Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 12(1): 297-307 (2024)

Ceramic Particle Reinforced Camshaft Lobes: A Performance Evaluation and Comparative Analysis

Afşın Alper CERİT[1], Fehmi NAİR[2], Hafız Muhammad Numan ZAFAR*

1 Erciyes University, Department of Industrial Design Engineering, Kayseri 38039, Türkiye

2 Erciyes University, Department of Mechanical Engineering, Kayseri 38039, Türkiye

3 Kim Technologies, Kayseri, Türkiye

Article Info

Research article
Received: 28/01/2024
Revision: 28/02/2024
Accepted: 02/03/2024

Keywords

Metal Matrix Composites
Camshafts, Tribology
Powder Metallurgy
Cam Materials

Makale Bilgisi

Araştırma makalesi
Başvuru: 28/01/2024
Düzeltme: 28/02/2024
Kabul: 02/03/2024

Anahtar Kelimeler

Metal Matrisli Kompozitler
Kam milleri
Triboloji
Toz Metalurji
Kam Malzemeler

Graphical/Tabular Abstract (Grafik Özet)

This study reports the wear performance of ceramic reinforced Al matrix composites as a replacement of the conventional camshaft lobes. / Bu çalışma, geleneksel kam mili malzemelerin yerine seramik takviyeli Al matris kompozitlerin kullanımı açısından aşınma performansını araştırmaktadır.

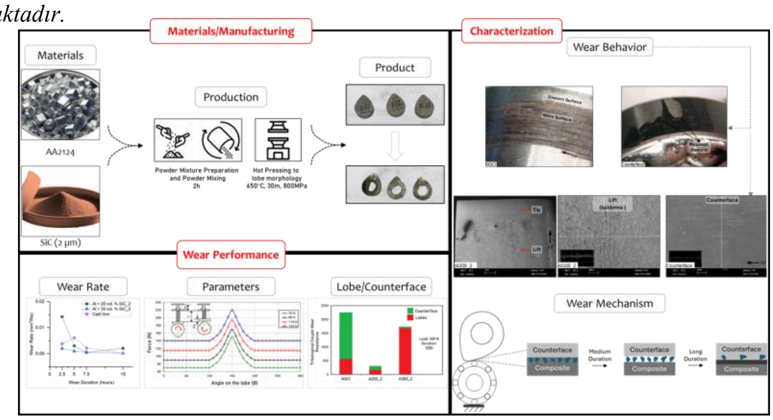

***Figure A:** Manufacturing, wear performance and characterization of wear behavior of particle reinforced Al matrix cams. / **Şekil A:** Parçacık takviyeli Al matrisli kamların üretimi, aşınma performansı ve karakterizasyonu.*

Highlights (Önemli noktalar)

- *Short-scale lab tests might not capture real-world wear of ceramic reinforced Al matrix cam lobes. / Küçük ölçekli laboratuvar testleri, seramik parçacık takviyeli Al matrisli kam mili malzemelerin gerçek şartlarda aşınma davranışını tam olarak yansıtmayabilir.*
- *Composites with higher ceramic content show improved wear resistance initially. / Seramik miktarı artınca kompozitler başlangıçta daha iyi aşınma direnci gösterir.*
- *Longer durations of wear cause surface-hardening and reduced wear, however, for highest ceramic content, it causes significant wear in the counterface. / Uzun süreli yüzey temasları kamların yüzeyinin sertleşmesine ve bunun sonucunda daha az aşınmasına sebep olur, ancak seramik miktarı fazla olan kompozitler karşı malzemenin aşırı aşınmasına neden olur.*

***Aim (Amaç):** This study aims to determine the wear performance of the Al matrix ceramic particle reinforced camshaft lobes. / Bu çalışmanın amacı seramik parçacık takviyeli Al matrisli kompozitlerin aşınma performansını değerlendirmektir.*

***Originality (Özgünlük):** The wear performance of ceramic particle reinforced Al matrix cams in the end product form and under semi-real conditions is not evaluated before. / Seramik parçacık takviyeli Al matrisli kamların aşınma performansı, daha önce nihai ürün formunda ve yarı-gerçekçi koşullar altında değerlendirilmemiştir.*
***Results (Bulgular):** Results showed that the ceramic content in the Al matrix cams can be changed in order to attain a pre-determined wear behavior. / Sonuçlar, Al matrisli kamlarda önceden belirlenmiş bir aşınma davranışı elde etmek için seramik içeriğinin ayarlanabileceğini göstermiştir.*
***Conclusion (Sonuç):** Al+20 vol. % SiC composite showed adequate wear resistance with a little counterface wear, offering a practical balance between durability and component protection. / Al+%20 SiC kompoziti, az miktarda karşı yüzey aşınması ile uygun aşınma direnci göstererek, dayanıklılık ve karşı parça koruma bakımından pratik bir denge sunar.*

*Corresponding author, e-mail: numan.zafar@live.com
DOI: 10.29109/gujsc.1427270

GU J Sci, Part C, 12(1): 297-307 (2024)

Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

Ceramic Particle Reinforced Camshaft Lobes: A Performance Evaluation and Comparative Analysis

Afşın Alper CERİT[1], Fehmi NAİR[2], Hafız Muhammad Numan ZAFAR[3*]

1 Erciyes University, Department of Industrial Design Engineering, Kayseri 38039, Türkiye

2 Erciyes University, Department of Mechanical Engineering, Kayseri 38039, Türkiye

3 Kim Technologies, Kayseri, Türkiye

Article Info

Research article
Received: 28/01/2024
Revision: 28/02/2024
Accepted: 02/03/2024

Keywords

Metal Matrix Composites
Camshafts
Tribology
Powder Metallurgy
Cam Materials

Abstract

Ceramic reinforced metal matrix composite (CMMC) lobes in engines could improve fuel efficiency and wear resistance compared to traditional steel lobes but require absolute evaluation. However, ensuring safe CMMC cam operation demands extensive wear testing, mimicking real-world conditions over longer durations instead of limited lab evaluations. This study is an extension of the previously reported feasibility analysis of the ceramic particle reinforced Al matrix composite lobes. The performance of the best selected (Al + 20, 30 vol. % SiC(2µm)) composites for wear durations of 2.5, 5, 7.5, and 15 h is reported with various combinations of pressures and compared with the reference lobes. Results showed that the higher content of ceramic particles improved the wear resistance, however, the influence diminished at larger durations due to surface hardening of the composites. The wear performance of the composite (Al + 30 vol.% SiC) reached 73% of the conventional cams but it also caused significant wear in the counterface due to initiation of three-body-wear by the dislodged ceramic particles.

