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Wear Behaviour of Non-Heat Treated, Hardened and PVD Coated Steel Cams

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Keywords
Wear,
Camshaft,
PVD coating

Abstract – In this experimental study, the wear behaviour of AISI 1050 steel camshaft cams subjected to different surface treatments was systematically investigated. The cam samples were divided into three distinct groups: non-heat treated, induction hardened, and CrN coated using the physical vapor deposition (PVD) method. The aim was to evaluate and compare the tribological performance of each treatment type under dry sliding conditions. As the counterface material, HS10.4-3-10 high-speed steel, commercially known as lathe tool steel, was selected due to its high hardness and abrasion resistance, making it suitable for simulating real-life contact conditions. Wear tests were carried out using a cam profile measuring device adapted as a wear tester. Each cam sample was subjected to abrasion for a total duration of three hours under varying test conditions, specifically under three different normal loads (4 N, 8 N, and 12 N) and three different rotational speeds (85 rpm, 100 rpm, and 115 rpm). This setup resulted in nine test configurations per sample group. During the tests, the weight loss of the samples was recorded at one-hour intervals using a high-precision analytical balance. The experimental results revealed that the CrN-coated samples exhibited the lowest amount of wear, demonstrating the effectiveness of the PVD coating in enhancing surface durability under dry friction conditions.

1. Introduction

Cam mechanisms are basic machine elements that convert rotary motion into linear or oscillatory motion depending on a specific timing. These mechanisms have a wide range of uses, especially in internal combustion engines, automation systems, and industrial applications requiring high precision (Litvin and Fuentes, 2004). The main function of cams is to ensure that the controlled motion is transmitted repeatedly, stably and efficiently. However, cam parts operating under difficult tribological conditions such as high surface pressure, sudden load changes and continuous contact encounter serious wear problems over time (Dowson, 1998; Hutchings and Shipway, 2017).

Wear is defined as the material loss that occurs during the relative movement of material surfaces with respect to each other, and this process depends on many parameters such as surface roughness, hardness, microstructure, temperature, load, speed and environmental conditions (Stachowiak and Batchelor, 2005). Especially in systems with inadequate lubrication conditions, adhesion, abrasion and surface fatigue wear mechanisms are among the main causes of wear (Bhushan, 2013; Jahanmir and Beltz, 2000). This situation is a critical problem that affects not only the efficiency of the mechanism but also the maintenance frequency and the overall life of the system.

The durability and wear resistance of cam mechanisms largely depend on the type of steels used in their manufacture and the microstructural properties of these steels. Cams are usually manufactured from low alloy carbon or medium alloy structural steels because these materials offer suitable mechanical properties in terms of both hardenability and impact resistance (Totten and Howes, 1997). For example, steels such as 42CrMo4 and 16MnCr5 are widely preferred in cam manufacturing due to their suitability for both heat treatment and surface

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hardening processes (ASM International, 1990). However, since the surface properties of these steels directly determine the wear performance, surface engineering applications are of great importance in preventing wear.

Surface treatments applied to reduce wear have been developed to increase surface hardness, reduce the coefficient of friction and keep surface roughness under control. Wear-resistant hard phases are formed on steel surfaces with surface hardening methods (e.g. plasma nitriding, induction hardening, cementation) (Vöhringer, 2001). In addition, with modern coating technologies such as physical vapor deposition (PVD), thin film coatings such as TiN, CrN, TiAlN and DLC with high hardness are applied to cam surfaces and improve tribological performance in both dry and oily conditions (Holmberg and Matthews, 2009; Podgornik et al., 2004).

The compatibility of PVD coatings, especially with steel substrates, enables the combination of hard coating and toughness, minimizing negativities such as microcracking and delamination (Zhang et al., 2011). The effects of surface modifications on microstructure, hardness profile and wear morphology have also been confirmed by experimental studies (Gharbi et al., 2015).

In this study, the wear behaviours of cam samples obtained from AISI 1050 manufacturing steel improved by surface hardening and PVD coating processes were comparatively investigated with the dry friction block-on-ring method. The obtained results are aimed to contribute to academic literature.

