Investigating the Effect of Surface Roughness on Tribological Performance of Machine Elements

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Abstract.

The effectiveness, dependability, and lifetime of machine components are greatly influenced by the tribological performance of those components. It has been established that surface roughness, a crucial aspect of engineering surfaces, has a major impact on tribological behaviour. With an emphasis on friction, wear, and lubrication, the goal of this study is to ascertain how surface roughness affects the tribological performance of machine components.A number of experiments on various machine parts, including gears, bearings, and sliding components, are part of the experimental inquiry. Using sophisticated surface profilometry techniques, the surface roughness parameters, including average roughness (Ra), root mean square roughness (Rq), and peak-to-valley height (Rz), are carefully regulated and quantified.The tribological tests are carried out under a variety of operating circumstances, such as varied weights, sliding velocities, and lubrication regimes. A tribometer is used to assess frictional behaviour, while optical profilometry and scanning electron microscopy (SEM) are used to examine worn surfaces and quantify wear. Additionally, the impact of lubricants is assessed, taking into account both their viscosity and additives.This study advances knowledge of the complex interplay between machine component surface roughness and tribological performance. The research will help engineers and designers choose the best lubrication methods, choose the right surface treatments, and improve the overall performance and longevity of machine systems. Additionally, the findings will offer insightful information for creating computational simulations and predictive models to further investigate the complicated tribological behaviour under various operating situations.

Keywords: surface roughness, tribological behaviour, composites, bronze matrix
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I. Introduction

For more than 40 years, a significant area of research has focused on the impact of surface roughness patterns on the tribological performance of mechanical elements. Understanding surface layer qualities is essential for understanding and improving tribological behaviour. Superior tribological qualities are necessary to ensure a long operational life for machine parts such bearings, gearboxes, camshafts, and crankshafts. Addressing scientific issues with friction, contact mechanics, heat conduction, electric current conduction, and component design requires a thorough understanding of engineered surfaces [1].Surface texture is a crucial factor influencing tribological behaviour, and surface roughness has received substantial theoretical and experimental study. In order to investigate the effects of surface roughness height and distribution between components on the lubrication of machine elements, Patir and

Cheng developed a stochastic analytic methodology [2], [3]. The effectiveness of cams and followers has also been evaluated using this methodology [4], [5]. For instance, in a direct-acting cam and follower configuration,[3] looked into the projected impacts of surface roughness on nominal film thickness, power loss, and load carried by asperities. Research on the possibility of surface texturing to minimise friction in boundary lubrication situations with high contact pressure, such as in cam/follower applications, is lacking.

It is necessary to improve copper's mechanical properties, notably in terms of tensile strength and tribological performance, in order to solve the limits of copper in specific application areas [9–12]. To do this, carefully chosen reinforcements that can preserve copper's natural characteristics while enhancing its matrix are needed [13]. Several studies have concentrated on creating well-structured composites with copper as the main component in this context. Researchers have recently paid a lot of attention to graphene-reinforced copper composites [2, 14, 15]. It has been determined that graphene is a superior reinforcing material with remarkable qualities.

In one significant study, Mai et al. [16] looked into the synthesis of nickel-reinforced graphene for the creation of self-lubricating materials. The study showed that copper's tribological characteristics were enhanced by the addition of a certain concentration of nickel-reinforced graphene. The results revealed that adding grapheme-reinforced nickel to copper-based composites improved their resistance to wear and friction.

These findings emphasise the promise of grapheme-reinforced copper composites as a potentially effective strategy to get over the drawbacks of pure copper, notably in terms of mechanical strength and tribological behaviour. Researchers may modify the characteristics of copper-based composites to satisfy particular application needs by choosing the right reinforcement elements and optimising their concentration, which improves performance and durability in a variety of engineering applications.

Therefore, it is unclear how surface texturing will behave under these circumstances. In particular, in boundary lubrication situations, more research is required to examine the possible advantages of surface roughness patterns and texture alterations on the tribological performance of machine elements. Investigating how surface roughness patterns affect load distribution, wear prevention, and friction reduction will help develop creative design approaches and surface engineering strategies that will improve the efficiency and durability of machine systems that operate at high contact pressures

II. Review of Literature

In a study, the tribological performance of copper pins made by adding MoS2 in comparison to AISI 52100 was examined. The ideal MoS2 content was established by an optimisation research [17]. Ti2SnC particles, which have better electrical and mechanical properties, were studied by Wu et al. [18]. The wear rate and friction coefficient significantly improved with the addition of Ti2SnC.The impact of sliding distance on the tribological behaviour of composite materials made of copper and graphite was studied in a different investigation by Ma and Lu [19]. Under various sliding distances, the study evaluated friction conditions and wear mechanisms. Additionally, a different study [20] looked at the impact of graphite particle size on the tribological characteristics of composites made of copper.