Seramik Partikül Takviyeli Kam Malzemeleri: Bir Performans Değerlendirmesi ve Karşılaştırmalı Analiz

Makale Bilgisi

Araştırma makalesi
Başvuru: 28/01/2024
Düzeltme: 28/02/2024
Kabul: 02/03/2024

Anahtar Kelimeler

Metal Matrisli Kompozitler
Kam Milleri
Triboloji
Toz Metalurjisi
Kam Mili Malzemeleri

Öz

Motorlarda yakıt verimliliği ve aşınma direnci artırmak için geleneksel kamların yerine Seramik Takviyeli Metal Matrisli Kompozitlerin (CMMC) kullanımı mutlak performans değerlendirmesi gerektirir. Bununla birlikte, kamların güvenli bir şekilde çalışması için gerçek koşulları taklit eden kapsamlı aşınma testleri gereklidir. Bu çalışma, daha önce yayınlanan seramik parçacık takviyeli Al matris kompozit kamların fizibilite analizinin bir uzantısıdır. Seçilen en iyi (Al + 20, 30 % SiC (2 µm)) kompozit kamlar gerçek şartları taklit eden düzenekte 2,5, 5, 7,5 ve 15 saatlik aşınma testlerine tabi tutularak referans kamları ile karşılaştırılmıştır. Sonuçlar, seramik miktarına bağlı olarak aşınma direncinin arttığını, ancak uzun süre aşınan kompozitler için yüzey sertleşmesi nedeniyle aşınma direncinde artırma eylemenin azaldığını göstermiştir. Ayrıca, Al + %30 SiC kompozitin aşınma performansı geleneksel kamların %73' üne ulaşmıştır. Ancak, kopan seramik parçacıklar üç cisimli aşınmanın başlamasına sebep olarak karşı yüzeyde ciddi miktarda aşınmaya yol açar.

1. INTRODUCTION (GİRİŞ)

The fuel injection during the engine operation into the combustion chamber is controlled by the cams that are attached to the camshafts. Therefore, the physical and operational characteristics of the cams can significantly influence the operational capabilities of the engine. High wear resistance and a long lifespan are necessary for integration as camshaft lobes. The successful integration of ceramic-reinforced lightweight cams into camshafts can lead to low production costs and fuel consumption, as ceramic-based composites possess excellent wear resistance and lightweight characteristics.

The failures in automotive vehicles are divided into isolated and widespread failures that are occurred due to abuse, age, human-machine interaction errors, and improper maintenance. Heyes et al. [1] studied 70 cases of vehicle component failures and reported a striking 41% share by the engine

*Corresponding author, e-mail: numan.zafar@live.com
DOI: 10.29109/gujsc.1427270

components. By using appropriate material selection, design, and processing techniques during the manufacturing stage and by properly evaluating the performance of different engine components, failures can be prevented.

The feasibility of using the Al matrix ceramic reinforced cams as a replacement to conventionally used high alloy steels [2-4] was investigated in the previous study [5]. However, results showed that the behavior of the cams was influenced not only by the types and ratios of the ceramic (B_4C or SiC) particles, but also by the size of the reinforcement particles. However, since the mentioned study [5] was intended to develop a virtual engine-like wear environment and conduct the feasibility analysis of the ceramic reinforced Al matrix composite as cams, influence of longer durations of the wear tests was not reported. But for a proper representation of said composites to be claimed as a replacement to conventional steels cams, performance evaluation is inevitable.

Barothi et al. [6] attempted to improve the engine performance by manipulating the camshaft lobe geometry. Results showed that changing the lobe lift height from 12 mm to 12.43 mm resulted in a 4.1% increase in cylinder filling efficiency during intake stroke. However, the power consumption was slightly increased (from 323.72 kW to 334.18 kW) owing to modified lift height in the lobes. Burdzik et al. [7] collected 40 cams from Cinquecento 700 engine that had already been exposed to real-life wear for a range of 1250 to 48500 km. It was reported that while wear intensity was fairly dependent on the cam angles, the justifications to these maxima required incorporation of pressure calculations. Overall, the wear behavior was independent of the type of cams used for assessment. Godino et al. [8] analyzed the recurring major failure in the valve train system (engine valves opening/closing system) of 130 buses (out of 400 urban buses fleet) and reported excessive damage on the cam nose, especially after 500 thousand km. The reasons for the failures, after a systematic analysis, were declared to be a combination of wear (low hardness of the cam nose) and fatigue cracking in the cam subsurface.

Using ceramic particles in a matrix with improved interface compatibility is an obvious way to counteract wear in mechanical parts that interact physically; ceramic particle reinforced Al matrix composites are a success from an engineering standpoint. However, as the sliding distance (or duration of wear exposure) increases, the wear response might not be similar throughout the experiment [11]. Supposing laterally uniform microstructure, friction induced elevated temperatures, fatigue induced surficial changes, and most importantly, the deformation induced hardening of the top surface triggers microstructural evolution that is absent at the initial stages of the wearing[16]. Such a situation necessitates considering the extended duration wear tests while defining absolute wear behavior of the composites.

Shinde et al. [11] manufactured Al-12Si matrix B_4C using ultrasonic stir casting and studied the influence of speed and sliding distance on the microstructure during wear. While the friction of coefficient remained fairly unchanged, the wear behavior was complex with respect to the sliding distance – combined influence of additional factors of load and sliding speed needed to be incorporated as well. Muley et al. [17] reported that ceramic reinforced metallic composites (Mg alloy-AZ31B + 1.5wt% Al_2O_3-1wt% Ca [9], Al 2219/SiC_p + Gr_p [18], and Al alloy LM25 + SiC_p + Gr[16]) show different wear behavior at different stages of the sliding distance. For example, Alidokht et al. [9] reported that wear mode changed from ploughing caused by ceramic particles to abrasion and adhesion after 1500 m mark for Mg+Al_2O_3. Basavarajappa et al. [18] also reported a non-linear increase in the wear rate with increasing sliding distances. The wear mode changed again after 1500 m mark to abrasive wear that was caused by the cracked Si_3N_4 particles. Raju et al. [12] examined the wear of SiC and AlN hybrid composites for up to 1000 m and reported improved wear resistance compared to single-particle reinforced composites and attributed it to synergistic effects at the interface. It can be seen from Table 1 that although studies on the medium sliding distance of the ceramic particle reinforced Al matrix composites at the laboratory scale are available, extended sliding distance/durations are not as abundant. A contributing factor to this is the smaller size of the specimens and the constraints of the tribology-related machinery. In order to solve this problem, a much-automated system with minimum performance degradation must be prepared. The working principles and the component details of the setup are already detailed in the previous study [5]. The setup mimics the real-life engine conditions based on the principles of the valve train system (actuation of engine valves using lobes on the camshaft) in dry and wet conditions. Setup has monitoring capabilities such as checking the temperature of the oil and angular speed wheel.

Table 1. Selected studies from the literature dealing with short/medium/long distance laboratory research and case studies (Literatürden kısa/orta/uzun mesafeli laboratuvar araştırmaları ve vaka incelemeleri ile ilgili seçilmiş araştırmalar)

Examples	No	Composite/Material	Wear Testing Standards	Environment	Counterface, Hardness	Rotation Speed	Sample Dimensions (mm)	Exposure Distance (m)	Exposure Duration	Load (N)	Velocity (m/s)	Ref.
Laboratory (short or medium distance)	1	Al + SiC (30 µm)/MS_2(5µm)	Pin-on-disk	Dry	AISI D3, 58HRC	630 to 1600 rpm	10	200 to 1500	nr	10, 25, 40	0.35	[9]
	2	Al + Al_2O_3 (<50 µm)	ASTM G 133	Dry	AISI 52100, 64 HRC	nr	1.5	500	nr	5.3	0.12	[10]
	3	Al-12Si + B_4C (<500 nm)	ASTM G 99	Dry	EN31, 60–62 HRC	nr	6	500, 1200, 3000	40 minutes	20	0.25 – 1.25	[11]
	4	Al + Li-Si_3N_4	ASTM G 99	Dry	EN24,-	600 to 1500 rpm	10Φx30 (Dxl)	1000	nr	9.81, 14.71, 19.62	nr	[12]
	5	Al + WC (8–15 µm)	nr	Dry	nr	nr	12x12x40 (txhxl)	1200	nr	10, 20, 30	2	[13]
Laboratory (long distance)	1	Al + Fe_2O_3-Mg	nr	Dry	Carbon Steel, 64 HRC	nr	6Φx30 (Dxl)	6000, 12000, 18000	60, 120, 180 minutes	10, 20, 30	-	[14]
	2	Al + fly ash	ASTM G 99	Dry	EN-31, 65 HRC	80 to	8Φx27 (Dxl)	18000	6 hours	10, 25, 35	0.628	[15]
Real Life Case Studies	1	Cinquecento 700 Engine	Real life wear	Wet*	nr	nr	nr	1250 – 48500 km	nr	nr	nr	[7]
	2	Medium Carbon Steel (C55E*) (from urban buses)	Real life wear	Wet*	High Hardness Steel (HRC 73+)	nr	nr	nr	nr	nr	nr	[8]