2. Materials and Method

Reducing the wear of machine components and minimizing the resulting economic losses have long been among the primary goals of engineers working in the field of tribology. Wear not only leads to material degradation but also incurs significant financial costs associated with the repair, maintenance, or replacement of damaged equipment. These cumulative effects represent a considerable burden on the global economy. While conducting wear experiments under actual operating conditions would provide the most accurate and relevant results, replicating such conditions in a laboratory environment is often technically challenging and resource-intensive. Therefore, it becomes essential to investigate the wear behaviour of commonly used machine parts, such as camshafts, through controlled experimental setups. Such studies can provide valuable insights into the mechanisms of wear and offer guidance for the development of more durable materials and surface treatments.

2.1. Selection of Materials

AISI 1050 steel was used as the cam sample material. HS 10.4-3-10 high speed steel, known as lathe tool in the market, was used as the abrasive counter element. The chemical structures and mechanical properties of these two materials are given in Table 1. The values of the cam material were taken from the manufacturer company that produces the camshaft.

Table 1. Chemical structures and mechanical properties of the cam material and the counter abrasive element

Materials	Chemical composition									Mechanical properties			
	C	Si	Mn	Cr	Cu	Mo	V	W	Co	$\sigma_ç$	σ_a	E	Hard.
	%	%	%	%	%	%	%	%	%	(MPa)	(MPa)	(MPa)	HV
AISI1050	0.5	0.3	0.75	-	-	-	-	-	-	650	360	190	240
HS10.4-3-10	1.28	0.45	0.4	4.15	-	3.9	3.25	9.5	10	617	445	630	950

2.2. Preparation of Samples

The samples were prepared by Estaş company, a camshaft manufacturer, according to the dimensions given in Figure 1. After the shafts were manufactured, their cams were cut and holes were drilled in their centers to make them suitable for the wear test bench. Their surface qualities are close to each other. The average surface roughness of the samples, which are 27 in total, is Ra = 0.3 μm and their surface hardness is around 240 HV.

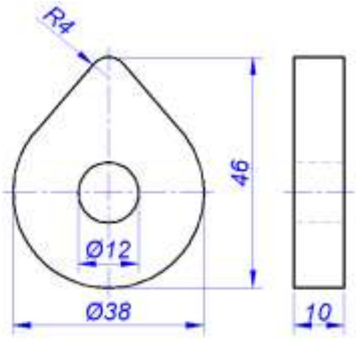


Figure 1. Shape and dimensions of the cam sample

2.3. Heat treatment

The total number of samples is 27. 18 of them were induction hardened. This process, with hardening parameters of 3 s at 870 °C, was carried out at Estaş, the company that produces the cams. 9 of the 18 hardened samples were coated with PVD-CrN. This process was carried out at 400°C; a hardness of over 2000HV was achieved. Figure 2 shows that the thickness of the PVD coating is over 7 µm.

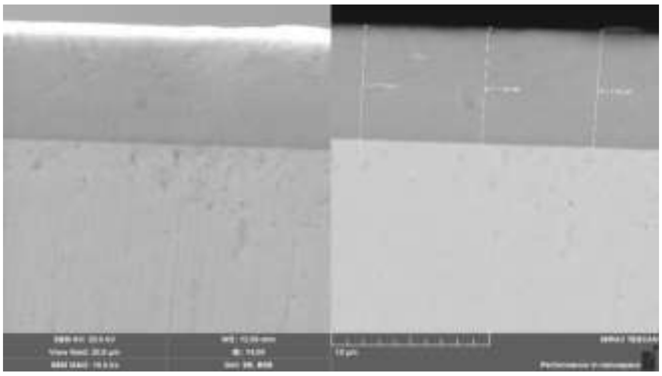


Figure 2. SEM image of the PVD coating

Microstructure images were taken with an optical microscope at Sivas Cumhuriyet University, Mechanical Engineering Laboratory. Figure 3 shows the optical microscope images of the hardened and PVD coated samples.