These studies illustrate numerous strategies for improving the tribological performance of composites made of copper. Researchers have successfully increased wear resistance, friction coefficient, and other tribological features by adding additives like MoS2, Ti2SnC, and graphite particles. For creating copper-based composites with improved tribological properties, the measurement of sliding distance and particle size impacts, as well as the optimisation of additive content, offer useful insights. These discoveries give up new opportunities for the application of materials with enhanced performance and durability in a variety of engineering sectors.

A different study [21] added graphite to a copper material's structure to look at how it affected the material's surface characteristics, tribology, and wear mechanisms. The impact of graphite on the overall tribological behaviour and wear properties of the copper composite was examined by the researchers.

Additionally, Cao et al.'s [22] research focused on graphene and tungsten- and copper-based composites. To assess the composites' performance in terms of wear resistance and tribological behaviour, different loads were applied to them. The goal of the study was to comprehend how adding tungsten and graphene affected the tribological characteristics and wear mechanisms of copper matrix composites.

Additionally, a team of authors looked into copper-based composites created especially for spacecraft rendezvous [23]. The goal of the study was to learn more about how these composite materials behaved and performed tribologically under the unique circumstances of space missions. In the context of spacecraft applications, the study concentrated on comprehending the tribological behaviour and wear properties of the composites made of copper.

These studies investigate the effects of several additions, including graphite, graphene, and tungsten, on the tribological characteristics of composites made of copper. Researchers want to increase wear resistance, enhance tribological behaviour, and better understand the underlying wear mechanisms by adding these materials. These discoveries aid in the creation of copper-based composites designed for certain uses, such as space travel and other high-performance industries.

III. Methodology and Material

The cylindrical bars of CuSn10 and GGG-40 with 22 mm diameters, according to the necessary chemical composition. These bars were then subjected to standard lathe machining without the use of cutting fluid. In order to obtain metallic chips for use in subsequent production processes, the machined bars were subsequently sieved using 2-1 mm sieves. Our previously published studies contain further details about the hot pressing procedure and the subsequent production steps.Metal matrix composites (MMCs) were created in the experimental experiments using GGG40 as the reinforcement material and metallic chips as the matrix material. These materials were selected due to their wide variety of uses and good mechanical qualities. Particularly due to its superior corrosion resistance and thermal conductivity, CuSn10 is preferred for machine parts.

As a reinforcing material, GGG40 has porous structures and graphite, which make it appropriate for use as a lubricant in a variety of applications. Due to its special qualities, it can be used as a lubricant in a variety of applications.

1. Production of Composite Materials

Four alternative mixture ratios were chosen for the creation of metal matrix composites (MMCs), and they were mechanically mixed by weight in accordance with the guidelines in Table 1. The components were distributed uniformly thanks to the mixing process. The mixture was then put into moulds made of hot work tool steels to begin the hot pressing procedure. Heat isolation techniques were used during the hot pressing process to reduce temperature losses.Three different pressures and two different temperatures were used during the production process. These modifications made it possible to investigate various production settings and how they affected the final MMCs. Raw CuSn10 and GGG40 were examined as reference materials, and their characteristics were contrasted with those of the MMCs created, specifically designated as "100B."

Depending on the particular production parameters used, the MMCs produced after the hot pressing process had a diameter of 19.6 mm and a length ranging from 32 to 36 mm. Based on the temperature and pressure settings used during the production process, the samples' pore density and presence varied. The morphology and final sample size were affected by these changes.Overall, the experimental process included establishing mixture ratios, mechanical mixing, hot pressing in moulds, and testing the created MMCs in comparison to reference materials. The temperature and pressure settings that were used to create the MMCs had an impact on their size and pore content.