*: Estimation, nr: Not Reported, D: diameter of specimen, l: length of specimen, t: thickness of specimen, h: width of specimen, rpm: rounds of disk per minute, HRC: Rockwell C hardness,

Current study deals with the extended duration (2.5, 5, 7.5, 15 h) wear of the camshaft lobes of Al+SiC and Al+B_4C composites under dry and wet conditions. While the composites are manufactured by a combination of stir casting and squeeze casting in a mold of lobe geometry, results were compared with reference samples (AA2124 matrix and nodular graphite cast iron).

2.MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Materials and Test Samples (Malzemeler ve Test Numuneleri

Starting materials were based on the powder forms of SiC (two particle size), B_4C (single particle size) and Al AA2124 alloy. AA2124 aluminum alloy is known for exceptional strength, fatigue resistance, and adequate weldability and is widely used in the aircraft and automotive industry as critical weight-to-strength sensitive structural components such as wing skins and pistons. B_4C and SiC are famous for having exceptional hardness and thermal resilience making them appropriate candidates for various fields. For example, B_4C is industrially known as an advanced ceramic used against ballistic threats, while SiC is used in the furnaces and resists oxidation for inherent chemical inertness.

Only the reinforcement ratios of 20 and 30 vol. % were used in the current study because the wear behavior of the ceramic particles containing 10 vol. % did not differ significantly. Moreover, the reinforcement particles, which were smaller in size (B4C: 1-7 µm, SiC: 2 µm), showed a better wear performance compared to larger ceramic particle size (SiC: 20 µm) composites [5]. For these reasons, only the 20 and 30 vol% SiC with an average particle size of 2 µm were used in the study – the selected raw materials are shown in Figure 1(a).

Samples are prepared using powder metallurgy in three steps: mixture preparation, powder mixing, and hot pressing in a mold. The parameters are detailed in Figure 1(b). Test samples are prepared with an increasing fraction (20 and 30 vol.% SiC) of ceramic particles (Figure 1(c)). These samples were selected after the feasibility tests conducted in the previous study [5] on a broader range of types of composites (Figure 1(c)). The final product is in the camshaft lobe form because of the geometry of the specially prepared mold (Figure 1(d)). The detailed images of the mold components can be found in the previous paper [5]. Finally, reference materials for validating and comparing the wear behavior were also prepared, as shown in Figure 1(e).

One of the major issues related to the manufacturing of powder metallurgy composites is the presence of porosity. While the reduction in the porosity is related to the powder particles' characteristics (size, size distribution, morphology), pressure (compaction during cold/hot pressing for increasing inter-particle contacts[19]), temperature (for initiating the mass transport at interparticle boundaries) and finally the duration of the treatment (in case chemical reactions happen at the interfaces that depend on atomic diffusion[20]), the pressure and temperature are most influential. Therefore, in order to achieve the highest density in the composites, different pressure-temperature values were attempted before the cams were produced.

As mentioned above, 200, 400, 600, and 800 MPa were attempted at temperatures of 23, 250, 450, and 650 °C for the samples reinforced with 10, 20, and 30 vol.% SiC. The maximum densities these composites reached (taking 100% as the theoretical density) are shown in Figure 2. It can be seen that at lower temperatures, it requires higher pressure values in order to reach closer to the theoretical density as shown in Figure 2(a). Additionally, the sintering of samples in which ceramic particles are present is unsatisfactory as compared to the non-reinforced samples. This is attributed to the ceramic nature and negligible yielding of the ceramic particles[21] under the pressure (Figure 2(a)). Regardless of the temperatures used, higher compression values increase the density of the composites that reaches a maximum value at 650 °C for 800 MPa as shown in (Figure 2(d)). This was the reason all composites were sintered at these parameters for 30 minutes.

Other than the composites used in the study, reference nodular graphite cast iron (NGCI) was also subjected to several characterizing stages in order to see the mechanical aspects of the used materials. That is to say that while the hardness of each specimen was measured individually, the hardness of the NGCI was also measured and it was checked whether it required any further hardening practices. For example, in literature authors have reported increasing the mechanical properties of the camshaft lobes using several treatments (chills to acquire ledeburitic surface [3], induction hardening [22], austempring of the ductile irons [23], and cathodic electrolytic plasma hardening [24]). Figure 3 shows NGCI has some influence of the induction hardening (8%) but almost negligible influence of the post hardening griding operation (0.1%). As for the composites, the hardness increased with the increasing content of the ceramic particles regardless of the types of ceramics used.

Finally, the images of the manufactured selected cams before and after the wear tests are given in Figure ***4***(a). Later, samples were perforated after being removed from the mold to fit the shaft as shown in Figure ***4***(b). Additionally, the bearings, that were used as the counterface, are also shown in Figure ***4***(b).

2.2. Wear Performance Tests (Aşınma Peformans Testleri)

Wear tests were conducted using a setup which is explained in detail somewhere else [5]. For reference, the tests were conducted under wet conditions in a virtual engine-like environment. Regardless of the working principles of the specially designed virtual engine-like environment for the wear tests, the load on the samples (70, 90, 115, and 140 N), test durations (2.5, 5, 7.5, and 15 h), and angular speed (500 rpm) could be controlled. The wear tests were conducted using a commercial oil (60 mlt DEW® SAE10W40) that could be heated (and maintained) to a temperature of 90 °C.