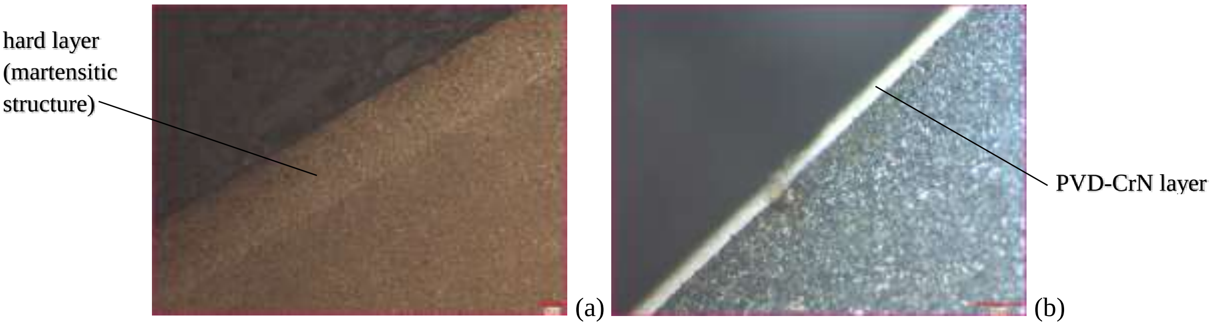


Figure 3. Optical microscope microstructure images a) induction hardened sample (100x) b) PVD coated sample (500x)

Three types of samples were used: non-heat treated, induction hardened and post-hardened PVD coated steel. Since the surface quality of the samples varied regionally, roughness measurements were taken from ten separate points for each sample and the average was taken. While the surface roughness of the non-heat treated and induction hardened samples was approximately 0.3, the surface roughness value decreased to 0.2 after PVD.

2.2. Wear test setup and conduct of the experiment

In this research, block-on-ring contact configuration was employed in the experimental setup due to its resemblance to the cam-follower mechanism as seen in Figure 4. This configuration provides a linear contact interface.

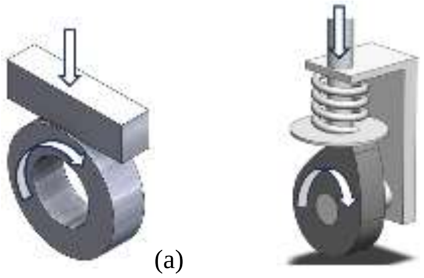
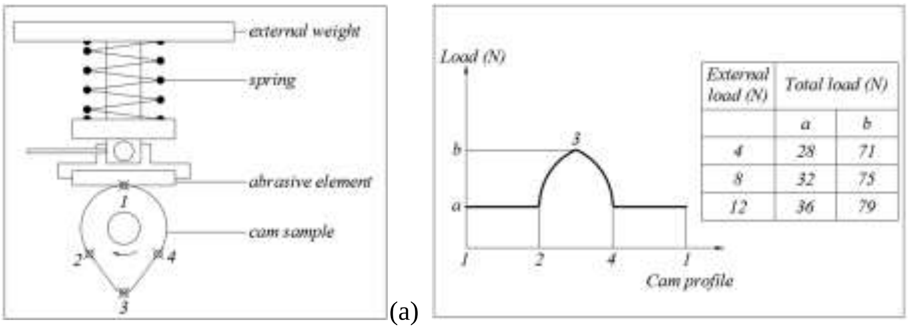

(a) (b)

Figure 4. a) Block-on-ring wear test model and b) cam-follower mechanism

The wear tester used for the experiments is illustrated in Figure 5. Wear tests were carried out using a cam profile measuring device adapted as a wear tester.

Figure 5. Wear tester

During testing, external loads of 4 N, 8 N, and 12 N were applied. The spring used in the system has a constant of 5.4 kN/m. The spring force acting on the cam samples varies depending on the cam profile and consists of two components. The first component arises from the initial compression of the spring during assembly, corresponding to the spring force at the cam's bottom dead center. This force is incorporated into the total mechanism weight, which is fixed at 24 N for all tests. The second component results from the cam profile's displacement between the bottom and top dead centers—a distance of 8 mm. Figure 6 presents the total force applied to the specimen. The samples were prepared by Estaş company, a camshaft manufacturer, according to the dimensions given.



(a) (b)

Figure 6. a) Schematic view of wear tester b) Force distribution on the cam sample in experimental setup

The cam sample and the abrasive counterface were weighed using a high-precision balance. For this procedure, an Axis brand balance with an accuracy of ±0.1 mg which is shown in Figure 6 and housed in the Mechanical Engineering Laboratory at Sivas Cumhuriyet University, was employed. Calibration was performed using external weights. The experiment commenced after setting the rotational speed with a tachometer, and the friction distance corresponding to roughly one hour of operation was used as the reference. Once the desired friction distance was achieved, the machine was halted, and the weights of both the cam sample and the abrasive element were recorded using the same precision balance. This one-hour wear cycle was repeated twice more, with weight measurements and photographs taken after each cycle.