Table 1: Summary of Composite material with parameter

Code	Weight Ratio (wt%) Mixture	Temp (°C)	P (MPa)
60B50C	61% CuSn11 - 41% GGG40	400 - 450	482, 650, 825
70B40C	72% CuSn11 - 31% GGG40	400 - 450	482, 650, 825
80B10C	82% CuSn11 - 21% GGG40	400 - 450	482, 650, 825
90B20C	91% CuSn11 - 11% GGG40	400 - 450	482, 650, 825
100B	110% CuSn11 - 1% GGG40	400 - 450	482, 650, 825

2. Measurement of Surface Roughness

The Mitutoyo SJ-201 surface roughness instrument was used to measure surface roughness. This particular kind of instrument enables the measurement of surface roughness in a range of materials, including metals, hard plastics, and wood. The device has a portable end piece and a main body, giving it flexibility in use.The device's needle tip was set up for our measurements to scan the surface roughness at a distance of 2.5 mm. Although the gadget has three distinct measuring distance settings, we carefully kept the distance constant to ensure consistency and accuracy of the measurements. The metal matrix composites (MMCs) and needle tip were held constant throughout the measurements to reduce any potential errors.

The Ra and Rz values could be determined thanks to the surface roughness measuring instrument. The examination of any changes in surface roughness before and after the abrasion tests is made possible by these factors, which provide quantitative information about the specimens' surface roughness characteristics.

3. The Microstructure sample

The scanning electron microscope (SEM) image of the 70B30C material produced at a pressure of 820 MPa. The material's porous surface features, as well as the matrix and reinforcing components, are all visible in the photograph. SEM pictures also reveal the modifications made to the contact surface after the metal matrix composites (MMCs) underwent wear tests. In every shot, the direction of wear can be seen moving from left to right.In the contact areas during the wearing process, noticeable adhesive wear zones were seen. This behaviour was attributed to the abrasion-damaged CuSn10 powders being reintroduced into the wear zone as a result of the revolving abrasive disc's effect. The contact zone experienced severe plastic deformation and elevated temperatures as a result of the abraded particles' re-entry. The identified adhesive wear zones were formed as a result of the interaction between plastic deformation and high temperatures [11, 12].

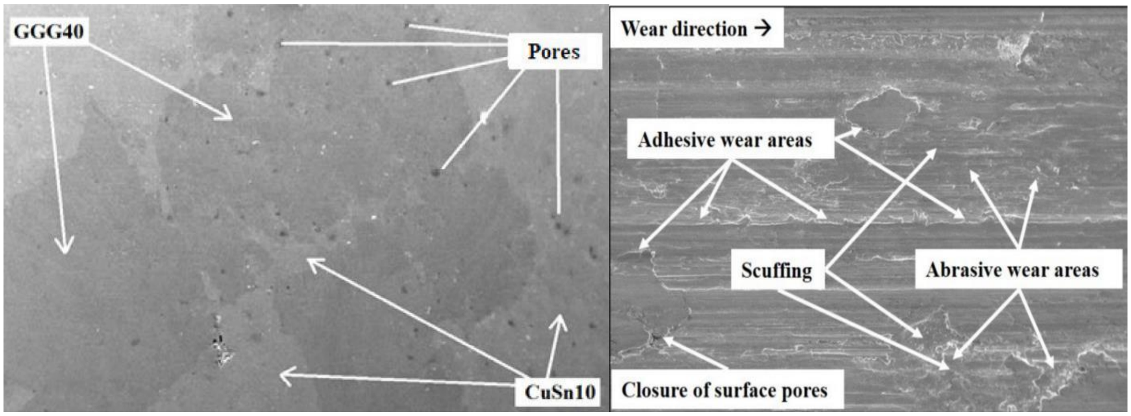
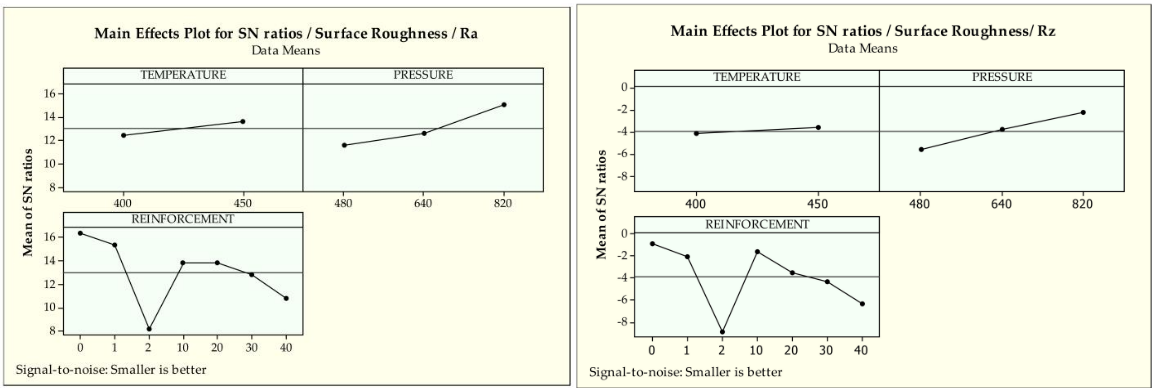