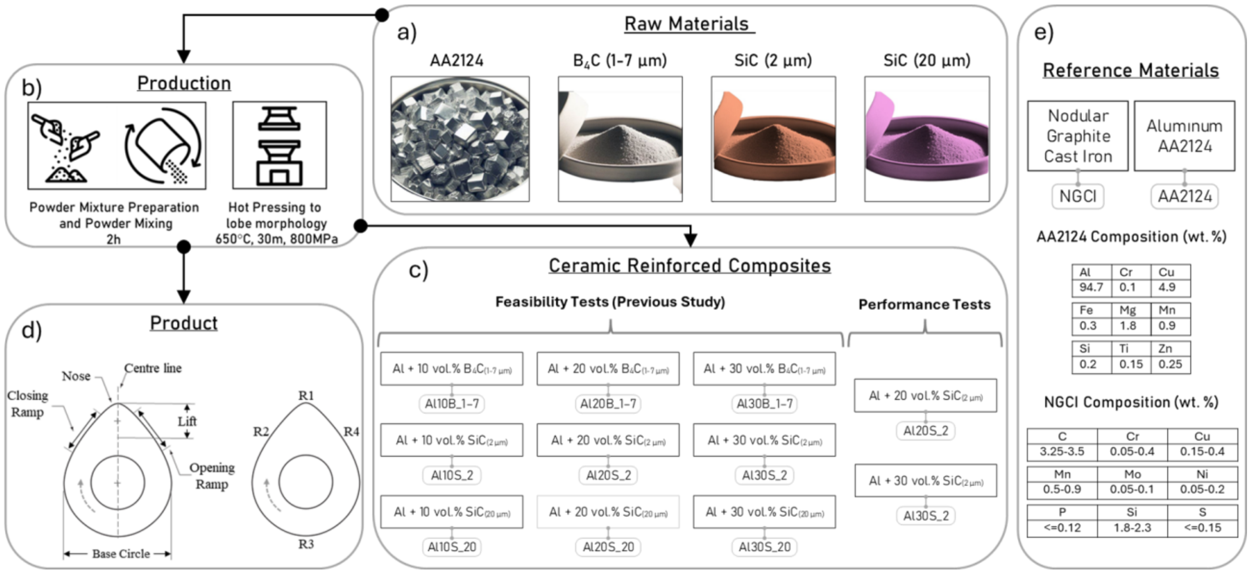

Figure 1. a) Starting materials, b) production conditions and steps, c) product mixtures and tags, d) final product and e) reference materials and their composition (NGCI: Nodular graphite cast iron), (a) Başlangıç malzemeleri, b) Üretim koşulları ve aşamaları, c) Ürün karışımları ve etiketleri, d) Nihai ürün ve e) Referans malzemeler ve içeriği (NGCI: küresel grafitli dökme demir),)

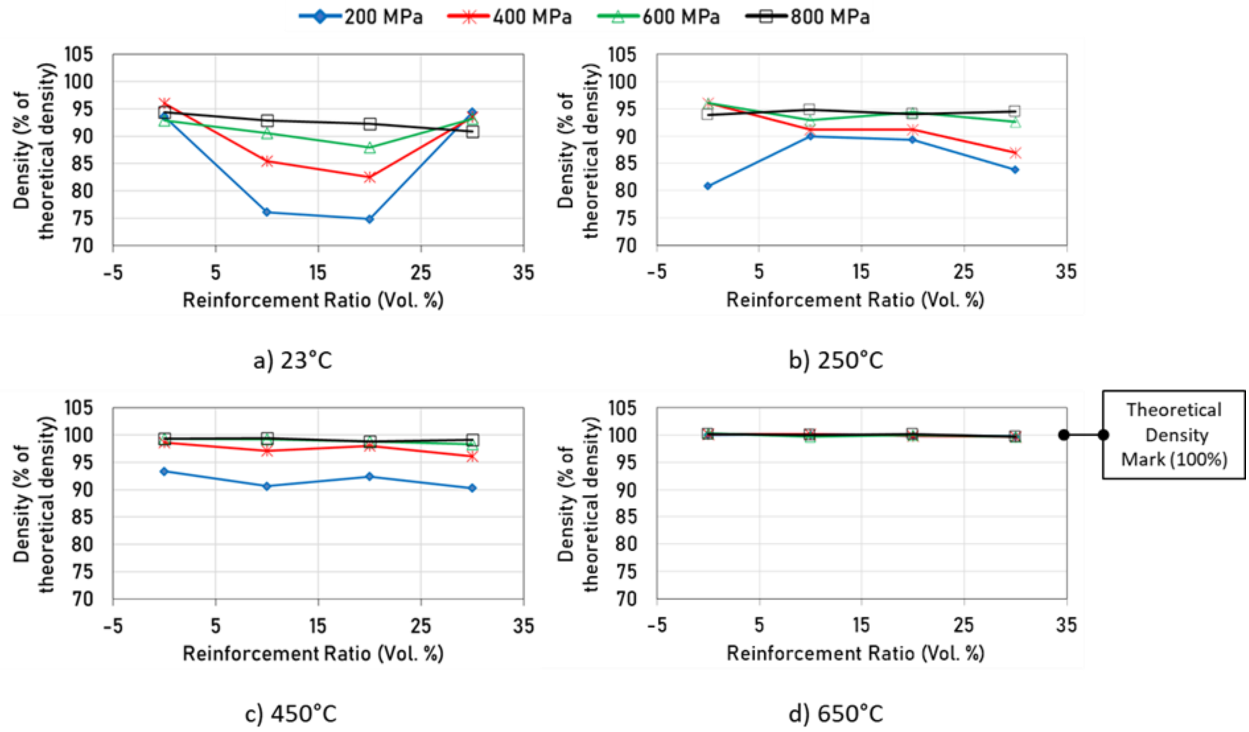

Figure 2. Details of the attempted pressure and temperature values for reaching maximum theoretical density in the composites (Kompozitlerde maksimum teorik yoğunluğa ulaşmak için denenen basınç ve sıcaklık değerleri)

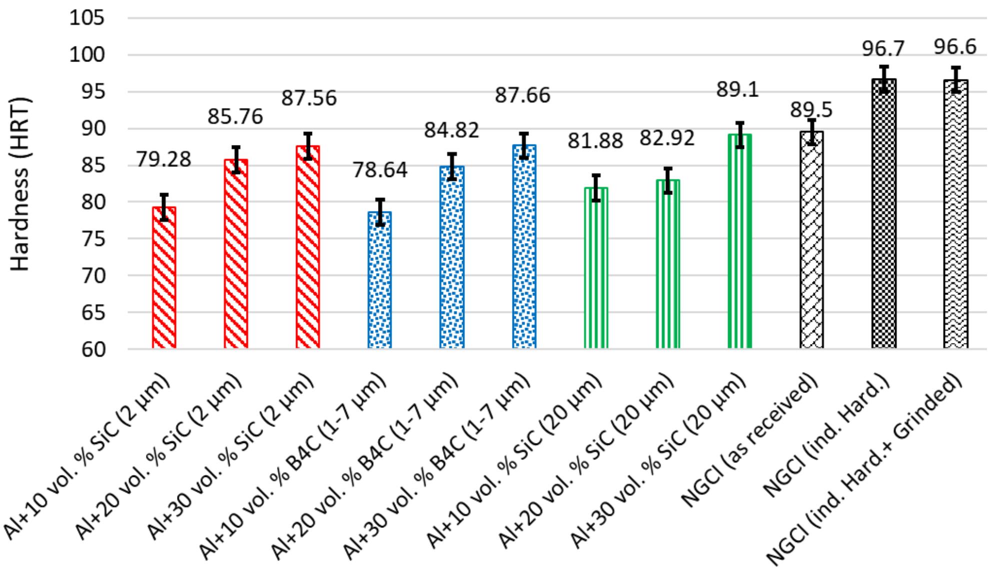

Figure 3. Hardness of the composites and influence of different treatments on the hardness of the counterface (NGCI) (Kompozitlerin sertliği ve farklı işlemlerin karşı malzemenin sertliği üzerindeki etkisi (NGCI))

The density of each sample was measured using the Archimedes principle. The mass of the samples before and after the wear tests was measured. Using the change in the mass (Δm) and the density (ρ), the volume of the material loss was calculated. Later, this volume was divided by the product of time and contact load to calculate the wear rate (W). The wear resistance is calculated by taking the inverse of the wear rate and it is further divided by the density of the sample to measure the specific wear resistance of the sample.