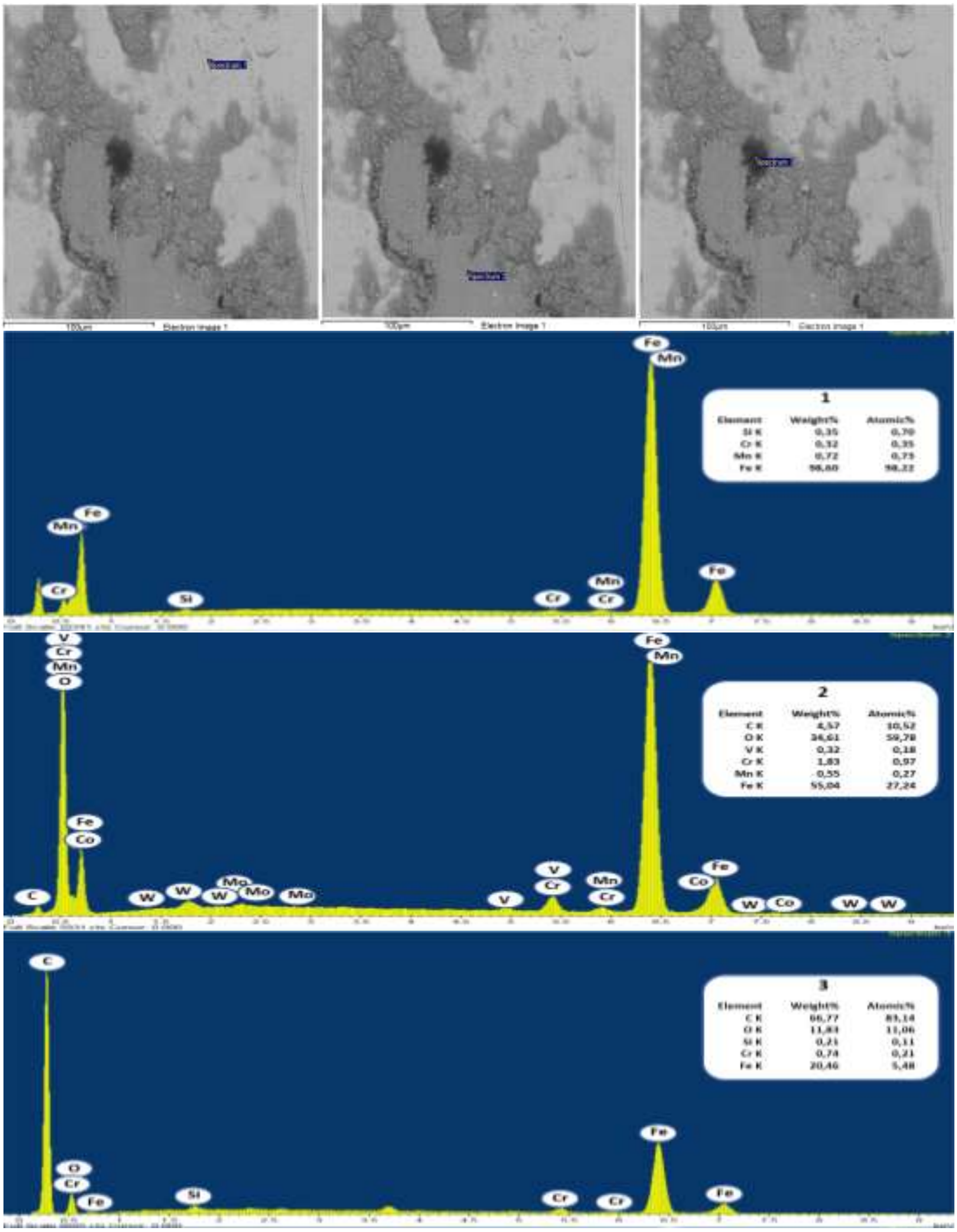


Figure 7. SEM image of the PVD coated sample after wear and EDX analysis taken from three different points