Figure 1: Sample Images SEM (a) prior wear (b) post wear

4. Optimization of the Parameter for Surface Roughness

A key element in assuring part quality and reducing energy usage is achieving optimal surface roughness values [7,8]. It's vital to remember that unique systems might be negatively impacted by both extremely low and high roughness levels. The operational range and performance of the work piece are significantly influenced by the quality of the machined surface, which includes elements like tensile strength, fatigue life, and tribological behaviour.One recognised truth is that machined items perform worse under fatigue when their surfaces are rougher [9]. The problem becomes more complicated, though, when considering how surface roughness affects tribological behaviour. Whether decreased surface roughness is intrinsically advantageous or unfavourable for particular tribological systems is not firmly established [10]. As a result, it is crucial to examine and assess product quality in order to comprehend the unique requirements and characteristics of a certain tribological system.

The surface qualities are consistently impacted by the production settings, as shown by an analysis of Figures 2 and 3. In particular, the surface roughness values decrease as the production parameters, such as pressure and temperature, are raised. This observed behaviour can be attributed to the enhanced production parameters' improved interfacial bonding quality between the metallic chips [3].The mechanics of the metallic chips' plastic deformation and softening are improved by increased pressure and temperature. These circumstances make it easier for the tin bronze chips to successfully penetrate the cast iron chips, which eventually improves structural integrity in the metal matrix composite (MMC) systems.



(a) (b)

Figure 2: (a) Signal to Noise ratio of surface RougfnessR$_a$(b) Signal to Noise ratio of surface Rougfness R$_z$

The control parameters, particularly temperature, have a rather negligible impact on surface roughness, as can be seen by analysing the Ra results shown in Table 2. As a result of the control factors' relative contribution percentages and the analysis's high error rates, identifying the controlling factor with the greatest influence on surface attributes becomes difficult.

However, the arithmetic average value of surface roughness shows a substantial influence from the reinforcement material and pressure. According to the percent contribution and p-values (0.001, 0.002 0.05), it is clear that pressure (17.5%) and the reinforcing material (51.6%) are key factors in influencing surface roughness. These variables significantly affect the surface roughness values and are statistically significant.

5. Tribological Behaviour

The findings show that the maximum contact load rises with the cam profile and achieves its maximum value at the cam nose (about 900 cam angles), regardless of lubrication state. When the preload is constant, the contact load around the cam nose is the same in both lubricated and non-lubricated conditions.The friction force and friction coefficient between the lubricated and non-lubricated cases, however, differ significantly. When opposed to a lubricated contact, friction values are higher when there is no lubrication. This shows in figure 3 that the presence of lubricating oil lowers the friction coefficient in the cam contact by reducing the friction force.