3. RESULTS (BULGULAR)

It was reported in the previous study [5] that overall, the wear rate of the composites decreased with the increase in the ceramic content under dry wear. Only the results from the 2 μm reinforced specimens are given for the performance evaluation

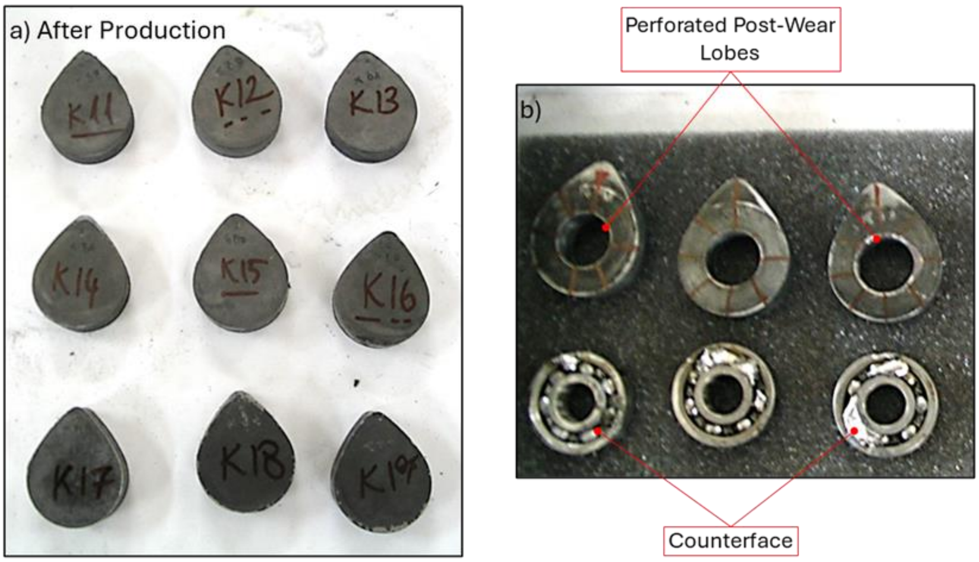

Figure 4. Images of the camshaft lobes a) before and b) after perforation, and counterfaces (Kam mili malzemelerin a) delme işleminden önceki ve b) sonraki ve karşı malzemelerin görüntüleri)

tests. There are two reasons behind that: i) the wear rate of the composites which had larger ceramic reinforcements (20 µm compared to 2 µm) initiated three body abrasive wear (especially A30S_20 specimens) and reduced the wear resistance of composites. ii) the difference in the wear rate was more prominent for the 20 and 30 vol. % ceramic content. In other words, based on the results of the previous study, only the best performing samples are selected for the extended duration wear performance evaluation. Finally, the lobes made of merely the Al matrix could not complete the testing because it was pasted to the counterface. With these realizations presented, performance wear test results are given in Figure 5.

It can be seen from the **Figure *5*** that the wear rate of the composites is slightly higher than the cast iron, especially at shorter durations. However, as the duration of the wear increases, the overall wear rate is almost similar for all the samples. Additionally, the higher ceramic content reduces the wear in the composites, much significantly, at the lower sliding distances/war durations. Reduced wear in the composites has been reported by various authors such as Bhowmik et al. [25] and Uzkut et al. [26] with increasing SiC content.

One of the important issues related to the wear of the metals or metal matrix composites is the plastic deformation due to repeating action of sliding. For example, when two surfaces interact for a longer duration, the top surface is plastically deformed and hardened [27]. Since samples are also subjected to a force of 115 N, the phenomenon of deformation under loading is further encouraged. The wearing of such a hardened surface can happen under two circumstances: a) spalling [10] that is possible if there are major cracks or grooves formed during wear in the subsurface, and b) further increasing the load so that cracks could be formed in the hardened surface. In comparison to the fresh surface, the hardened surface that has deformed past its plastic limit is more difficult to wear in both situations. Because of this, regardless of the ratios of reinforcement, composites exhibit somewhat less wear over extended periods of time, as shown in **Figure *5***(a).

The A30S_2 and NGCI specimens exhibit comparable wear loss in the composites, but their wear behaviors are not the same. It should be mentioned that the study's goal is to offer a lightweight substitute for the cast iron camshaft lobes that are currently in use. The benefits of adding ceramic-reinforced camshaft lobes are thus much more accurately represented when the wear resistance (inverse of wear rate) is divided by the density of the tested samples. The specific wear resistance of the camshaft lobes tested in this study is given in Figure 6 and the advantage of the A30S_2 specimen can be clearly seen.

It's critical to realize that a mechanical component's wear cannot be addressed separately. It is imperative that a component not be added to the machine if it exhibits adequate wear resistance but results in excessive wear on the counterface. Therefore, current study reports the results of the wear tests in conjunction with the wear in the counterface. Figure 7 shows the combined wear resistance of the counterface and the composite lobes.

It can be seen in Figure 7(a) that although wear resistance of the 30 vol.% SiC reinforced composite

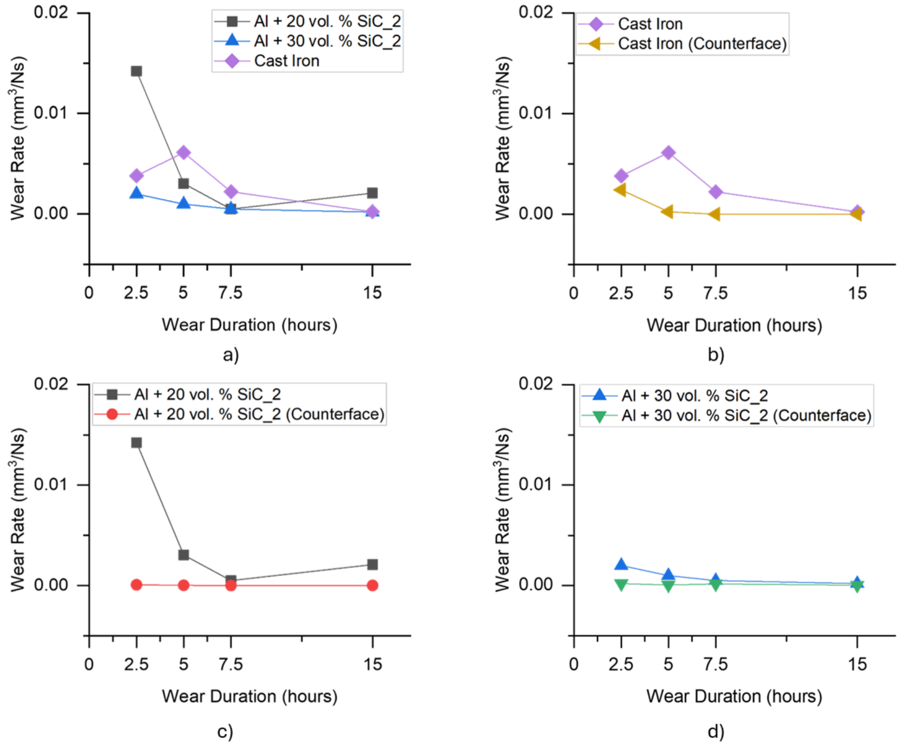

Figure 5. Wear rates of the a) tested samples and comparison with the counterfaces for b) NGCI, c) A20S_2, d) A30S_2 under a load of 115 N, angular speed of 500 rpm (a) test edilen numunelerin aşınma oranları ve b) NGCI, c) A20S_2, d) A30S_2 ile karşı yüzeylerle karşılaştırılması, 115 N yük, 500 rpm açısal hız)