3. Results and Discussion

Following the wear tests, SEM imaging was conducted on the worn surfaces of the PVD-coated steel samples, and EDX analyses were carried out as displayed in Figure 7. The bright regions correspond to exposed, worn metal and are relatively hard. EDX results revealed a very small amount of chromium in these areas, suggesting that the PVD coating was worn away at those locations. Meanwhile, the dark regions, rich in carbon and oxygen, point to oxidation and thermal damage caused by frictional heating. Furthermore, given that the counterface material is high-speed steel, the presence of alloying elements such as cobalt (Co), vanadium (V), molybdenum (Mo), and tungsten (W) suggests material transfer through adhesive wear mechanisms.

Table 2. Wear losses of samples after (a) 1 hour, (b) 2 hours, (c) 3 hours

Velocity (rpm)	Load (N)	Non-heat treated (mg)	Hardened (mg)	PVD + Hardened (mg)
85	4	28.5	5.2	3.3
85	8	29.0	5.0	3.5
85	12	32.4	5.6	3.8
100	4	38.3	7.5	5.3
100	8	40.3	7.8	5.1
100	12	41.2	7.6	5.4
115	4	52.8	9.5	6.2
115	8	55.5	11.0	6.2
115	12	58.1	11.5	6.4

(a)

Velocity (rpm)	Load (N)	Non-heat treated (mg)	Hardened (mg)	PVD + Hardened (mg)
85	4	55.5	11.7	7.5
85	8	55.0	13.5	8.0
85	12	58.4	13.3	8.2
100	4	69.2	14.4	9.2
100	8	75.6	15.6	9.8
100	12	74.5	17.8	9.5
115	4	90.8	17.4	10.2
115	8	93.1	17.7	10.1
115	12	98.1	19.0	10.8

(b)

Velocity (rpm)	Load (N)	Non-heat treated (mg)	Hardened (mg)	PVD + Hardened (mg)
85	4	84.8	18.1	10.8
85	8	86.0	21.5	11.5
85	12	92.4	21.6	12.6
100	4	113.4	23.4	11.1
100	8	118 .3	25.4	15.2
100	12	118.0	27.8	15.8
115	4	131.0	24.6	16.0
115	8	133.5	29.4	16.2
115	12	135.0	29.5	17.5

(c)

The wear losses obtained at one-hour intervals for different rotational speeds and different external loads for steel with three different surfaces are given in Table 2 and Figure 8. In general, as the rotational speed and external weight increased, the amount of wear also increased. However, only a few measurements showed results contrary to expectations. For example, in the hardened sample, wear under 8 N load at 100 rpm was measured as 7.8 mg after 1 hour, while in Table 2(a), wear under 12 N load was measured as 7.6 mg. Similarly, in the PVD-coated sample, wear under 8 N load at 100 rpm was measured as 9.8 mg and under 12 N load after 2 hours, wear was measured as 9.5 mg in Table 2(b). These samples returned to normal after 3 hours, i.e., the amount of wear increased as the load increased. In Table 2(c), only the amount of wear in the unheated sample was measured as 118.3 mg at 8 N and 118 mg at 12 N at 100 rpm after 3 hours. This situation can be interpreted as follows. While the external weight increases by 50%, the load on the sample increases from 32 N to 36 N in the circular area of the cam; and from 75 N to 79 N at the top of the cam, approximately 5%. Since these values are very small, it is normal to see such unexpected results.