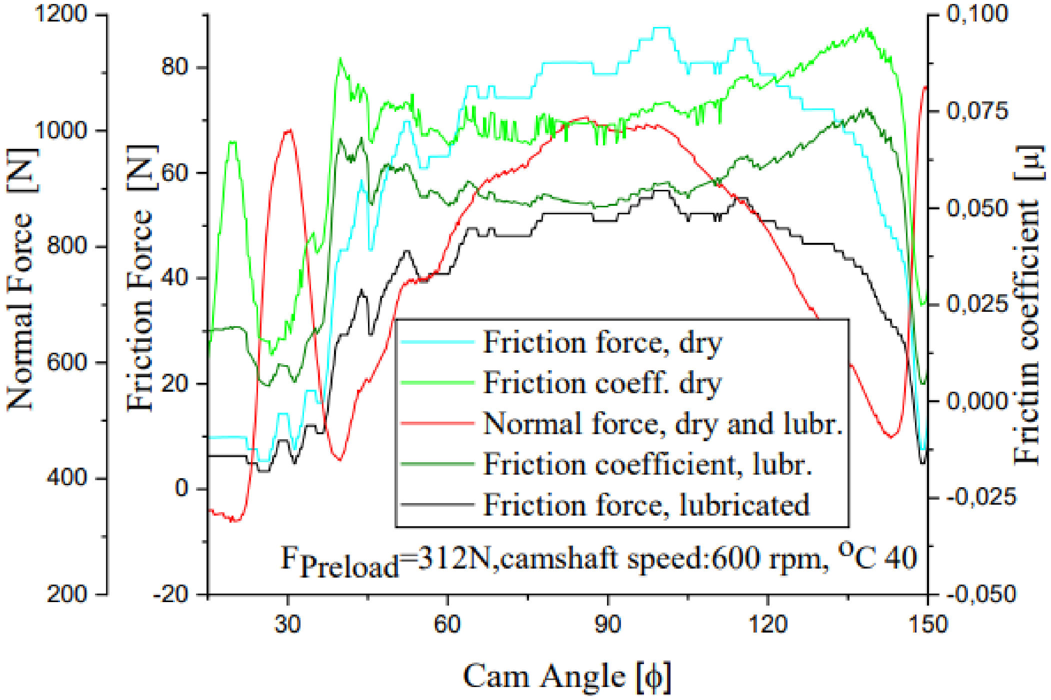


Figure 3: A cam is lubricated with base oil, normal force, friction force, and friction coefficient are present

Table 2: S/N ratios of surface roughness (Ra) were the subject of a variance analysis.

Source	(DOF) Degree of Freedom	(SoS) Sum of Squares	(MS) Mean Square	(F) The F-Value	(F) The p-Value	%of Contribution
Temp (T)	1	13.76	16.759	3.29	0.183	2.7
Pressure (P)	3	88.69	44.845	9.59	0.011a	17.5
(R) Reinforcement	7	277.18	47.364	11.03	0.001a	53.6
(RE) Residual error	31	146.88	5.621	-	-	28.9
Total	42	529.51	-	-	-	-

Table 3: S/N ratios of surface roughness (Rz) were the subject of a variance analysis.

Source	(DOF) Degree of Freedom	(SoS) Sum of Squares	(MS) Mean Square	(F) The F-Value	(F) The p-Value	%of Contribution
Temp (T)	1	3.96	3.97	2.29	0.133	0.7
Pressure (P)	3	77.825	34.845	23.59	0.001a	17.5
(R) Reinforcement	7	297.18	47.364	49.03	0.001a	67.6
(RE) Residual error	31	56.88	1.621	-	-	19.9
Total	42	439.51	-	-	-	-

IV. Conclusion

It has been thoroughly investigated and analysed how surface roughness affects the tribological performance of machine components. The tribological behaviour of machine components has been found to be highly influenced by surface roughness, which has been highlighted as a key parameter.To comprehend how surface roughness affects friction, contact mechanics, heat conduction, electric current conduction, and component design, experimental and theoretical studies have been carried out. Surface texture has been found to be essential in regulating tribological behaviour.Numerous investigations have concentrated on adding reinforcement components to the copper matrix in an effort to enhance its mechanical and tribological properties, such as graphene, MoS2, Ti2SnC, and graphite. The wear resistance and friction levels of machine elements have been improved by these reinforced copper composites, with encouraging results.Furthermore, it has been discovered that the manufacturing variables, such as pressure and temperature, significantly affect surface roughness. Reduced surface roughness during the manufacturing process as a result of higher pressure and temperature during the process suggests greater interfacial bonding between metallic chips and better structural integrity in the composite systems.The best surface roughness for a given tribological system can be difficult to determine. It is crucial to take into account elements like part quality, energy usage, fatigue performance, and particular application needs. On the tribological performance of machine elements, surface roughness values that are both too low and high might have negative impacts.

V. Future Direction

Investigating how surface roughness affects the tribological performance of machine parts can help to increase the robustness and effectiveness of diverse mechanical systems. In light of the study's results and recommendations, the following are a few possible future lines of inquiry:

Enhance tribological performance by optimising the surface roughness characteristics. This is the main area of interest for future research. This may entail investigating various surface texturing methods, such as electrochemical polishing and laser texturing, to precisely regulate and change surface roughness at the micro- and nanoscale.

Examine the impact of lubricants: Additional research can be done to determine how different lubricants and surface roughness affect tribological behaviour. Studying how different lubricants, additives, or solid lubricant coatings function in reducing friction and wear under varied surface roughness conditions might help with this.

Think about various machine element geometries: Surface roughness can have a variety of effects on tribological performance, depending on the particular machine element shape and contact arrangement. To further understand the tribological interactions unique to each machine element, more research can examine the effects of surface roughness on other types of machine elements, such as gears, bearings, or sliding components.

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