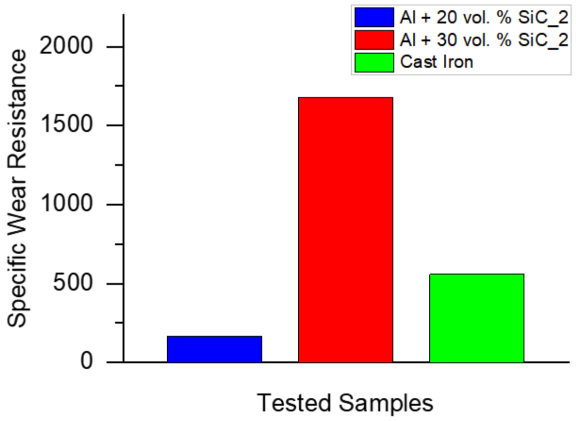

Figure 6. The specific wear resistance of the camshaft lobes (Kam mili malzemelerin spesifik aşınma direnci)

lobes is higher; it occurs on the expense of excessive wear in the counterface – a situation that is not preferred. Although the wear resistance of the 20 vol.% SiC composites is lower, it shows a fairly (almost 1:1) ratio of the wear that is divided between counterface and composite lobe. Figure 7(b) shows the comparative specific wear resistance of the samples taking the wear resistance of the NGCI as 100%. Here again, the specific wear resistance of the A20S_2 is lower than the A30S_2.

In order to analyze the influence of the impact force on the wear resistance of the composites, some samples were selected to complete the wear tests at increasing loads. The load profiles for increasing loads at the tip (180° represents tip) are shown in **Hata! Başvuru kaynağı bulunamadı.**(a). The d etails about the springs compression and the methodology that is used for calculating the load value is given in detail somewhere else [5]. One of the influences of the higher loads is the reduction in the vibration between the contacting surfaces of counterface and camshaft lobe. Reduction in the vibration also reduces the repeating impacts on the wear specimen. As the angular speeds increase, so does the impact intensity. Because of this, the composites' wear resistance is increased, and their wear rate is slightly reduced as a result of the higher load values as shown in **Hata! Başvuru kaynağı b ulunamadı.**(b). Alidokht et al. [9] reported a slight increase in the wear loss 25% for increasing load from 10 to 25 N and 30% for increasing load from 25 N to 40 N for Al + SiC composites. Other authors [12-15] have also reported the influencing of increasing loads on the wear behavior of similar composites (see Table 1), however, the results might not agree with the current experiment. The reason behind that is the difference in the wear setup mechanism (such as reduction of vibration at increasing loads) peculiar to the current wear evaluation setup this project uses. As for the wear of the counterface, except for the NGCI specimen, the wear rate remained fairly

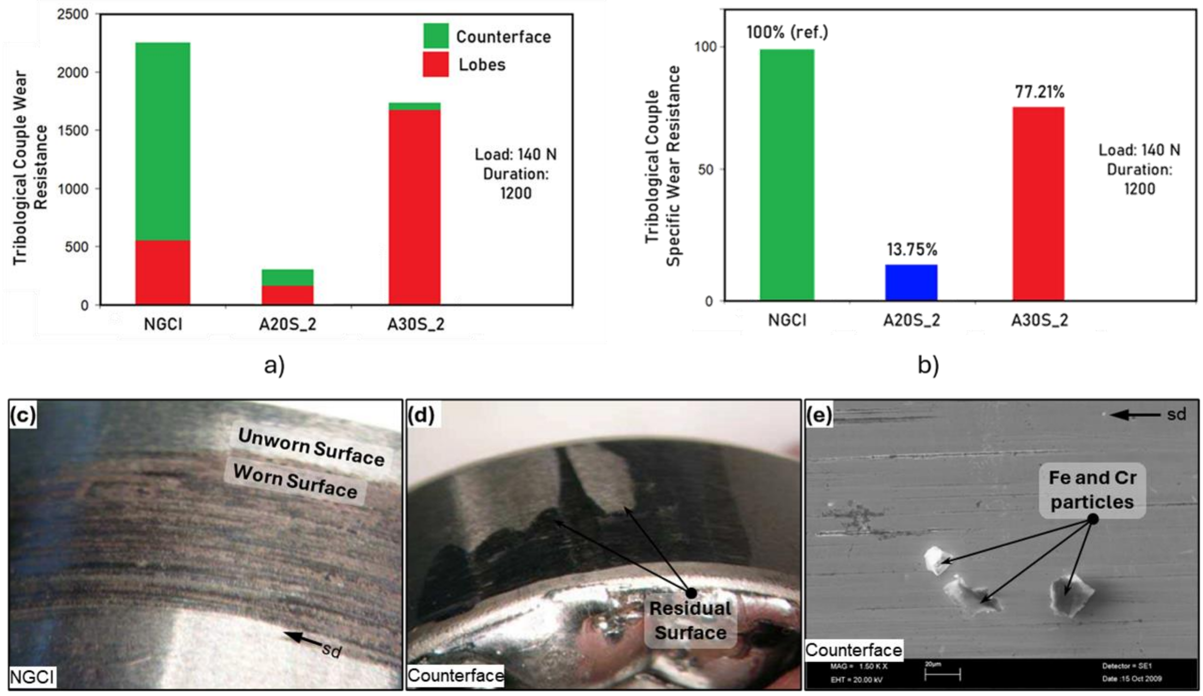

Figure 7. a) Tribological couple wear resistance and b) tribological couple specific wear resistance of the selected composites and reference cast iron. Wear in the c) NGCI and d, e) counterface (a) Seçilen kompozitlerin ve referans dökme demirin tribolojik çift aşınma direnci ve b) tribolojik çiftin spesifik aşınma direnci. c) NGCI ve d, e) karşı yüzeyinde aşınma)

similar at all wear durations (Figure 5(b, c, d)). The reason for higher wear in the counterface against the NGCI is the higher hardness[28] of NGCI which in turn was intentionally improved using the induction hardness treatment [22] (Figure 3) at shorter durations. As the wear duration increases, the surface of the counterface or the NGCI is deformation-strengthened and wear in both interacting faces is reduced. Additionally, Figure 7(c) shows that the worn surface of the NGCI lobes has sliding wear traces where aggressive grooves are not formed. The counterface, while being worn against NGCI, also lacks excessive wear traces Figure 7(d).

It can be seen in **Hata! Başvuru kaynağı b ulunamadı.**(a) that surface of the Al + 30 vol.% SiC (2 µm) is much susceptible to wear at tip and at the lift region, based on the surface roughness.