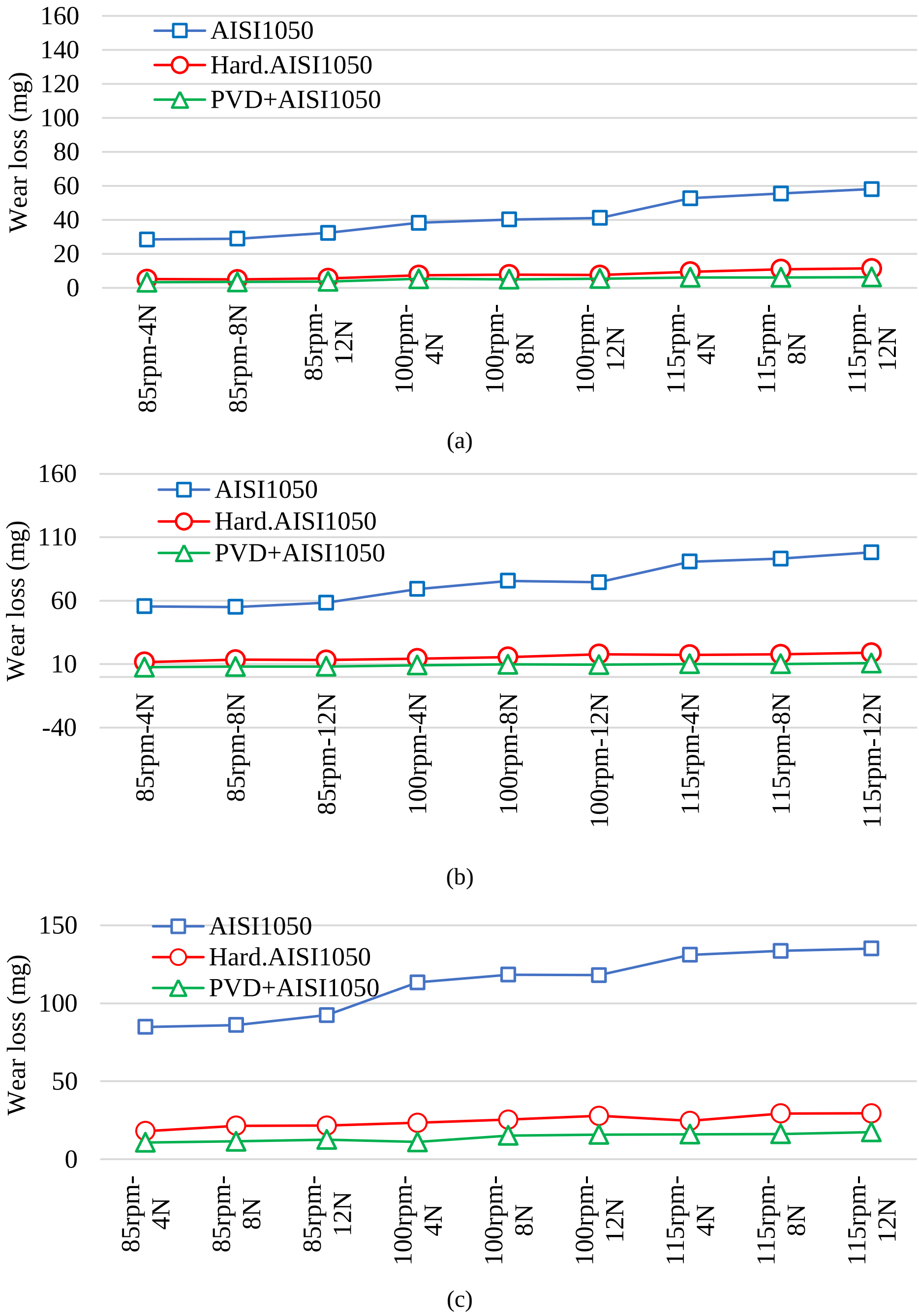


Figure 8. Wear losses of samples after (a) 1 hour, (b) 2 hours, (c) 3 hours

In the experiments, the wear in induction hardened steels compared to non-heat-treated steels was approximately 80% less, as calculated from Table 2. In order for the PVD coating to be applied, the surface must be somewhat hard. Therefore, induction hardening was performed before the PVD coating. When the PVD coating was calculated as induction hardened, Wang and his colleagues (2023) found similar results using the same coating material.

4. Conclusion

Normally, heat treated steels such as AISI 1050 without heat treatment are not used as materials for parts exposed to wear. It was used here only for comparison. In the experiments, wear in induction hardened steels was 80% less than in non-heat treated steels. When PVD coating was applied, surface roughness was reduced by approximately 30%, and wear was reduced by approximately 35% compared to induction hardened samples. If too much cost is not desired, induction hardening is satisfactory. However, if more hardness and longer life are desired, PVD coating will definitely meet the need.

Ethics Permissions

This paper does not require ethics committee approval.

Author Contributions

The topic was determined by Burhan Selçuk in his capacity as a consultant, who also oversaw the material selection. Ersin Arslanbulut performed the experiments and was responsible for writing the article.

Conflict of Interest

Authors declare that there is no conflict of interest for this paper.

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