of the HV0.3 indentation of the a) C25; b) C45; c) 34CrNiMo6; d) EN-GJS-400-15.

Table 5. Microhardness values for the investigated specimens (HV0.3).

Alloys type	Attempt 1	Attempt 2	Attempt 3	Attempt 4	Attempt 5	Mean value
C25	175	192	182	202	198	190
C45	250	255	251	249	260	253
34CrNiMo6	374	377	382	393	386	382
EN-GJS-400-15	240	260	251	175	226	231

The highest microhardness value (382 HV0.3) is found for the 34CrNiMo6 steel due to the heat treatment which was subjected to. This behaviour may attributed to the ferrite-pearlite structure which is known to possess a higher microhardness [42-44].

Even if the microhardness value of the EN-GJS-400-15 cast iron is lower (231 HV0.3), in the case of dry sliding wear resistance, it displays the best behavior compared to other tested steels, which mean that the microhardness value do not influence the sliding wear resistance.

4. Conclusions

This work has presented a comparative study on dry sliding wear resistance of specimens obtained from carbon steels C25 and C45, heat treated alloyed steel 34CrNiMo6 and cast iron EN-GJS-400-15.

For the same working conditions regarding the tribological environment, the coefficient of friction (by graphic representation) and wear rate (by analytical calculation) was presented.

For the three steel grades, the COF evolution was quite similar, with a mean friction value between 0.34-0.56 during the tests, presenting a good stability. For cast iron, the COF had a mean value between 0.16 - 0.28. Moreover, a smaller wear rate was calculated for cast iron ($3.68 \cdot 10^{-6}$ mm^3 N^{-1} m^{-1}) followed by that of C45 steel ($7.51 \cdot 10^{-6}$ mm^3 N^{-1} m^{-1}). In the case of these alloys, the lowest volume loss was also estimated. Similar to other studies, the wear resistance is attributed to the carbon content.

The adhesive wear occurrence during the POD tests has been taken into consideration. The friction coefficient values are in good agreement with the dry sliding wear of steels and cast iron materials friction value range.

The current investigations revealed for the gray cast iron with nodular graphite, a lower friction coefficient, correlated with a reduced wear rate of the material, which leads to the fact that this type of material has a better resistance to sliding wear resistance compared with the other analyzed steels. Even if the microhardness value is significantly lower in the case of the analyzed cast iron, this aspect does not influence the dry sliding wear resistance.

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