The micrographs subsection provides the surface roughness of the scanned line on the micrograph. It is commonly known that wear-induced scratches and grooves increase surface roughness. Additionally, there remains a transition region

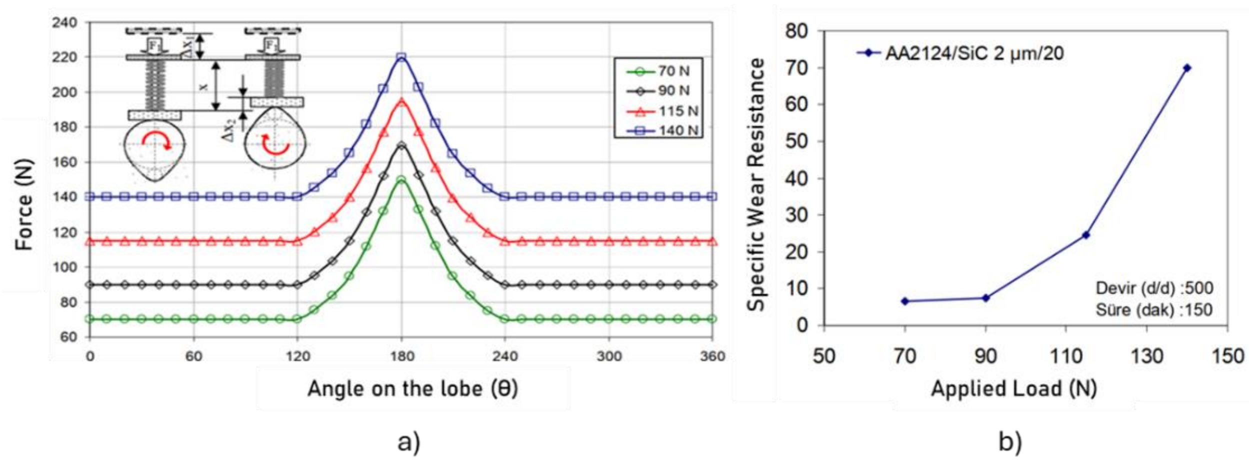

Figure 8. a) The load profiles of the camshaft lobes and b) influence of increasing applied loads on the specific wear resistance of the camshaft lobes (a) yük profilleri ve b) artan yüklerin kamların spesifik aşınma direnci üzerindeki etkisi)

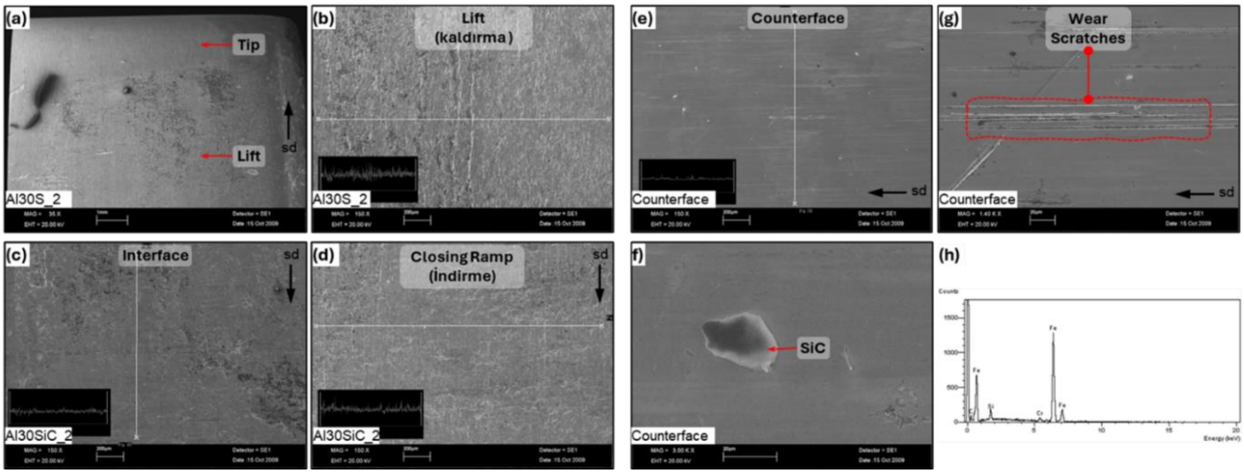

Figure 9. Microstructure of the different regions of the composite lobe and the counterface (Kompozit kamın ve karşı yüzeyin farklı bölgelerinin mikro yapısı)

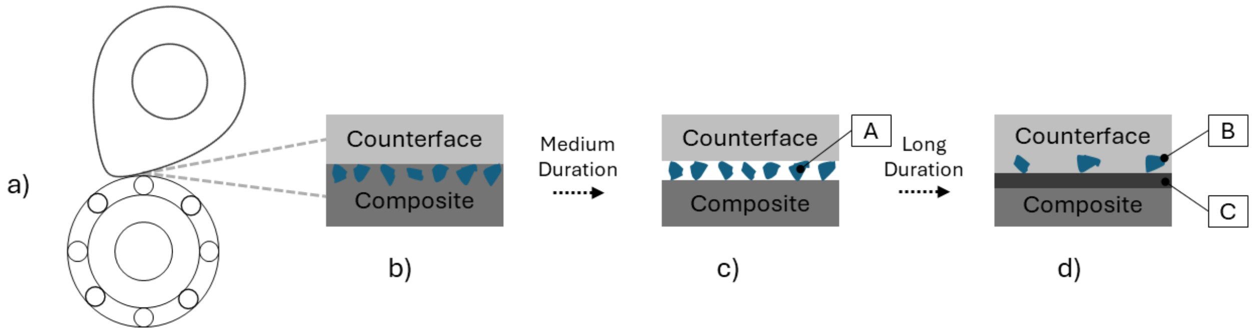

Figure 10. a, b, c, d) Various microstructural features at the counterface and composite interfaces. A: dislodged ceramic particles, B: embedded ceramic particles, C: hardened top surface. (Karşı yüzey ve kompozit arayüzlerde çeşitli mikroyapısal özellikler. A: yerinden çıkmış seramik parçacıkları, B: gömülü seramik parçacıkları, C: sertleşmiş üst yüzey)

between the lift and tip that has lower roughness **Hata! Başvuru kaynağı bulunamadı.**(c) compared to tip **Hata! Başvuru kaynağı bulunamadı.**(b) and lift **Hata! Başvuru kaynağı bulunamadı.**(d). As for the closing ramp, the roughness is slightly lower than the tip since this region of the cam does not counter the load imposed by the springs. Our previous study [5] as well as Burdzik et al. [7] reported a region dependency of wear in the camshaft lobes after 2.5 h and a distance of 1250 – 48500 km, respectively.

The microstructure of the counterface reveals that the wear scratches on the counterface are not considerable deep (**Hata! Başvuru kaynağı bulunamadı.**(g)) enough to increase the surface roughness dramatically (**Hata! Başvuru kaynağı bulunamadı.**(e)). This behavior is attributed to the smaller size (2 µm) of the ceramic particles. However, it must be noted that the there was a significant wear in the counterface against the A30S_2 specimen (as shown in Figure 7 (a)). So, if the surface roughness of the counterface is lower, wear has to occur via mechanism of excessive ceramic particles that must have initiated the three-body abrasive wear and not via the mechanism of the aggressive ploughing in the counterface. This claim is supported by the transferring and embedding of the SiC particles from the composite to the counterface as shown in **Hata! Başvuru kaynağı bulunamadı.**(f) and confirmed with the EDS analysis shown in **Hata! Başvuru kaynağı bulunamadı.**(h). Because of the viscous oil, some of the counterface's broken particles remain inside the wear system for an extended period of time, as shown in Figure 7. Figure 10 schematically shows the initiation of three body abrasive wear due to dislodged ceramic particles (annotation A) and formation of hardened layer due to repeating sliding loads (annotation C) for a longer (above 10 hours) duration.

4. CONCLUSIONS (SONUÇLAR)

This study reported the performance potential of ceramic-reinforced Al matrix composites (CMMCs) as lightweight alternatives to cast iron camshafts in engines, with a particular focus on their wear performance under semi-engine like conditions. Following conclusions from the study can be deduced.

- Ceramic reinforced Al matrix composites exhibited a positive correlation in wear with higher SiC content (20% and 30% tested), showcasing their potential for weight reduction without significantly compromising the performance.

- As the duration of the experiment increased, the wear loss of the composites showed similar values due to formation of hardened top surface. The surface is hardened due to fatigue and sliding under loads that yields the metallic matrix beyond its elastic limit.

- Al + 20 vol. % SiC composite showed adequate wear resistance with a little counterface wear, offering a practical balance between durability and component protection. As for the Al + 30 vol. % SiC, it showed superior wear resistance, but it triggered significant counterface wear due to dislodged SiC particles that initiated three-body abrasive wear.

ACKNOWLEDGMENTS (TEŞEKKÜR)

The authors are grateful for the financial support of the Erciyes University Scientific Research Projects Coordination Unit, grant number FBT07-55, and the Scientific and Technological Research Council of Türkiye (TUBITAK), grant number 106M021. Authors are grateful to Kim Technologies, Kayseri for providing assistance in the characterization of the produced samples.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The authors of this article declare that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIDenklemi buraya yazın.N KATKILARI)

Alper Afşın CERİT: He designed the testing setup, manufactured the test samples, conducted the experiments, created test reports and analyzed the results.

Test düzeneğini tasarladı, test numunelerini üretti, deneyleri gerçekleştirdi, test raporları oluşturdu ve sonuçları analiz etti.

Fehmi NAİR: He supervised the project, designed the wear testing setup, created sources, guided the manufacturing process, conducted the experiments, and analyzed the results.

Projeyi denetledi, aşınma testi düzeneğini tasarladı, kaynaklar oluşturdu, üretim sürecini yönlendirdi, deneyleri yürüttü ve sonuçları analiz etti.

HM Numan ZAFAR: He analyzed the test results, designed the tests report methodology, explained the wear mechanisms and prepared the manuscript.

Test sonuçlarını analiz etti, test raporu metodolojisini tasarladı, aşınma mekanizmalarını açıkladı ve makaleyi hazırladı.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] Heyes, AM, Automotive component failures. Engineering Failure Analysis, 5 (1998) 129-141.
[2] Colin García, E, et al., Microstructural and Mechanical Assessment of Camshafts Produced by Ductile Cast Iron Low Alloyed with Vanadium. Metals, 11 (2021) 1-18.
[3] Gafur, MA, Haque, MN, and Prabhu, KN, Effect of chill thickness and superheat on casting/chill interfacial heat transfer during solidification of commercially pure aluminium. Journal of Materials Processing Technology, 133 (2003) 257-265.
[4] Dahuri, SM, Subri, NHA, and Noor, NM, Stress analysis of engine camshaft from light metal. International Journal of Scientific and Engineering Research, 2 (2018) 37-44.
[5] Cerit, AA, et al., Comparison of the surface morphologies of ceramic reinforced metal matrix composite cams after wear tests under dry and wet conditions. Journal of Composite Materials, 57 (2023) 1541-1556.
[6] Barothi, L, et al. Study regarding the influence of geometrical characteristics of the distribution system on truck engines efficiency parameters. in IOP Conference Series: "Materials Science and Engineering". 2022. Chisinau, Republic of Moldova: IOP Publishing.
[7] Burdzik, R, et al., Attempt to assess operational wear of camshaft cams. Archives of Materials Science and Engineering, 57 (2012) 57-62.
[8] Godiño, JAV, et al., Failure analysis of an overhead valve train system in urban buses.

Engineering Failure Analysis 96 (2019) 455-467.

[9] Alidokht, SA, Abdollah-Zadeh, A, and Assadi, H, Effect of applied load on the dry sliding wear behaviour and the subsurface deformation on hybrid metal matrix composite. Wear, 305 (2013) 291-298.

[10] Jamaati, R, Naseri, M, and Toroghinejad, MR, Wear behavior of nanostructured Al/Al2O3 composite fabricated via accumulative roll bonding (ARB) process. Materials & Design, 59 (2014) 540-549.

[11] Shinde, DM and Sahoo, P, Influence of Speed and Sliding Distance on the Tribological Performance of Submicron Particulate Reinforced Al-12Si /1.5 Wt% B4C Composite. International Journal of Metalcasting, 16 (2022) 739-758.

[12] K, R and M, B, Dry Sliding Wear Behavior of Aluminum Metal Matrix Composite Reinforced with Lithium and Silicon Nitride. Silicon, 14 (2022) 115-125.

[13] Buliwal, A, Dhakar, B, and Pare, V, Fabrication of aluminum based metal matrix composite using stir casting method and characterize its tribological properties. Materials Today: Proceedings, 61 (2022) 78-83.

[14] Singh, C, Mer, KKS, and Kumar, H, *Synthesis and Dry Sliding Wear Characterization of Aluminum based Metal Matrix Composite Reinforced with In-situ (Iron ore) Alumina*, in *Department of Mechanical Engineering Govind Ballabh Pant Engineering College Ghurdauri*. 2010. p. 198.

[15] Shivaprakash, YM, Basavaraj, Y, and Sreenivasa Prasad, KV, Comparative study of tribological characteristics of AA2024+ 10% fly ash composite in non-heat treated and heat treated conditions. International Journal of Research in Engineering and Technology, 2 (2013) 275-280.

[16] Suresha, S and Sridhara, BK, Effect of silicon carbide particulates on wear resistance of graphitic aluminium matrix composites. Materials & Design, 31 (2010) 4470-4477.

[17] Muley, AV and Ruchika, Wear and friction (Tribological) characteristic of aluminum based metal matrix hybrid composite: An overview. Materials Today: Proceedings, (2023).

[18] Basavarajappa, S, et al., Dry sliding wear behavior of Al 2219/SiCp-Gr hybrid metal matrix composites. Journal of Materials Engineering and Performance, 15 (2006) 668-674.

[19] Schumacher, EE and Souden, AG, Some aspects of powder metallurgy. The Bell System Technical Journal, 23 (1944) 422-457.

[20] Zafar, HMN and Nair, F, Fabrication and Microscale Characterization of Iron Matrix Composite Wires Reinforced by in situ Synthesized Iron Boride Phases. Arabian Journal for Science and Engineering, 48 (2023) 3909-3930.

[21] Zafar, HMN and Nair, F, Quantitative Analysis of Codeformation Behavior of Ceramic and Metallic Particle System. Journal of Materials Engineering and Performance, (2023).

[22] Doyon, G, Rudnev, V, and Maher, J, *Induction hardening of crankshafts and camshafts*, in *ASM Handbook*, V.R.G.E. Totten, Editor. 2014, ASM International: Ohio, USA. p. 172-186.

[23] Cruz Ramírez, A, et al., Evaluation of CADI Low Alloyed with Chromium for Camshafts Application. Metals, 12 (2022) 1-24.

[24] Dayanç, A, Karaca, B, and Kumruoğlu, L, The cathodic electrolytic plasma hardening of steel and cast iron based automotive camshafts. Acta Physica Polonica B, 131 (2017) 374-378.

[25] Bhowmik, A, Dey, D, and Biswas, A, Microstructure, mechanical and wear behaviour of Al7075/SiC aluminium matrix composite fabricated by stir casting. Indian Journal of Engineering and Materials Sciences, 28 (2021) 46-54.

[26] Uzkut, M, Abrasive wear behaviour of SiCp-reinforced 2011 Al-alloy composites. Materials and Technology, 47 (2013) 635-638.

[27] Alpas, AT, Hu, H, and Zhang, J, Plastic deformation and damage accumulation below the worn surfaces. Wear, 162 (1993) 188-195.

[28] Gangopadhyay, A, Soltis, E, and Johnson, MD, Valvetrain friction and wear: Influence of surface engineering and lubricants. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 218 (2004) 147-156.